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Generating Innovative Perforated Patterns for Perimetric Structural Walls with Openings in Multi-Storey Buildings

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Generating Innovative Perforated Patterns for Perimetric Structural Walls with Openings in Multi-Storey Buildings

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INTERNATIONAL DOCTORATE in ARCHITECTURE AND URBAN PLANNING

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IDAUP Coordinator Prof. Roberto DI GIULIO

Thesis Title

Generating Innovative Perforated Patterns for Perimetric Structural Walls with Openings in Multi-Storey Buildings

Curriculum Architecture / IDAUP Topic 1.3 Innovative technologies and material for industrial building and structural design. (Area 08 – SDS: ICAR10 Building design)

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Abstract_EN

Due to the very fast urban development and population growth to the most big cities all over the world, the multi-storey buildings have increased a lot in number. Increasingly, interest is growing in exploring structural systems that allow to build multi-storey buildings.

As stated also in the literature and also by Ali. M., M, in his study in 1990, among the major issues that govern the design of a multi-storey building is fulfilling the architectural aspect such as space, function, light while ensuring also the building structural rigidity.

Considering also the fact emphasized by Aminmansour & Moon, 2010; Elnimeiri & Gupta, in their study in 2008, that many times, the multi-storey buildings tend to be very inefficient in terms of organisations of the interior spaces. In this regard, based on engineering logical reasoning, in order to provide the sufficient structural rigidity, it requires in many cases, considerable cross section dimensions of structural elements.

On the other hands, in engineering design practices there are several cases where to ensure the stability of the building, rigid elements are placed on the building perimeter. The problem is that often, in these cases, these structural elements may interrupt several architectural aspects of the multi-storey building such as its façade, interior space, or even the entire building architectural volume.

This study present reinforced concrete Structural Wall elements which are recognized as one of three main structural systems putted on the perimeter of multi-storey buildings among rigid frames and bracing systems. This research aims in suggesting an innovative structural element be implemented in the design process by both being considered as an architectural and structural element.

The Structural Wall patterns with different arrangement of openings, called Perforated Structural Wall Panels, are characterized by a pattern of openings in different sizes and forms. This panel should provide the required resistance from the lateral load acting on it while offering at the same time a visual resistance presence.

From the architectural point of view, this element offer the possibility to create several configurations of geometric forms, through following a precise methodology explained in further detailed study analysis presented in this study. The methodology can help towards obtaining an optimized panel by creating also a common vocabulary for both the architect and the engineer.

This designed vision based on collaboration between architects and engineers aims in fostering an alternative design method outlining an effective structural scheme of multi-storey buildings composed mainly by perforated Structural Wall elements in the building perimeter. Following this design methodology, vertical structural elements would be modified in terms of preserving the required structural members and cutting of the unnecessary ones.

The research concludes by discussing on how perforated Structural Wall element can help in fostering the design process and facilitate the decisions steps within designers in concluding the proper building configuration, the architectural performance and the structural rigidity.

Abstract_IT

A causa del rapidissimo sviluppo urbano e della crescita della popolazione nelle più grandi città di tutto il mondo, gli edifici a più piani sono aumentati molto di numero. Di conseguenza cresce sempre di più l'interesse per l'esplorazione di sistemi strutturali che permettano di realizzare edifici a più piani.

Come affermato anche in letteratura come ad esempio da Ali. M., M, nel suo studio del 1990, tra le grandi questioni che regolano la progettazione di un edificio multipiano c'è il soddisfacimento di alcuni aspetti architettonici come spazio, funzione, luce, garantendo anche la rigidità strutturale dell'edificio.

Considerando anche il fatto, sottolineato da Aminmansour & Moon, 2010; Elnimeiri & Gupta, nel loro studio del 2008, molte volte gli edifici a più piani tendono ad essere inefficienti in termini di organizzazione degli spazi interni. A questo proposito, sulla base di logiche ingegneristiche, per fornire la sufficiente rigidità strutturale, si richiede in molti casi, notevoli dimensioni della sezione degli elementi strutturali.

Nelle pratiche di progettazione ingegneristica, invece, sono diversi i casi in cui, per garantire la stabilità dell'edificio, vengono posti degli elementi rigidi lungo il perimetro dell'edificio. Il problema è che spesso, in questi casi, questi elementi strutturali possono interrompere diversi aspetti architettonici dell'edificio multipiano come la sua facciata, lo spazio interno o addirittura l'intero volume architettonico dell'edificio.

Questo studio presenta elementi di pareti strutturali in cemento armato che sono riconosciuti come uno dei tre principali sistemi strutturali, posti lugo il perimetro di edifici multipiano, tra telai rigidi e sistemi di controventatura. Questa ricerca mira a suggerire un elemento strutturale innovativo da implementare nel processo di progettazione che possa essere considerato sia come elemento architettonico che strutturale.

I modelli di parete strutturale con diversa disposizione delle aperture, chiamati Pannelli di parete strutturale perforata, sono caratterizzati da un modello di aperture di diverse dimensioni e forme. Questo pannello dovrebbe fornire la resistenza richiesta dal carico laterale agente su di esso, offrendo nel contempo una presenza di resistenza visiva.

Dal punto di vista architettonico, questo elemento offre la possibilità di creare diverse configurazioni di forme geometriche, seguendo una precisa metodologia spiegata in ulteriori approfondite analisi di studio presentate in questa tesi. La metodologia può aiutare ad ottenere un pannello ottimizzato creando anche un vocabolario comune sia per l'architetto che per l'ingegnere.

Questa visione progettuale basata sulla collaborazione tra architetti e ingegneri mira a promuovere un metodo di progettazione alternativo che delinei un efficace schema strutturale di edifici multipiano, composti principalmente da elementi di pareti strutturali perforate nel perimetro dell'edificio. Seguendo questa metodologia di progettazione, gli elementi strutturali verticali verrebbero modificati in termini di conservazione degli elementi strutturali richiesti ed eliminando quelli non necessari.

La ricerca si conclude discutendo su come l'elemento di parete strutturale perforate, può favorire il processo di progettazione e facilitare le fasi decisionali dei progettisti nel decidere la corretta configurazione dell'edificio, le prestazioni architettoniche e la rigidità strutturale.

Università degli Studi di Ferrara | DA Dipartimento Architettura Ferrara

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INTERNATIONAL DOCTORATE

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Thesis Contents

List of Figures

List of Tables

List of Graphs

Abstract

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This journey would not have been possible if not for them, and I dedicate this milestone to them.

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Abbreviations

ACI	American Concrete Institute
AISC	American Institute of Steel Construction
ASCE	The Magazine of the American Society of Civil Engineers
DFG	Deutsche Forschungsgemeinschaft grant
CO-DESIGN	Collaboration Design, designers have the same decision making of the project goals and outcomes
CSA	Canadian Standard Association
CTBUH	Council on Tall Buildings and Urban Habitat
T, Z, U, L-shaped	Structural Wall plan configuration similar to T, Z, U or L letters
FEA	Finite Element Analysis
FEM	Finite Element Method
kN	Unit of measurement in kilo Newton
kNm	Unit of measurement in kilo Newton meter
MPa	Unit of measurement in Mega Pascal
PBD	Performance Based Design philosophy in structural design
P.V.C.	Poly Vinyl Chloride material used in construction industry
RC	Reinforced Concrete
SLS	Serviceability limit state
SOM	One of the largest and most influential architecture, interior design, engineering, and urban planning firms in the world
ULS	Ultimate Limit State

Symbols

Latin upper case letters

A_{sv}	total area of normal force reinforcement, intended as the sum of all bars crossing the section in which the normal force resistance is checked
Ct	coefficient that depends on the type of structures
E_c	modulus of elasticity of concrete
EI	stiffness of the structural wall
H	total height of the building from the foundation up to the top
Hw	full wall height
I_{eff}	effective moment of inertia for a wall
I_g	gross moment of inertia of the cross section for a wall
I_t	moment of inertia of the transformed section
I2, I3	moment of inertia
J	torsion constant
K1	seismic lateral action coefficient to the vertical loads
Kw	factor representing the influence of the predominant form structure failure
M_{cr}	applied moment to the structural wall
Med	design bending moment according to the analysis
M3	value of the moment
MRd	design bending resistance
N_{Ed}	axial normalized load in section

M_y	the corresponding moment of the curvature of the section at first yield
Pk	story weight and is taken by default to the forces and the geometry of the panel
Sk	seismic forces applied at each story level
T1	fundamental period of vibration of the building in the direction of shear forces VEd
Tc	upper limit period of the constant spectral acceleration region of the spectrum
Xk	panel z-coordinate
Ws	seismic load for vertical wall length

Latin lower case letters

b_w	thickness of a wall cross section
b_c	width of the original unspalled concrete section
b_0	width of the clamping core on the barbell or the flange
dr	interstorey drift evaluated as the difference of the "average lateral displacements ds" in center of mass "the top and bottom of the storey"
ds	design displacement
de	elastic displacement
d_b	distance where is concentrated a portion of the steel bars
dc	distance of steel bars from the nearest concrete face
$f_{yd,v}$	design yield resistance of vertical bars of reinforcement
f_{cd}	ultimate design concrete compression strength in section

f'c	concrete strength
hcr	height of the critical area above the base of the wall
h_c	depth of the original unspalled concrete section
hs	net height of the floor
l_c	the minimum length for the compressed boundary zone of the wall
l_w	length of a wall cross section
q_o	basic value of the behavior factor
s	spacing of placing steel bars
v	reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement
vd	normalized axial force value
x_u	height of the neutral axis for the compressive zone
x_y	height of the neutral axis for the tensile zone

Greek upper case letters

Δtop	displacement at the top of the building

Greek lower case letters

α	confinement effectiveness factor
αu / αi	ratio depending on the type of the structural system
β	dynamic coefficient

ε_{cu2}	compressive deformation for which concrete is expected to be destroyed
ε	strain component of the material
ε_{sy}	tensile deformation for which steel is expected to be yield
Φ_u	ultimate ductility factor of wall
Φ_y	yield ductility factor of wall
Φ'_y	curvature of the section at first yield
ηk	lateral acting coefficient to each story and depends on structure deformation scheme
κ	gaussian curvature at a vertex of a mesh
μ_Φ	curvature ductility factor of wall
ω_{wd}	required reinforcement in the boundary elements for rectangular section walls
ωv	mechanical ratio of the vertical bar reinforcement
σ	stress component of the material
Γv	coefficient of the vertical reinforcement required to be calculate
π	mathematical constant taken as 3.14
γ_{yz}, γ_{zx}	transverse shear deformation for thin plates

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CHAPTER 1

Problem Statement | Research questions & Objectives | Proposed Methodology | Limitations

CHAPTER 1

1.1 Introduction

There are stated several aspects while considering designing a good building project. These aspects covers the topics on building aesthetic, optimization process, innovation and efficiency. On the other hand as stated by the following authors:

> "Structural engineering advancements can do facilitate novel architectural forms, showed by historical precedent." (Adam R. P, Helene R. and Matthew R. E., 2016)

In this regard, this thesis offers the possibility to inspire designers to develop innovative architectural performance of Structural Wall Panels with openings in multi-storey buildings while following an appropriate structural analysis procedure.

In this context, it is of interest to investigate different Structural Wall patterns with different arrangements of openings by suggesting their application in multi-storey building designing using a specific methodology that facilitate the communication within the design team and in specific between the architects and engineers. Perforated Reinforced Concrete (RC) Structural Wall Panels, are called the Structural Wall patterns with different arrangement of openings, which are characterized by a pattern of openings in different sizes and forms extracted from a solid material, from a concrete wall. The resulting Structural Wall panel has a significance presence to the architectural aspects of the entire buildings while providing also the structural rigidity.

As stated in the study of Paulay T., Priestly. M.J.N., in 1992:

> "The usefulness of structural walls in the framing of buildings has long been recognized. Walls are situated in advantageous positions in a building, can form an efficient lateral-force-resisting system, while simultaneously fulfilling other functional requirements." (Paulay T., Priestly. M.J.N., 1992)

So based on the above assumptions, the structural system composed by the structural walls, used to satisfy several basic criteria, such as stiffness, strength, and ductility. Moreover, placing the structural walls on the building perimeter provide more stiffness compared to frame structures. Very good results shows in term of reducing the torsional phenomena and the results on excessive deformations under seismic events.

1.1.1 Problem Statement

In general, in the co-design practices the design team who design multi-storey buildings face three main issues: how can be intertwined the structural rigidity and architectural aspect, resulting in a cost efficiency design process. In more details, these issues are summarized as follows:

- In preliminary building design practices, there are several cases where to ensure the stability of the building, rigid elements are required to be located in the building exterior perimeter.
- On the other hand, several architectural aspects are being affected by these structural elements, referring the building facade, the interior space or even the entire building architectural volume.
- In the time history of multi-storey buildings, despite the fact that it is short, about a hundred years, there have been numerous developments in terms of architectural volume and evolution of structural systems. In fact, in the total cost of the building design, the structural scheme of a multi-storey building has a greater effect than the structure scheme of a low-rise building. The selection of sustainable structural systems often becomes difficult.

Addressing the three issues above gives rise into generating a new reinforced concrete element panel that can be seen as an architectural element itself. The element, in addition to the aspect of structural stability, offers opportunities to be used in different architectural design and to be recognized at the same time both as a structural and architectural feature of the multi-storey building.

1.2 Argumentation on the aim of the Research

The choice for selecting the structural systems of the buildings is a primary function of the purpose of the service function, the organization of the interior spaces, the traffic flow of internal and external movements, the loads of use and the architectural treatment of the building as a whole and its elements especially.

The choice of building configuration is the primary aspect of the calculation referring to design standards, which may require strict constraints on the solution of structural systems and on their structural behaviour against the seismic loads.

Important components of the buildings configuration are symmetry in the plan, regularity in the vertical, uniformity in the distribution of loads, uniformity in the structural elements resistance and rigidity and ductility of the structural elements as a whole.

Therefore, it is important that through a co-design, the architect and the structural engineer are able to discuss among themselves, development concepts on structural configuration selection alternatives, to make it possible for undesirable interventions in the geometry of the structural system to be consulted with the preliminary results of the structural calculations, before starting the final phase of structural calculations.

Structural irregularities, sometimes unavoidable, contribute to the complexity of the structural behaviour of buildings that sometimes lead to undesirable damage and with serious consequences even to the collapse of the building itself.

Thus, it is of great importance for designers to choose the adequate structural systems with seismic performance satisfying also the architectural requirements.

The suggestion offered in the description of the object of this research also serves this purpose. Especially for the cases of buildings with pronounced structural irregularities in the plan, with eccentricities due to location of core walls or single concrete walls putted in a non-symmetrical configuration in building plan, which lead to the overloading of the object by the effect of significant unbalanced torsions in the plan.

1.3 Guides to Planning and Detailing

In terms of structural irregularities, buildings with a minimum of inaccuracies of their sections in plan and verticality are preferred.

Although it is often not possible to realize completely symmetrical buildings, there is also a lack of efforts to reduce the eccentricity of inertial forces due to the mismatch of the centre of mass and stiffness. This lead to increased stresses in the torsion of the structural elements of the object, which may be critical in the columns and corner walls of the building, moreover can significantly damage the non-structural elements located in these areas.

Stabilization of the horizontal torsion effects can be achieved by maximizing the stiffness of the side elements, by placing structural walls or grids close to the frame elements located near or along the periphery plan of a building.

Often in building plan configuration, there are placed the concrete structure of the stairwell, the so called the core wall, in the lateral parts of the extension of the object, which lead to a considerable unbalanced torsion.

An acceptable solution would be in this case the placement of additional walls on the other three sides of this building.

So it can be stated that, for effective balancing of torsional resistance, as much lateral-force-resisting structural walls, should be located at the periphery of the building

Although these solutions are architecturally forced to be placed on the facades of buildings but at the same time, they are needed to be used structurally, as much as possible, for the best torsional resistance of the building.

Therefore, as a way of solving this dilemma, in this topic is treated the use of reinforced structural walls with a special architectural performance, designed to be used in the composition of building facades, as a rational solution in improving the structural behaviour of buildings.

1.3.1 The Building Aesthetic

Both architects and engineers explore the aesthetics of the building frame. It is understandable that architectural styles were originally attributed to buildings with regular configurations, which on the other hand were highly suitable in seismic oscillations. However, several styles often reflect several characteristics such as elevation of the building, the interior load bearing walls elimination or the invention of the lightweight curtain wall. As a consequence these intervantions led to poor seismic performance.

An actual issue which in fact is most discussed is related to architectural building volumes reflecting the structural schemes designed in consideration with the seismic events. This shows that many common architectural configurations do not satisfy the seismic design requires. In order to face these conflicts, the design team should be organized in a co-design process. This allows these issues to be taken into account in the earlier phase of design when it is done the selection of the scheme and constructive elements.

Beside, it should be noticed that the architectural building volumes consit of both functional and aesthetic. Here comes the importance of a closer collaboration between architects and engineers on building design by sharing their experience among each other. In general, the engineer tries to explain to building designers of several specifics of a seismic design. In this regard, a regular building configuration consisting of simplicity and symmetry, represent a very good structural behaviour of the building. On the contrary, dealing with irregular forms, the structural analysis and the elements reinforcement details, should be deeper. It is also true that with the help of new softwares, the structural analyzes are performed more simply and quickly, but on the other hand, designers must always be attentive to the results they get from them by interpreting logically any data.

1.3.2 Building Configuration

Always has an attempt from engineers to encourage the use of regular configurations but did not succeed any time. The seismic code is oriented towards economical building and imposes limits on the use of irregular configurations. In case there are used irregular configurations, the increase of design forces is expected. In this sense it becomes necessary to pay more attention to specific detailed structural elements, specifically in the joint sections where the stress and strain are concentrated. Two main irregularities that are encountered most in buildings are soft stories and torsion phenomena. To get an optimum configuration, it should be developed a strategy which will permit architects to use irregular forms during their design intentions. An ideal design configuration should be considered when:

- First of all, should be an economical design which includes analyses based on the design code
- It should show simplicity of structural components
- It must have best seismic performance at lowest cost

It is obvious that extreme building configurations are accompanied by also extreme engineering solutions. In this senarios, all the structural schemes chosen, are reflected directly in the total cost of the project. It is understandable that would be additional costs in materials since the extreme engineering solutions would require several structural measures to be taken to ensure sustainability, as well as an additional reinforcement of the structural elements to cope with those kind of building configurations.

In the design of multi-storey buildings, between the gravity and lateral system, is more predominant in the structural analysis, the lateral system. Selecting the proper lateral system, contribute in material efficiency as well as in total multi-storey building cost.. Often, there is a lack of co-design process between the architect and the civil engineer due to missing transferable skills between this two professions. Generally, during the design process, it happens that the architects after have almost finished their work give it to the structural engineers in order to complete the remaining part of the design project. In these conditions, not joining a team work for either of them, it usually shows difficulties in obtaining a satisfactory solution in terms of aesthetic, functionality and an appropriate structural elements used.

To facilitate the selected structural system that of structural wall panels with perimeter openings in multi-storey buildings, which will be addressed in the following chapters, it is important to analyse in general the structural systems in multi-storey buildings but also in high-rise buildings. Based on the studies of five authors, a classification of structural systems has been made, dividing these systems into main categories and subcategories, materials used (concrete and steel), advantages and disadvantages of each of them as well as an example building for each category. It is obvious that several of the case studies are evidenced in this table.

It is very important to underline the fact that individual walls maybe subjected to axial displacements, translational displacements or even to torsional displacements. On the other hand, the geometric configuration of the structural wall and its location, contribute to a great extent to the resistance to the wall internal forces.

Very often, the functional requirements dictate the structural wall location within a building. These requirements may not suit the configuration of the overall structural plan. However, the structural engineers, in collaboration with the architects, do raise some recommendations in order to better position the main structural traces in the building plan, in general and to beeter alocate the distribution of the structural walls. With the adequate distribution of the structural walls is obtained also the optimized seismic resistance.

1.3.3 Conceptual Design Characteristics

Usually the architect and the structural engineer inform each other of their design process through a communication of conceptual design characteristics. It is important that this cyclic information exchange, allows new directions in conceptual design. Based on this, the creation of a guideline containing different structural schemas must be useful and helpful to the team work during their first project design. This proposal set an accordance between stakeholders reduces time during the early design process. In general the design procces even in the case for multi-storey buildings, follows the following steps. It starts with the architectural design of a basic floor plan, and then the structural engineer, based on it, develops its structural plan. This process is not so easy. The structural engineers has to develop several structural plans and after discussing with the architects, select only one of them. It is obvious that the final version fulfils several requirements, from optimal structural weight to structural strength and serviceability; in conform to the architectural layout, specified by the architect.

The design process following the above steps mentioned could result in a slow and sometimes inefficient practise, since it requires a repetitive approach of generating a final version, which several times it tends to be not a rational solution. In order to help in facilitating this design process, this thesis tend to develop a methodology towards obtaining an effective pattern that fulfils the structural and architectural requirements. A flowchart methodology for perforated structural wall is introduced. The method describes several steps combining different architectural and structural requirements proposing several perforated structural wall panels with constraints on area ratio, plan position, openings size, and loading condition.

Referring to the main objective of this thesis, it can be found a limited research. There are several existing literature focused only in one perspective, referring to architectural aspects or structural aspects. The optimization process is rather present in the structural engineering field, consisting mainly of lateral configuration system in elevation view or the plan layout composition. There have been several attempts to present the optimal structural plan. The case presented by the authors Zhang and Mueller among Liang as well are some of many researchers in this field. They all represent in their study the performance-based design method. This design method helped in removing inefficient materials. Although not solving all concerns regarding the optimized schemes in plan for lateral system, those researches do address some useful and important aspects in accordance with the design team decision-making.

On the other hand, referring the architectural perspective, the above authors cited Peng et al. whom had studied floor plan layout topology while proposing a program-based design. This approach used some given templates for building interior spaces organization whether a new software was developed by Terzidis, called autoPLAN. This software used to generate architectural floor plans in a given site. It is also interesting mentioning the shape grammar, proposed by Stiny, which helps in the formulation of floor plans. Several geometric shapes were generated using this technique and on the other hand is Shekhawat who developed another algorithm. This algorithm consider the connectivity in the optimization process.

Often not proper attention paid to the lateral system for multi-storey and high-rise buildings, seemed to affect their structural performance. Consequently, this situation has led to the separation between design team approaches. The architects and the engineers had different distinguished perspectives. In spite of all above mentioned, Zhang and Mueller, do stress an author named Aminnia, whom deals in his study with representing the optimal pattern for Structural Wall element in the overall lateral building system. The configuration of Structural Walls was represented in different shapes such in T, Z, U or L-shaped. Instead, in their paper they did enhance the broader general topology optimization problem, which according to them remains unaddressed. As well as the authors mentioned in the above paragraphs, Zhang and Mueller presented in their paper, a computational method developed for generating architectural layouts for Structural Wall element with reduced structural weight. The basic analysis that is subjected to is under the classic structural analysis. There were introduced also several case studies, sometimes complex ones, with different configurations of openings throughout the height of the structural wall.

So as conceptual overview in their research was developed a system to optimize the layout of Structural Walls in terms of structural weight, under structural and architectural constraints. The method is compatible with a large variety of buildings, from low-rise to high-rise, from wide to tall (aspect ratio), from office to residential, and from box to irregularly shape. Furthermore, it can be incorporated flexibly either before or after the design of architectural floor plan, sparking new inspiration or conforming to an agreed upon system. Integrating structural performance and architectural design, the diverse optimized results not only provide designers with a wide range of distinct layouts to choose from, but also pre-calculated the structural performance, ensuring that any layouts selected from this subset are among the best-performing ones. Once a conceptual design for the Structural Wall layout is selected, it can be analyzed and detailed much more precisely by the structural engineer later in the design process.

1.3.4 On Rationale Design

In multi-storey buildings, the structure's weight is one of the main problems that faces the designers. Sometimes there is a need to reduce the weight of a structural element which is not less important than increasing its strength at the same time. In this context, the conceptual and structural design aspects for buildings composed by perforated concrete Structural Wall elements have not been adequately explained.

As often cited in literature, the art of building design, is considered the architecture. Besides this, also it is very important for architects to know the technologies, techniques, structural elements and the materials which are the genesis of the work to achieve a satisfying result. Furthermore this knowledge doesn't limit the architectural creativity and freedom. Sustainability of structural systems often is effected by the architectural volume configuration of the building. Anyway, structural may be combined with architectural configurations, in a rational way to obtain efficient solutions.

A very good structural performance have been derived from the stiffened forms. The stiffened architectural configurations and the core location of the building seemed to have a great impact on the overall structure behaviour. In other cases, the core positioning govern also the main architectural building configuration and at the same time determines the choice of a structural system.

The invantion of new construction materials, at the end of the nineteenth century, enabled the building design, to avoid the restrictions posed by the previous material, that of load-bearing masonry. The buildings composed by steel frame or reinforced concrete frame, enabled the disconnection from previous architectural configurations used which were all based to load-bearing masonry. These constructions did not disappear but survived even in the twentieth century, even in tha cases when buildings were supported by arches or steel frames.

Today the main dimensions of revolution in architectural aesthetics are: aesthetic, technical and economic. The purpose is to give aesthetic validity to highly economical and regular shaped buildings. In literature this is known as the architecture international style which is represented by aesthetic enjoyment. Elegant steel or concrete frame structure with slender structural members, had made it possible.

Brief Summary

As a conclusion, there are still some gaps in this research considering the fact that was only consider Structural Wall cross section in the construction building plan. However, the dimension variation along the height of the element should be considered carefully. In this regards, it is important that in the future research, improvements should be made towards considering the overall structural wall arrangement of openings.

This process will help to widen the application of this structural element in the building design. Considering some basic aspects in the detailing of the structural wall, there is a possibility in the future, to produce stable panels of structural wall with openings, studied and verified in advance, to be launched in production line and to be applied in the multi-storey buildings design. Moreover, there is a need to offer some trainings or courses for engineers in order to access in the computational software's proposed in above paragraphs, to take all the advantages that these computational systems offer.

1.4 Research Objectives

The main aim of this research is referred to presenting **a rational way** to improve the structural behaviour of multi-storey reinforced concrete buildings by **suggesting the use of Perforated Structural Walls**, with a special aesthetic performance, located near or along the periphery plan of a building, as an architectural and structural element, conceived to be treated in the composition of the facades of those buildings.

In this research, perforated structural wall elements of multi-storey buildings are being analysed. The main objective is by exploring their potential as part of structural system to further integrate many building aspects, considering the structural rigidity, architectural, and cost efficiency. Following a disctintive methodology that is represented by a multidisciplinary approach, this research aims in addressing the following issues of structural, architectural, construction costs, and sustainability. Hence, it can be distinguished two main objectives listed as below:

- To generate different innovative perforated patterns for Reinforced Concrete Structural Wall Elements

- To underline the necessity of using this elements in perimeter of the building as a result obtaining a rational design satisfying also architecture requirements.

1.5 Hypothesis and Research questions

The purpose of this research is to represent a methodology for generating structural analysis of perforated Structural Walls panels with different arrangements of openings. Hence, a primary research question is:

"What are the advantages of using Perforated Structural Wall elements suitable for multi-storey buildings considering structural efficiency, architectural integration and low cost designed?"

Two main research questions which are sub-divided by the primary above question, are given below:

1) How can it be achieved the integration of architectural and structural aspect in a single co-design process?

2) To what extent can Perforated Structural Wall elements be a form generator for a proposed building.

The main hipothesis is linked directly to the objective of research, generating different innovative perforated patterns for Reinforced Concrete Structural Wall Elements. As above, it can be stated that this element can offer the possibility to fulfill both criteria of this study investigation; the rationality and the architectural aspect.

1.6 Proposed Methodology

The study element is the reinforced concrete Structural Wall element with different arrangements of openings. Overall, the research may be presented in two parts. The first part would be generating different patterns of a Structural Wall element. This first part has to do with setting the configuration and the geometry of the element. The software of Rhino Grasshopper V.6 will be used in this regards. With the help of the software and its plugins such as LunchBox, it is attempted to generate several patterns of this element.

The second part would be generating a methodology of structural modelling and verification for each of the patterns generated. For this second step will be used a Grasshopper plugin, Karamba 3D which do permit the structural analysis using the FEM analysis of the structural elements. Both parts present a single methodology, which do offer the possibility for enhancing the integration of different tasks composing by both architectural and structural design. In support, the patterns generated aim in presenting a rational solution in terms of cost efficient design. In addition to above, it is intended to apply one of the patterns generated and putted in a real situation of a multi-storey building design. For that purpose an existing structural modelling in software SAP2000 of a residential building will be take in consideration.

An alternative solution would be proposed via using the perforated structural wall element selected from the generated forms from grasshopper and will be running the analysis again in ETABS. Through using a comparison analysis of the two models build, the existing and the proposed with perforated Structural Wall elements maintain the same building behaviours components, especially the first three vibrations of the structure, interstory drifts and maximum displacements, will be presented the effect of using perforated Structural Wall element in residential multi-storey building. The goal will be reducing the overall cost of the building by resulting in smaller plan dimensions of all other structural elements.

1.6.1 Thesis Research Framework

To better elaborate the research framework, a figure is compiled in this regard, by stating all the important steps that the research will follow. Below are summarized also some key points of the framework. The literature review is the first step, emphasizing the role of the perforated Structural Wall in the multi-storey building design. The literature review also helps and influences research perception on the research gap. After conducting the review of the literature, it is represented the rationale for the potential of applying the perforated Structural Wall in the design of multi-storey buildings. The research follows a distinctive methodology of quantitative and qualitative aspects. At the end, the conclusions are being summarised, there are revealed several research, and many aspects, which requires further development, and are being discussed.

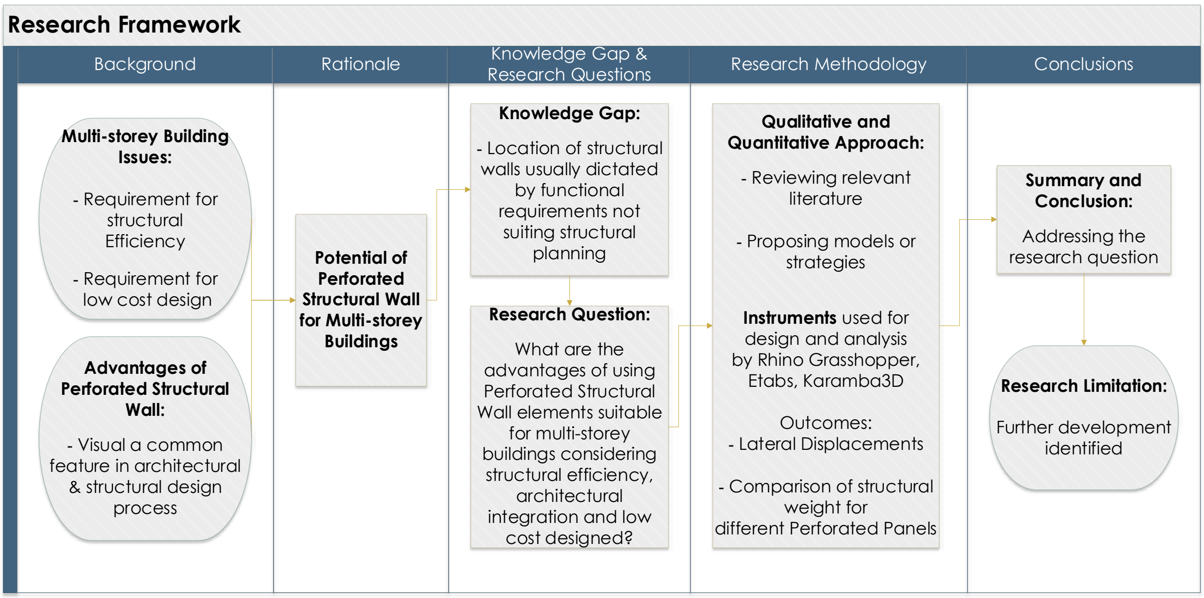


Figure 1.6.1 Research framework (source: the author)

1.7 Limitations

- Limitations will be observed in terms of architecture styles described in this research. There will be references and stated only those styles that do enhace structure expressure in a building. So in conclusion it can be stated that all information that are not covered in this study are specified as main limitations of the research.

- **The perforated panels are not suitable for high rise buildings since they generally tend to be narrower on plan and therefore generally the element that cover their façade is the entire structural shell.** The perimetric proposed panels in this thesis, are suitable for multi-storey buildings, which have considerable extension in the plan, towards improving their global structural behavior, as in the example analysed in this thesis for a 10-storey building high.

- The analysed model is not that of a real building but a schematic model that substitute the structural elements of the building with the presence of the perforated structural wall panel.

- It also refers to different kind of structural analysis and to the structural details of panel reinforcing that are not going to be applied to the modelling cases of multi-storey structures instead of linear analysis under seismic exitation. In terms of loads applied to the structure, only gravity loads and dynamic loads of earthquake are going to be considered.

- This thesis it is intended to run into a practical example of applying a perforated pattern generated by a proposed methodology. In this regard, it is obvious that a lack of laboratory tests on pattern behaviour is considering a limitation. But on the other hand it seems to lead steps for a future research under this topic.

1.8 State of art

Throughout the history, the Master Builder was the only person that used to built. His figure reprented the architect, the engineer and also the project manager. The complexity of the constructions with the beginning of the industrialization, influenced in the increasing demand for the construction of the buildings. Also with the technical development, also were developed the materials. In this situation, it became difficult for a single person to be in charged for every construction process. The two disctintive branches were the designing process and the constructing. Then the:

> "... work was divided between the architect, the many different engineers, and the builder. With the distribution of work came other problems. A good communication is required in all building projects and collaborations. In the last decade, this issue has got more and more focus, both in the universities and out." (Larsen, O.P. and Tyas, A. 2003)

In this regard, it becomes necessary for professionist to work together much closer, both in the university and company.

Reflecting in academic field, the interaction between two fileds, has almost not existed. Like most European technical universities, the Engineering Faculties have throughout their courses, offered traditional engineering programs as well as in architecture discipline. Due to attitudes gained, the architects and the civil engineering students have gained very distinguished tasks during the educational processes. Structural analysis and optimisation of the structural elements are some of the main learning tasks that the civil engineering students are trained to carry out.

On the other hand, designing creative buildings forms used to be the other task for the architecture students. These conflicts are discussed more thoroughly by Davison J.B, Popovic O. and Tyas A. (1998).

Focusing on aesthetical and rationality has recently been an awareness of the designer's team and the following authors have stated several points in this discussion, as below:

> "A basic reason for erecting a building is the need for a certain function. To raise a building one needs a structure to create and enclose this space. For an engineer, fundamental are structures making buildings rise above the ground. The tie between architecture and structure has in some respects grown stronger during the last decades, when new generations of architects seek their own styles from the structural shapes of past times." (Eekhout, M. and Lockefeer, W. 2004)

While significant statement has been extracted from the study of both authors, Falahat and Kalami:

> "Paying attention to the relationship between structure and architectural space as well as considering aesthetic principles can play a role in determining form and the structure function and expression of optimal space concepts for humans." (Falahat, M.S. Kalami, M. 2007)

On the other hand, Menn in his study stated that there are several cases when less attention is paid to to structural issues or economic aspects whereas deeper considerations have took the basic requirement of achievin a balance between functionality and aesthetics in a design process. Moreover, he states:

> "In contrast, engineers regard the satisfaction of structural safety requirements at the least possible cost as the most important sign of quality. They leave all problems of careful shaping to architects." (Menn, Christian. 2008).

This general perception has led to a polarization between architects and engineers.

Figure 1.8.1. Different books and edition list of research learning (source: the author)

Six broad headings describing in more details the relationship between structure and architecture are represented in the book of the author Macdonald A.J, in 2001. Beginning from Greek and Roman antiquity where the architect and engineer were usually the same person, the so called the Master Builder and then to the "Modern Master" from the early Modern architects.

A new area of collaboration between the professionist, with very positive relationships occurred then between the architects and the engineers in the twentieth century by giving examples of different structures build by the architect who were also engineers as well, as the following mentioned names of Eduardo Torroja, Ricardo Morandi, Owen Williams and in more recent times Felix Candela and Santiago Calatrava.

In the second book of the same author, was represented a flowchart-type design. By using this flowchart it was intended to present the methodology for following a process which is comprised by a technical and aesthetic aspect. All mentioned considerations aimed towards attempting to summarize the process.

Also he dedicates an entire chapter to professional collaboration and communication of a design teamwork. In "Creative Engineering" the author tells how engineers contribute to architecture going through the history of architectural engineering. He talks about competences that should possess an engineer to actively contribute to architecture.

The stabilizing elements are discussed in (Allen E. & Iano J., The Architect's Studio Companion: Rules of Thumb for Preliminary Design (fourth edition), stated that all buildings are designed against wind and earthquake lateral forces. In this context three main structural configurations that effect the building form and the arrangement of its interior space are the Structural Wall, the braced frame and the rigid frame.

Fu gives the major modelling programs in current design practice (Abaqus, Ansys, SAP2000, ETABS, Autodesk Revit, Rhino3D, BIM and definition to structural systems used in multi-storey buildings by describing to main resisting systems: gravity load resisting systems and lateral load resisting systems.

Examples of multi-storey building such as Burj Khalifa (Dubai), Taipei 101, Willis Towers (Chicago), Gherkin (London) etc and analyze the structure model for each of them from bracing systems, outrigger and tube structure to super frame (mega frame) structures (Fu F., Advanced Modelling Techniques in Structural Design, City University London).

Whereas Adams talks about building the designer own competence. Starting from critical thinking, improving the productivity, project management, computer usage, communicating their ideas (David K. Adams, S.E The Structural Engineer's-Professional Training Manual, 2008).

From historical precedent, both aspects of functional and aesthetic are in the base of architectural buildings composition. Both architects Le Corbusier and Adolf Loos declared that the foundation for beauty is provided by the order. In the works of Le Corbusier, the order was represented by the geometry.

His manifesto Towards a New Architecture, published in 1927, describe the laws of geometry. He stated that the engineer "puts us in accord with universal laws" and "attains harmony", whereas architecture is for "stirring emotion." On the other hand, Loos emphasized the building materials. In his essay, "The Principle of Cladding", published in 1898, he expressed the idea that "materials should not imitate other materials, but should be true to their own nature".

Jonathan Glancey, an architectural critic and writer, expressed that:

> "One of [architecture's] purposes, from the smallest well-put-together building to the highest skyscraper, is to lift the human spirit. In architecture we find a way of celebrating our humanity and of raising ourselves above the concerns of the matter-of-fact, the here and now".

Moreover, Glancey states on the social impact of a good architecture saying that:

> "Exposed structural elements incorporated into the architectural form can evoke a sense of strength and security for its inhabitants".

In the contemporary buildings design, there have been observed several examples of incorporating structure into the architectural design. This expose technique often require an adequate communication between the design team members. Mario Salvadori expresses another interesting contribution referring this topic. He used to be a professor of architecture and a structural engineer. In his book *Structure in Architecture*, he expresses on a "common vocabulary", by developing a steel plate Structural Wall panel. An interdisciplinary team conducted its design.

It was conducted a research so far, related with an exposed Ring Shaped – Steel Plate Structural Walls. Several configurations of steel plate were analyzed and a considered number of factors, including architectural and structural aspects, were considered. The Ring Shaped – Steel Plate Structural Walls, were part of the lateral load resisting system of the building, while the architect through means of given variables, were able to modify different parts of the panels. At the end, the result panel of the wall was also considered as a visual display. The lateral load resisting system was considered as primary structural system in those building examples.

The final panel configurations although showing different visual variations, do have some basic structural properties and well suited against earthquake, high initial stiffness towards meeting the required structural needs. The discussion occurred for the design principles for the above-mentioned panels, enhanced further on proposing a "common vocabulary".

This proposal aimed towards facilitating process and enhancing the collaboration between the architect and engineer. In this regard, this process may help the design team in pursuit of a building form that satisfies the design goals of each. Throughout this scenario of using a shared vocabulary, it is also possible to suggest the utilization of the perforated Structural Walls in a given design project of a multi-storey building. At the end of this process, this can result in achieving a satisfying result of an effective communication between the architect and the engineer.

1.8.1 Historical Background

According Mark Sarkisian, due to the cause of large fires occurred in the city of Chicago, there were initiated since then, diverse thinking in both designs and technologies.

> "The fire of 1871 devastated the city of Chicago but created an opportunity to re-think design and construction in an urban environment, to consider the limits of available, engineered building materials, to expand on the understanding of others, and to conceive and develop vertical transportation systems that would move people and materials within taller structures." (Sarkisian M.P., 2012).

In high-rise buildings there can be found traces of application to the building exterior, the technological components complemented with also architectural components. Both components use to complement each other in a single design. These are circumstances that a very close cooperation between architects and engineers is required.

Professor and author Andrew Charlesson, has expressed very interesting thoughts related to the integration of both architectural form and structural integrity. He states that:

> "As places, where structure is given a voice, and it contributes architectural meaning and richness".

Stone arches and masonry columns used in Roman buildings present a starting point in influencing the building architectural form. Several examples of this influence is also referred to innovation to structural schemes. One of the most well known structures to human kind such as the Colosseum used the arch element. Professor Remo Pedreschi expresses his idea as following:

> "The disciplines of structural art are efficiency and economy, and the freedom lies in the potential it offers for the expression of a personal style motivated by a conscious aesthetic search for engineering elegance".

Nervi, based also in Salvadori's Structure in Architecture, expressed his idea as following:

> "In order to invent a structure and give it exact proportions, one must follow both the intuitive and the mathematical paths".

The finding of David Billington is also very interesting. By carefully analyzing the advantages of each building material, it became possible for designers to cover large spaces with stable structures. On Nervi's use of concrete, Billington states as below:

> "Nervi saw that structure could be art when it arose out of correct form, careful construction practice, and a conscious aesthetic intention".

Glancey states that:

> "Architecture students still study Nervi's works today as an example of elegant structural form. A significant technological advancement that allowed architects and engineers to build higher into the sky was the development of structural steel from iron core." (Glancey 2006)

In this regard, it is worth mentioning also Santiago Calatrava. He used to be an architect, a structural engineer, as well as a sculptor and a painter. In his structure designs, he use to give a unique structure expression by emphasizing the transmission path of the carry loads acting on the structure. One of the most representative buildings designed by him is the Turning Torso in Sweden. The building form is in the shape of a twisted human body. The primary structural system is composed by steel bracing which are exposed in the façade.

1.9 Thesis Structure

Chapter 1 introduces the thesis and demarcates it in terms of research questions, limitations, and contributions. Chapters 2 and 3 flesh out its background, while chapters 4 and 5 present original research. Specifically, the chapters make the following contributions:

Chapter 2 surveys the theoretical background of the thesis, covering the evolution of high-rise buildings from the 19th century in terms of main architectural design styles that do represent the exposing of structure systems. Then some co-design practices have been reviewed and at the same time argues thesis relevance as an interdisciplinary field of study. Under this chapter are given also some main cases or examples of high-rise buildings worldwide and for each of them a visual and interpretative analysis have been conducted. The analysis is focused more in the architectural design idea, the structural systems and their advantages in term of reducing the overall cost of a building. Therefore, it was presented the perforated element of shell, which in all cases is a reinforced concrete shell with different arrangement of openings as entire building façade, which represents at the same time the main architectural and structural element of the given building.

Chapter 3 addresses the evolution of structural systems in multi-storey buildings. It is proposed the perforated reinforced concrete (RC) Structural Wall element, which is same as a shell element but putted mainly in several positions of the perimeter of a multi-storey building as well as in the internal building plan. The main goal of this chapter is to describe the theory of structural evolution leading to shell and Structural Wall elements and represent the advantages of using this element in a multi-storey building but with a different technique, those of a perforated panel. The panel itself combines both several design patterns ensuring also the structural sustainability.

Chapter 4 surveys multivariate visualization method, easy-to-use and as a key concept for generating the perforated patterns of a Structural Wall panel. The methodology describes a pioneering, visual and interactive, performance informed tool using software of Rhino Grasshopper and different plugins such as Karamba 3D, Lunchbox indicating the designer's preferences and concluding with the safety control of the model build. This methodology aims in supporting the integration of structural rationality into architectural design processes of multi-storey buildings.

Chapter 5 addresses a comparative analysis in terms of overall cost of a multi-storey building. Two different models are being compared. The first model is a real building, and the other is the same building but with some interfere in the structural plan adding in the perimeter one of the patterns generated in the previous chapter maintaining the same results of the first model and observing the differences in terms of overall cost.

Chapter 6 summarizes the thesis and discusses directions for future research.

1.10 Summary

“Generating innovative perforated patterns for Structural Wall with openings in multistory buildings” is the title of the research topic introduced in this chapter. The main structure of the research is divided in several sub topics while this first chapter begins with the intertwining of two design perspectives: the architectural and structural design of multi-storey buildings.

Underlining since in the beginning the typology of the structure analyzed, it is very important for the whole objective and the aim and conclusions proposed in this thesis. The main advantages were then described, representing in this way the rationale of the research using the perforated structural walls in the multi-storey building design. Further on, are stated the objectives and the main scope of the thesis while representing a distinctive methodology on perforated patterns generation.

This study present Structural Wall elements design following a clear methodology on generating an innovative pattern for its design. The resulting Structural Wall with different arrangement of openings, called Perforated Structural Wall Panels, characterized by a pattern of openings in different sizes and forms cut into a solid web concrete wall, provide a strong presence as visual screen and at the same time resisting lateral forces in a multi-storey building.

An alternative design method outlining an effective structural scheme of multi-storey buildings composed mainly by perforated Structural Wall elements in the building perimeter is based on the design methodology. In this regard, vertical structural elements would be modified in terms of preserving the required structural members and cutting of the unnecessary ones.

The research concludes by discussing on how perforated Structural Wall element is suggested toward fostering a more integrated co-design process.

CHAPTER 2

Theoretical Framework | On Rational Design | Case Studies Analysis

C H A P T E R 2

2 Theoretical Framework

2.1 Introduction to high-rise design

It is considered that in the late of the 19th century, the social, economic and technological developments contributed towards emerging the high-rise buildings. These types of buildings were built in several developed countries of the world such as in the continent of North America, Western Europe or Asia. Regarding North America, there are two main states distinguished in the literature, New York and Chicago and even a kind of war between them is often perceived to stand out in the most modern and high-rise buildings.

It was the investor's aspiration of these buildings who invested large sums of money to stand out in the business world. It should be noted that, at that time, the interior spaces of high-rise buildings generally were organised as offices and very few of them were residential apartments. This taking into account the position of their location in the centre of the cities where the financial and economic activity took place.

There were also two important technological factors that contributed in emerging multi-storey buildings that of steel structures and lifts. An illustrative example of this aspect is the 300 metres tall tower in Paris. Designed by Gustav Eiffel in 1889, using pre-assembled iron. This iron structure in those years doubled the height of the previously tall structure, the Washington Monument in States. As mentioned above, the other important technological factor are the lift. The first vertical transportation inside a building was introduced in 1852 by Elisha Graves Otis. The elevator facilitate the transportation within the multi-storey buildings or even taller buildings.

During the industrial revolution, and with the new materials invented, in Europe also, was distinguished a huge need for warehouses, factories and multi-storey buildings. In this regard, the Western Europe countries, played a fundamental role. Glass, reinforced concrete and steel were the new materials introduced to the building desing and other construction structures.

Despite the long history of architecture, the history of multi-storey buildings is short, is only about a hundred years or a little more than a hundred years. In spite of that very short history of multi-storey buildings, the do have experienced numerously transitions that produce very different buildings forms. In this context, trying to begin the study by conducting first a classification on multi-storey buildings seems to be an important aspect of the research. Since there are many buildings forms, and their variations and combinations, it is very challenging test to even just classify multi-storey buildings depending on their form characteristics.

For now, it was attempted to go with more general, broad category, multi-storey buildings form that is accepted by many people, which are four form categories: tapered, tilted, twisted, free form. There are many multi-storey building structure systems developed specifically for multi-storey buildings among them diagrid structure which is more recently emerging and architecturally is kind of unique structure in a very general context.

From structure, it is very efficient structurally system because of this axial axes of diagonals in terms of carrying lateral loads. This scheme shows the workflow diagram. The first category is the twisted towers usually using stiffness based design methodology. Two main parameters here are the rate of the twisting and the height of the building. The stiffness reduction ratio is not as much as sensitive to the building height in diagrid structures.

In literature are given various definitions for high-rise buildings. Refering to the author Moon, he states that:

> “A high-rise building is one with four floors or more, or 15 meters or more. Structures between 75 and 491 meters (23 to 150 m) are considered high rise buildings too and higher than 150 meters are classified as skyscrapers. The structural system of a high-rise building often has a more pronounced effect than a low rise building on the total building cost and the architecture. The issues involved with structural design and technology are ones of both natural and human implications. A structure must be designed to carry gravity, wind, equipment and snow; resist high or low temperatures and vibrations; protect against explosions; and absorb noises. Adding to this the human factor means considering rentable spaces, owner needs, aesthetics, cost, safety and comfort.” (Moon. K. S, 2011)

It is interesting to analyze also the components that affected the rapid developing of high-rise and tall buildings as explained in the text below:

- *High rates of population growth*, maybe is one of the most important factor, refereing to an increase number of the urban population, evidenced in the statistical data of several countries worldwide.

- *Scarcity of land in urban area,* refers to the lack of building constructions due to the limited territory. Moon gives the example of three cities which do face this urban condition:

> "Some of the largest cities lost the opportunity for growth and development due to the limited territory (Shanghai, Singapore, Hong Kong). This is connected to the obstacles of the physical terrain and to the inconvenience of their expansion for management and residence. China has announced to create a megacity, the population of which will exceed 130 million people. Megacity will be created by agglomeration of large Chinese cities: Beijing with a population of 22 million people, Hebei with a population of 14 million people and Tianjin, which has about 72 million people. The combination of such a large territory means the appearance of large distances, despite plans to provide the population with a convenient transport infrastructure." (Moon. K. S, 2011)

- *Increasing demands for residential and business space,* businesses and residents found both the center of the cities very attractive locations. But due to insufficient space to accommodate them all, in general there can be a harsh competition between the commercial and the residential properties.

- *Economical growth,* the general economic conditions and the fundamentals of real estate, seems to affect in a considered way the total construction height of multi-storey buildings, fearing in several times, the extreme heights.

- *Technological advancement*, technological advancements are in the core of contemporary high-rise building design. There can be distinguished several examples of buildings that reflect their scientific progress and at the same time, offering inspiration for future development.

- *Innovation in structural system,* the innovation in structural schemes is based in the integration process of cost efficient materials, construction technologies and structural design. It is obvious that, the innovative structural systems provide several challenges and as well as opportunities for future researcher in this field.

- *Desire for aesthetic in urban setting*, this component contains the concept of having a comfortable living. On the other hand this tempted to be a trend of the 21st century, the desire for a favorable urban environment for residents and for different life activities.

- *Concept of city skyline,* high rise buildings have changed the symbolic skylines of cities. This process occurred due to globalizing trends all over the world. It is also of a great importance mentioning the fact that, the city skyline is widely spread as a concept to the detecting criteria for urban transformation. As a consequence there are being distinguished several planning tools for preserving historical skylines and developing global world cities.

- *Cultural significance and prestige,* it is mainly refered to tall prestigious headquarters and their important role towards bringing an aesthetic and efficient development. Beside the reason for building tall structures could be solutions for density problems and lack of available land, sosmetimes these tall buildings represent more power and prestige status.

- *Overpopulation and need for saving resources and protecting the environment,* it seemed to had a great impact on the expansion of the city. The buildings were built far away from their center, forming the so-called horizontal cities, but on the other hand, this tend to affect the ecological aspect since they would require new facilities such as communication or transport systems, that not always are done effectively.

- *Human aspiration to build higher,* Fis refererd mainly to those people who own a similar builidng, live in or work. The architecture of these towers symbolize simultaneously wealth, social status and prestige. According to developer Donald Trump :

> "Ego is a very important part of the building of scyscrapers. It is probably a combination of ego and desire for financial gain." (Nationale Geographic, 1989)

After analysing different factors that had led to the development of vertical cities, going back to structural systems that had had a more pronounced effect to several multi-storey buildings worldwide, below is given a brief summery to the first multi-story buildings of concrete and steel structures.

- **The Home Insurance Building in Chicago** is considered the first steel construction. This system is composed by a gravity system using steel frame elements. The steel columns replaced the masonry walls, which were used before. So in this regard there were provided windows with greater dimensions in the high-rise building perimeter.

Figure 2.1.1. The first steel frame system (the Home Insurance, Chicago) on the left and the first reinforced concrete skyscraper (the Ingalls / Transit Building, Cincinnati USA) on the right

- **The Ingalls Building, or the Transit Building**, as it is called today, was built in 1903 in Cincinnati, USA. The building is considered as the first "reinforced concrete skyscraper" (Condit 1968). The structural system of this 16-storey building was composed by concrete elements such as the columns, slabs and vertical walls. The concrete class of concrete determining its strength was lower than 20 MPa (mega Pascal).

The factors analysed above explaining the increasing trend in high-rise and multi-storey buildings construction mainly in developed countries worldwide, have in common an important element. This element is referred to the main technological advancement occurred in the emerging economies of these countries. In the table below, based on the study of (Kayvani, 2014) are listed several technological advancement refering to the different period in a chronological way.

Time Period	Technological advancement
	Multi-storey buildings
1950's	High-strength bolts replaced hot-driven rivets
1950's	Emergence of glass-metal curtain wall facade - United Nations Secretariat Building, NY (1952)
1960's	Electric arc welding dominated shop fabrication
1960's	f'c=40MPa achieved for concrete strength
1970's	f'c=65MPa achieved for concrete strength
1990's	**f'c>100MPa achieved for concrete strength**

Table 2.1.1. Technological advancements that leads constructing multi-storey buildings (source: Kayvani, 2014, illustration by the author)

More over the author explained:

> "A fundamental economic driver for the growth of tall (particularly residential) buildings is the scarcity of land in the densely urbanised parts of the world. The competition for constructing the tallest building in a city, country, region or the world has acted as another driver for the

> growth of buildings worldwide. In the past decade or so, the race for constructing the tallest has been extended to include the contest for constructing the most iconic and spectacular high-rise building often characterized by complex geometries and leaning/twisting forms." (Kayvani, 2014)

Satisfying all above aspirations of building design as stated in the study of Kayvani, the structural engineers gained an important role. By selecting the proper structural scheme in the design process for multi-storey buildings, aimed in approaching the whole structure configuration. In this regard, it was of a great importance the aspect of integrating the structure geometry and architecture volume of the building. The final decision by the design team tend to have a direct impact on the overall cost of the building. This was the moment that the concept of a rational design or even an optimize process design was first elaborated.

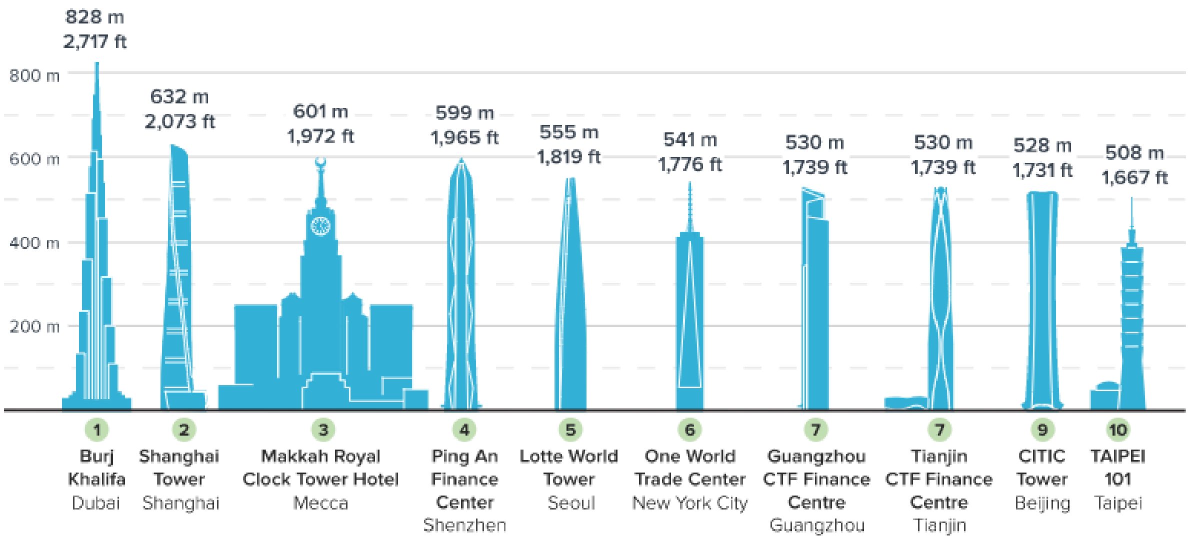


Figure 2.1.2. The tallest 10 Buildings in the world according to architectural top (source: CTBUH 2020)

Referring to CTBUH (Council on Tall Buildings and Urban Habitat) 2010:

> "A building can be characterized as "tall" based on its absolute height, its relative height to the surrounding, or its slenderness. The Council on buildings and Urban Habitats designates heights of 200m, 300m and 600m as the thresholds for "tall", "super tall" and "mega tall" status." (CTBUH 2010)

To obtain a taller or a slender building design, there is an important factor that influenced in regard, which is referred to the dynamic behaviour of multi-storey building. The dynamic forces acting on the multi-storey building are considered two: the dynamic force of the earthquake and the dynamic force of the wind. Both of them have a more pronounced effect to the lateral resistance system of the building than to the gravity resistance system. Therefore, it is of great importance the fact that the vertical structural elements play an important role while providing the required stiffness to the dynamic forces.

Now, what happens in the case of a slender building? First, the above factor do not determine the measure for "tall behaviour." A slender building tend to behave like a cantilever, based on the ground. The working scheme of a cantilever tend to have great top displacement and to show high values of self-vibration modes.

Therefore, the structural elements contribute in absorbing a large amount of the energy and control the self-vibration modes of the multi-storey building. More over the above situation is further adjusted by adding perimeter walls to the structural plan of a multi-storey building. However these concepts will further elaborate in the following chapters where will be described the element of the structural wall as in it "classic" form and the perforated structural wall with different arrangement of openings.

2.2 Brief overview on high rise Architecture

In the late of the 19th century, there are distinguished three main distinct elements representing the new style:

1) The abstract forms composing by lines, rectangles and planes. These forms were intertwined with each other but were not represanted in ornament lines;
2) The elaboration of the exteranl and the interanl part of the building. A single unit was represented in this regard, that of the interior space and exterior façade; and
3) The implemention into the construction site of new structural materials such as steel and concrete.

One of the most represantative concstruction in North America is without a doubt the Rockefeller Center in New York City. As it can crearly seen the building form do reflect the similarity with a monumental structure. The monumental design idea dates to the early stages of American architecture and was further elaborated to american architectural forms of high-rise buildings.

Figure 2.2.1. Rockefeller Center, New York City

The 60 high story building, started building since 1931, the Rockefeller Center in New York City was organised as a small city inside it. There were offices, recreational facilities composing the interior space of the building. On the other hand, this center represented the first step in architectural thinking, the developing concept from a single use to multi use structures.

It was no later that those years, that other high-rise buildings in the city were build as multi use constructions such as the case of Twin Towers, now the nonexistent World Trade Center. The towers were 110 story high and in their sourroundings were also composed by four other smaller buildings, all of them grouped around a plaza.

From years 1950s to the 1960s, the American architects embrace the International Style of Architecture. The style elaborated building design that were represented by glass boxes in the structural system of concrete or steel frame. Several buildings examples are the Seagram Building, built in 1950 and the Whitney Museum, built in 1966, both in New York City, and the John Hancock Center, built in 1968, in Chicago.

During the mid 1960s there were an objection to the International Style. This reaction aimed in achiving a greater freedom of design. The glass boxes were no widely implemented in high-rise building designs. The structural scheme of the building became more visible. There were introduced new forms and other materials for vible expression and innovation.

A “cold war” between many cities as well as in the case of North American cities of New York and Chicago, began. The most powerful people of that time and the biggest investors invested their money in imaginative shapes of high-rise building. They tend to hire the well known designers to design buildings in several special forms other than regular or prismatic forms.

Their inspiration was built a new generation of flamboyant headquarter buildings by bringing new visible aspcet to cities. Some of these buildings represant spectacle buildings that took the public attention while increasing also the revenues to the investitors that build them.

It was almost clear that the main purpose of the building these type of concstructions was the economic background. The high-rise building reflected to be good investments. The investitors had the main objective, that of maximaxing the profit by serving more rentable areas. Their request to the architects were by increasing the number of office spaces. Regarding the overall volumetric shape of the building, as was stated before there were distinguished several shapes.

There were buildings that contained sculptural shapes at their tops and a more regular forms throghout the building height or their base. Hovewer, between years of the 1950s and 1960s, a disctictive design idea that based to the functionalist ideas. The building should satisfy the visual anf functional aspects. Nowadays, this idea of functionalist design is still being practising although regarding the functionalism, several discussions are being elaborated.

As an attempt to trace the development of the high-rise architecture of the United States, although it is very difficult to clearly define a classification due to a wide diversification, below are given some key characteristics for each phase. It is worth mentioning that although in the text are given some time periods in years, this was with the aim of specifying an approximate period of time for each phase. Clearly, there is no a distinct division, since the architectural styles are intertwined and the analysis is attributed to each building individually.

The first stage is reffered to the early of 1940s. The natural daylight and ventilation seemed to affect the building form. The building width was limited to ensure that the light and the air can reach all building parts. This happened before the development of air conditioning or the fluorescent light. The interior spaces of the buildings were organised in the layout of small apartments or hotels. In order to obtain more rentable areas, the main structural configuration of the building was composed by a single central core. This structural configuration expressed the entire architectural volume of the building in the form of a rectangular or square block.

The second phase represent the interact process of the willingness in a given space, to create more rentable area and obtaining the sufficient air conditioning and fluorescent lighting. This second phase correspond also to the modern movement in architecture. The modern movement tend to emphasize more the simplicity, there can be easily be recognised in façade treatment. Very simple shapes are being used in this regard such as cubic shapes, rectangles, squares, circles, and sometimes ovals. The building maintain a regular architectural volume throughout its height whereas the curtain wall is stretched tightly over the skin. The structural system used several times to be exposed, at the same time in keeping with the International Style, as well as the use of glass boxes.

The architectural development of high-rise building represent *the third phase*. This phase is am intertwined process between the marketing experts and the architectural community. As also in the second phase, it was present the element used of glass boxes. Since the prismatic shape is composed by four corners, it can offer the interior organization of that represented by the four corner offices. Referring to the marketing experts, this solution while obtaining more corner offices, tend to have a greater advantage. From both the interior and the building exterior, these corner offices provide clear view. The perimeter exterior volumes were enabled by using several nicks, notches, and other angular shapes at the building perimeter.

A fourth phase elaborated the postmodern architecture. During this phase, several articulated buildings were constructed. The common features of these buildings were stepbacks, angles, notches, and curves. Also several structural schemes were used since the geometric building forms did allow it. Around 1970, was also known as an aesthetic reaction to the cubism period, evolved in three main stages. First, the roof element of the building was being used receiving more architectural attention than the prevoius design, that of a flat roof. There were several configurations, from a pyramid roof, a dome, or any combination of these. The second stage represented entrances to the building as an effort to give it also an identity. The third stage focuses to the building forms articulations by no longer idetifing sufficiently a building.

The fifth phase provided a modification of the shapes of the building in terms of energy conservation. In this context, the building interior spaces are being seen as a whole, in accordance with the space influenced by the light. During this phase that was a great awareness from the building designers, to consider the solar controls outside and inside the building and to find possibilities to not depend depend totally on mechanical heating, cooling and electric light. As well as for the lighting design, there were identified various light sources outside the building, distancing in this way from the previous evaluated scenarios of an electrical engineering standpoint.

After elaborating the developing stages of high rise architecture in North America, it is also of a great importance to investigate the development of structural systems. As stated above, ther were some stages where the architectural trends do allow more stuctural configurations because they offer a variaty of building geometries and forms.

Hovewer, it worth mentioning the the above appriciations were corresponded to high-rise buildings. On contrary, in the low-rise building these assumptions have a lower pronounce effect. So, taking the example of the pyramids or the early 10 story high-rises of the 1870s. In terms of lateral load resistance, they required little attention. The high-rise buildings tend to be more narrow in plan so they were of limited width.

This aspect was reflected in the structural traces of the building plan. The interior columns were putted at a relatively close spacing of 6-8 m. The structural frame of the building was mainly refered to a rigid frame composed by deep beams conected to the the columns. In order to obtain the required stability of the scheme, the frame was often supplemented by cross braces throughout the building perimeter. A passive support in the building stability, was added also by the masonry infills and the exterior cladding.

It is interesting to invistigate more on architectural consideration over different time period. Distancing from the pervious prismatic forms, a special attention was given to the top of the building. Generally the top of the building was differentiated from the rest of the building form. But this consideration ocurred gradually. Already was passed from the flat forms of the top of the building in keeping with the "less is more" norm, to new forms. So the buildings were identified by those forms. A good example of this is the 48 story high, cited as American version of the pyramid, the Transamerica Corporation in San Francisco. The form of the building was reached using sloped columns.

Figure 2.2.2. Transamerica Corporation, San Francisco

The main structural system corresponding to the third stage of high-rise architectural development was the tube system, which was very suitable to prismatic, square and rectangular shapes. Generally the building maintained the same form for almost the entire height. The tube system, on the other hand, seemed to very appropriate in terms of rapid construction of the buildings.

Following the first consideration over the top o fthe building, it was logical to consider also the entracies of the buildings, so not caring only for the city skyline but also for its bases. This period was combined with the structural logic conceived by Fazlur Khan. Fazlur Khan an american citizen with an origin from Bangladesh did reveal a very interesting structural concept on tubular systems, as well as he was known also as the father of the tube structure.

Khan stated that while moving most of the columns to the outside of the building, in its perimeter, it is logical that also it is moved also in the perimeter, in this sense, the lateral forces resisting system. He further explained that this action, tends to be more efficient and economical. A comparative analysis he does mentioning beams in I-profile cross section.

So, he explained that with moving mass away from its center, the moment of inertia, increases, like in I-beams. The tube system, was either used with deep exterior spandrels or as an exterior braced tube, known as diagrid system also. In the case of headquarters, the John Hancock Tower in Chicago, the diagonals were expressed on the building facade, but in the Citicorp Building in Manhattan, they were hidden by a glass wall.

Figure 2.2.3. Citicorp Building, Manhattan

Then a special attention was paid to details. The architects tended to use many articulated forms. The high-rise architecture was represented by this trend. There were several building examples that do reflect in their facade technological progress by showing their structural elements. The aim was not expressing the structure but rather their building skin to reflect the architectural expression.

Satisfying all the above requirements, it was obvious that in many cases there were used two or more structural systems for the entire building height, and not just one single system. In the case of slicing and dicing architectural forms, the engineers had to combine different structural schemes, by cutting a brace somewhere or using a partial tube somewhere else, and so on. The main problem they faced in this regard, was to ensure the overall continuity of the loads transimition path.

The current trends in architecture require for several structural schemes to be studied and tested throughout the enginerring softwares to decide on the selection of the final scheme. The reasons behind this choice are linked with the concept that in nowadays there is no a distinguish architectural style that it is use. The designers use to experiment with the most unimaginable shapes, so every building by it structural scheme, use to have an unique response to the particular architectural volumetric form of the building.

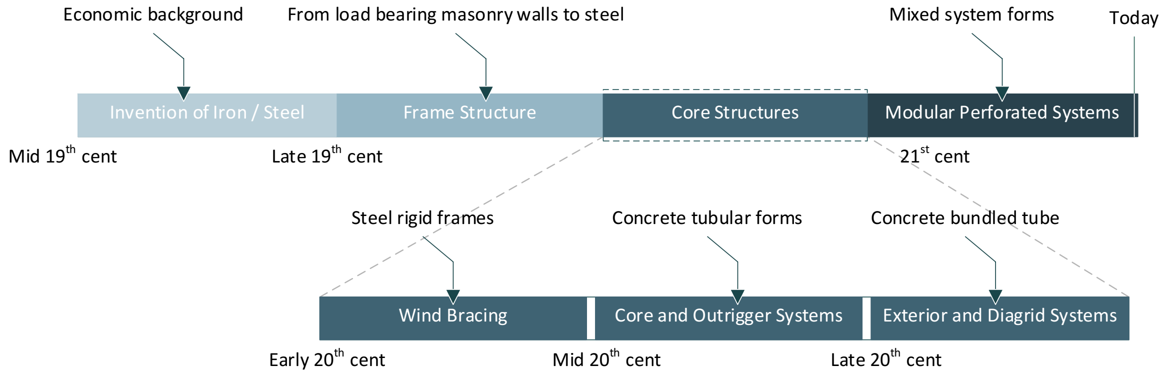
As it is often quoted in engineering theories, for any architectural project no matter how complicated it is, the structural solution always exists. The only problem in this analysis lies in the fact of the total cost of the building. Today, the structural engineers aim towards obtaining the most rational solutions for a building structural system combined with elegant structural elements in their cross section dimensions, to reduce the overall weight of the building and consequently its cost.

2.2.1 Elaboration of structural schemes by Architectural styles of 19th century

In the late 19th century, it is known the fact that the construction of many multi-storey building had the economic background. The main purpose was to increase the rentable surface by having more office spaces thus maximizing the rents of these offices. The natural light on the other hand was very important key in this regard.

The offices should meet this condition. In this regard, this process was further spread by the new technologies that helped in improving clearly in the application of new construction materials. The heavy masonry walls with small openings were replaced with steel frame structure.

The new system used contributed in reducing cross section dimensions of the structural members at the perimeter of the buildings. As a consequence, the larger openings obtained, the more natural light was introduced within the building interior spaces. Usually the transparent glasses were used for the windows, while brick or terra cottawere used for the steel structures cladding. Unlike the traditional masonry walls, the steel frame system carry onlu the self weight and the lateral loads.



Graph 2.2.1. Main structural systems used in high-rises from 19th cent until nowadays (source: the author)

2.2.2 Elaboration of structural schemes by Architectural styles of 20th century

There have been many attemptions to elaborate the main structural schemes that did foloow the architectural styles of the 20th century and from the literature research some of their concepts will be cited as below.

The author (Beedle et al., 2007) in his research has stated that many multi-storey buildings:

> "...champion technology, exploration or innovation by embodying certain physical forms. The proliferation of new structural systems and advanced technologies, combined with Modernism's principles of structural clarity, helped to give birth to the movement of Structural Expressionism." (Beedle et al., 2007)

On the other hand, the authors (Ali and Armstrong, 1995; Curtis, 1996) in their research paper, reveal on Late Modernism period and its influence on the main structural systems used in those years, by stated that.

> "This movement began in the 1960s and flourished throughout in the 1970s, and tailed of in the 1980s, during the architectural period known as Late Modernism. Many Modernist high-rises have been bestowed with an explicit trait of structural expression, given that they were vigorously attempting to "honestly" display their structural systems. However, in Structural Expressionism, aesthetic quality has been redefined to emphasize the role of new structural systems and innovative building materials." (Ali and Armstrong, 1995; Curtis, 1996)

In the same line with the other architectural style, the International Style and its formalism, in the building facade design was being applied directly the structural element. The expose structural system in building facade did for sure follow the architectural expression of the whole building.

This was the moment when for the first time was used the concept of structural expressionism. Its roots were in the structural material of steel and concrete that had the potential to create diverse forms, in regards to buildings, bridges, and many other construction objects.

A good example of the above concepts is the designer Pier Luigi Nervi who has designed many particular structures. His designs include many diverse forms such as vaulted forms, or forms dispalying the loads transmission path, large-spanning design, etc. William Le Baron Jenney and John Wellborn Root were also two different architects from Chicago, that reveal interesting forms in their multi-storey buildings. In the Jenney's buildings were present the skeleton frame system as in the Home Insurance Building although it is not so much distinguished due to cladding of its masonry facade.

(Ali, 2001) analyzes much more the figure of Kahn and his new structural concept. He states that:

> "Khan's exposure to the architectural/engineering practices at SOM, helped shape him for a remarkable career path in the 1960s and 1970s. He quickly realised that with the increasing heights of buildings, the status quo of structural systems was no longer acceptable. This means that "function follows form" (Billington, 1983) since "form control the forces". (Khan, 1969, 1972, 1973; Ali, 2001)

And on his building cost concerning, Khan:

> "...recognized that placing the lateral-force-resisting supports away from the building's center would create a large moment arm to resist overturning of the building. Additionally, it would allow the structure to respond to lateral loads, providing the most efficient performance while consuming the least amount of physical materials." (Khan, 1969, 1972, 1973; Ali, 2001)

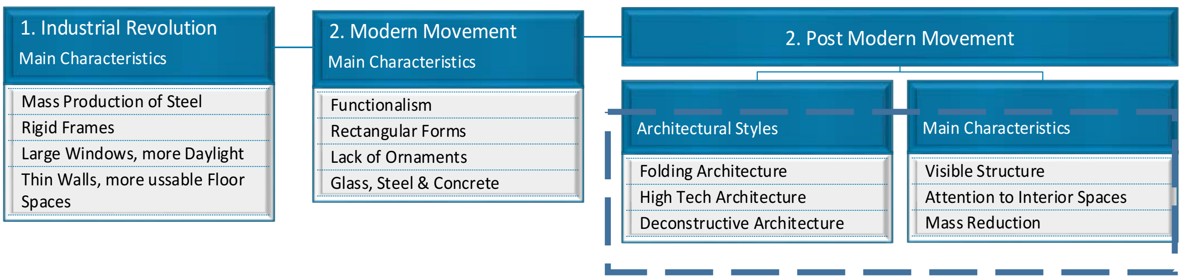
A revolutionary developments came from his "premium for height" notion:

"Khan also recognized that when a building's structural system is scaled vertically, the loads created by its heavier weight and the increased wind forces of higher altitudes are magnified exponentially. So he elaborate studies on the scale effect and eventually articulated his findings as the "premium for height", a notion that led to revolutionary developments in height-based structural system charts for the use of steel and concrete in buildings." (Khan, 1969, 1972, 1973; Ali, 2001)

There have been also distinguished three main architectural styles from the modern thought in architecture that do enhance structure expressionism. Talking about Folding Architecture which is also known as Origami, High-Tech Architecture and Deconstruvism which have all in common the same elements.

They do refer to a total building mass reduction, more attention to interior spaces by creating at the same time visible structure. So at the end, a giving building represents technology advancement as an achievement of the new era, representing the building process and manifesting also its transparence.

So in this sequence, is also important to mention and refer to main architects and practioners of each style. As above beginning with the first style, it should be mention the main architect of Origami who is M. Chatani. And then refering to High -Tech architects who are B. Graham, F. Khan, N. Foster, M. Hopkins, R. Piano, S. Calatrava and R. Rogers. And for Deconstructivism style the main practioners are P. Eisenman, F. Gehry, Zaha Hadid, R. Koolhaas, D. Libeskind, B. Tschumi etc.



Graph 2.2.2. Chronology of periods that lead to main architectural styles that expose structure systems at the facades of buildings (source: the author)

Folding Architecture

The Folding forms, known also by the name of Origami, represent the Folding Architecture. This is used to be a technique, which is simple explained by a paper folding. The Folding technique is widely applied, as well as in architectural design. They are broadly explored by "learning by doing" methods. Many researchers using papers try to create different three-dimensional forms and got inspired for their design.

Therefore, this technique help to obtain more intuitive solutions for architectural design. The distinctive stimulation in architectural form design, help also the engineer to better elaborate the structure of these constructions by properly understand the load carrying capabilities and the diagram of the stress forces inside the system.

Figure 2.2.4. Gallery of Muqarnas Tower by SOM, Saudi Arabia

The base unit of a folded plate is assembled from a thin steel reinforced concrete or steel surface that is bent to increase its strength and span like a beam. Folded plates resist the primary bending stresses across their inclined section with peak stress at the ridge and valley of the folds.

The depth of the plate's folds is proportional to its resistance to bending. The distribution of load through the depth of the steel-reinforced concrete or steel section embeds the folded plate with an affective property of pleating and arching that remains consistent within any space it defines.

Folded plates add diffusion to modify the acoustical affective property of their geometry, which can be curved or flat. The rate and scale of the folds can vary, changing the overall subdivision of the section. The deeper the folds, the more structural depth they gain, thus the more resistance they offer to bending moments.

As stated by Farshid in her book the function of form, when the base unit of a folded plate is intertwined with external desires, its affective properties are multiplied. As a result, in addition to pleating and arching, a folded plate can transmit other optical affects, including flatness, wrapping, vaulting, corrugation, tubularity and asymmetry. The acoustical affects are diffusion and specularity.

High-Tech Architecture

The High Tech Architecture began as a development of British Modernist architecture concept. It dated from the late 1960s and it represented a preference for lightweight materials. The technological advancements in construction made possible the visual structure in the building facades.

The most representative architects of this movement were Norman Foster and Richard Rogers. From the years of the 1970s, they used to design buildings by exposing their structures. Considering the fact that British Movement covers a broad range of expressions related to technological innovations in mechanical engineering, electrical engineering and computer science, the building façade exposed also some of this services, such as pipes, air ducts etc. A good example of this architectural language is the HSBC building.

Pelli (1982) has stated that structural expression is a means to resolve an aesthetic goal, not a goal by itself, in 1982, he wrote:

> "In 1970s and 1980s, architects have investigated alternate structural systems that liberate the façade from these obstructive supports. Mies van der Rohe sought structural expression as an architectural objective." (Pelli, 1982)

2.2.3 Elaboration of structural schemes by Architectural styles of 21th century

The Architectural styles of 21th century combines with Postmodern Movement. In this period, a special attention was paid to the strict structural logic of facades. They represented irregular forms, such as polychromatic and flamboyant forms. Therefore, following the concept of

Fazlur Khan, the structural support systems of multi-storey buildings was moved to the exterior of the building, known also as Core - Outrigger system.

In 2015, Moon wrote on revival of Structural Expressionism, manifested in two major trends: innovative bracing systems and advanced diagrid systems. Moreover, he states that:

> "This revival is consistent with the Green Movement which advocates structural efficiency and minimum consumption of physical materials. These two systems often provide equal spacing, balance, rational composition and harmony and manifest simplicity which is a key design principle of Modernism and Structural expressionism." (Moon, 2015)

Figure 2.2.5. The HSBC Hong Kong headquarters

Deconstruction Architecture

The Deconstruction Architecture is the design language that interfere with the building skin, creating non regular shapes while often the visual appearance seemed to be characterized by unpredictability and controlled by chaos. As a movement of postmodern architecture, Deconstructivism appeared in the 1980s. Architects represented this style are distinguished in their work by whose work the impression of the fragmentation of the design building.

Some of them are Peter Eisenman, Frank Gehry, Zaha Hadid, Rem Koolhaas, Daniel Libeskind, Bernard Tschumi, and Coop Himmelb. Besides fragmentation, there seems in their design to not follow the concept of a symmetry building, continuity or harmony.

Figure 2.2.6. Prague Dancing House

In the online platform wikiarquitectura, it was a statement underlined by Toyo Ito as follow:

> … "The meaning and significance of technology in my work is changing. In the past, technology was very visible. Presented in a visible way. Now it's different. Technology is something that I hide, you have to look for it, you do not see it, you can not see it. It is an element to be used and exploited in an indirect way. Before, I used to imagine an architecture that nobody could touch, impossible to grasp and hold. Now, what is new, is different, now I want to make an architecture that can touch and feel, I'm now working in physical reality, the object in the real. This interests me in this moment…" (https://en.wikiarquitectura.com/building/mikimoto-ginza-2/)

2.3 Co-Design Practices: Architect Engineer Collaboration

Some of the common questions getting even now a days is What is the difference between engineering and architecture. It is really not an easy answer and maybe it should not be. Some people say engineering are focussed on safety and equations whether architects are focussed on aesthetics, engineers tend to be logical, architects tend to be creative and somehow all these statements are partially true but rather it is quite so simple.

There are two very interesting statements made on this issue by two wellknown profesionist, an architect and a structural engineer.

> "*I would distinguish the difference between the engineer and the architect by saying the architect's response is primarily* ***creative****, whereas the engineer's is essentially* ***inventive***" **Peter Rice** (Rice, P., 1998)

> "*These are the engineer's responsibilities: the respect of the* ***physical laws****, the strength of* ***materials****, supply,* ***economy*** *considerations,* ***safety*** *etc. And there are the architect's:* ***humanism****, creative* ***imagination****, love of* ***beauty****, and* ***freedom*** *of choice. In my drawing, the engineer's sphere casts a reflection on that of the architect – the reflection of the knowledge of physical laws. Similarly, the architect's understanding of human problems is reflected in the sphere of the engineer*" **Le Corbusier** (Larsen, O.P. & Tyas. A., 2003)

Throughout the history of time, astonishing structures have been raised, and are shown to have had a great impact and influence on the structures of newer age. The greatness of these structures does not only lie within the incredible architecture, but also the complexity of the structure compared to in what age they were built.

A common denominator for these structures is that the same person was in charge of the design and construction. In fact it is an anachronism to use the words "engineer" and "architect" about the designers in the ages before the 1450s. Many of the constructors were artists and mathematicians, using the concepts of geometry and physics to figure out the shape of the structures.

The roles of architects and engineers have changed from having one Master Builder in charge of the both the artistic and technical part of the design, to having a clear distinction between the two disciplines. Today, the continuing specialization of their disciplines has caused a growing gap in the understanding between architects and engineers. The architect and the engineer, working on the same project, will use different measures and be concerned with different objectives while heading for their goal.

Development of new technology has made it possible to enhance the synergy between the architect and engineer, permitting the design to become more efficient and complex. An example of this is parametric design, which is a flexible tool that allows for effortless changes to the design without deleting and redrawing. It is highly beneficial compared to the traditional CAD-software where the geometry is more time consuming to change. The model is generated in an environment where the geometry is parametrically defined and assigned properties that are either fixed (constrains) or variables (parameters). The designer can modify the parameters, and the model will adjust accordingly. This opportunity of freely alternating between and comparing options allows for a more dynamic design.

In traditional methods of design, the structural engineer would optimise the structure mainly after the design is finalised. This work flow leads to a distinction between the architect and engineer. By combining parametric design and structural analysis, the structural principles can be considered parallel with designing the structure's geometry.

This enables the structural engineer to contribute in the design process by performing structural optimisation from an early stage. As a result, this could advance the constructability and thus reduce time and cost without compromising the structural performance and architectural shape. It must however be mentioned that parametric design opens the door for a better cooperation, but do not ensure it. It is up to the architect and engineer to make sure their priorities are shared and that they have a common understanding for the perfect structure to be realized.

In structural engineering practice, as stated above while describing the main structural system of the five phases on the development of high-rise architecture, one key element is the concept of low cost design. Conceving the requirement, is very important for design team to elaborate within them and to participate in the conceptional stages of the project. Since in general the structure takes 20%–30% of a total building cost, it is necessary for designers to understand that structural schemes have a profound influence oin this process.

Therefore it is seems to be of interest to explore the idea of different structural systems. It is obvious that every type of them impact the architecture volumetric aspect of high-rise building. The main purpose is invastigating a way to inform both aspect of a building design.

There do exists the necessity to have engineers who are creative and architects who understand basic math and can absolutetly collaborate effectively. Most of succesful buildings were designed by a team of people, a large team not just a single architect and engineer and so the collaboration is probably the most important part.

It is very challenging to make all aspect of a building project work together so it is important to concept this collaboration between two parties as a partnership. Both bring different talents, architects obviously bring a greater design focus than engineers, both are equaly good at project management and overall it is very important that the enginner is part of the team from the start and be part of the goal setting in the value of the project.

2.3.1 The preliminary design strategies

While "the architectural form" directly affects a building's structural behaviour, inadequate considerations of the "schematic design process" can reduce structural efficiency. Rittel (1992) describes four design strategies: (1) the linear strategy, (2) a trial-and-error process relying on the application of known precedents, (3) the systematic, successive generation of alternatives with a single solution chosen for further development at each step, and (4) the systematic, branching generation of alternatives that considers multiple solutions over different steps.

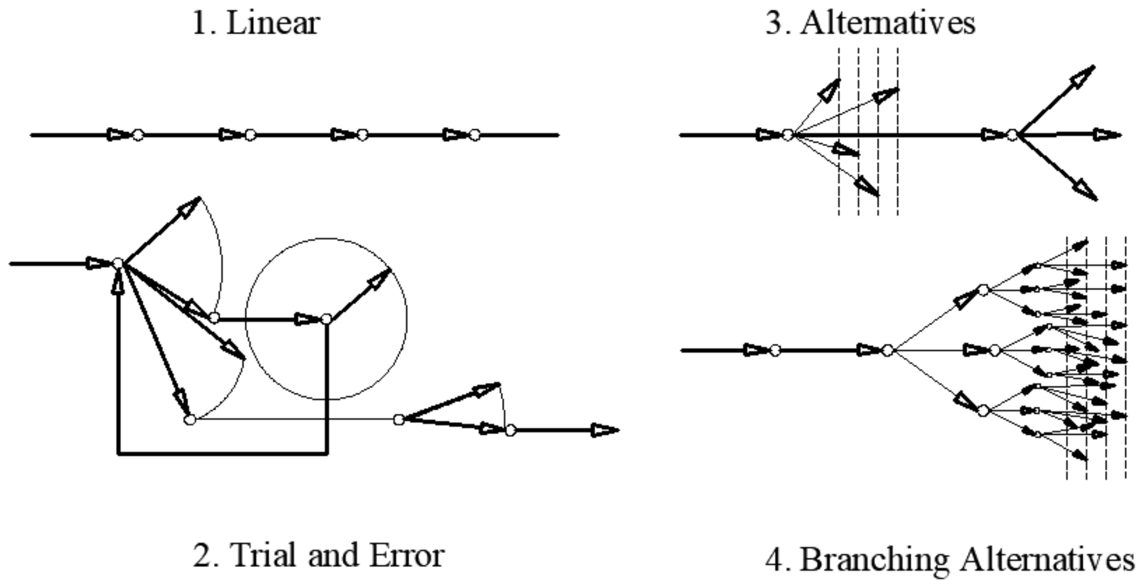


Figure 2.3.1. Four design strategies. (source: Wortmann, 2018, author's redesign from Rittel, 1992, pp77-81)

In multi-storey building design, the process is mainly as in 3 and 4 cases. In now a days there have been applied different modelling software that do enhance the collaboration between the designers.

2.4 Buildings Design Considerations

2.4.1 Architectural Considerations

This study is focused in presenting an innovative structural element suggested mainly to be applied in multi-storey buildings. As was stated in the introduction of the thesis, this structural element justifies in the best possible way its using. In this regards, it is of great importance to furthe invastigate on some general architectural considerations while designing a multi-storey building.

Building Function: Selecting the building function, is one of the significant architectural parameters of multi-storey buildings. Mixed-use residential buildings, office buildings or mixed-use commercial premises are the three main function types recognised for this building typology. Dealing with each of them determine directly the location of structural elements. In the case of a mixed-use commercial premises, the location on the perimeter of structural walls can be seen as obstacles or interference in the facade of the building. In this case other solutions are being investigated.

Base Plan: It represent an important factor which determine the entire geometry and form of the building. The building base plan shape, can be one of the main plan characteristic forms such as the rectangle, ellipse, circle, curvilinear, triangle, polygon and parallelogram shapes. On the other hand, it is a totally different the consideration regarding this topic while considering the designing of a high-rise building. Since in this type of buildings, it is dealing with unprecedented heights and forces because of increased wind speeds, there are considered new structural strategies that aimed in improving the efficiency of the design process.

Macro modifications, contains the concept of different building forms such as tapering, setback and twisting. All the above mention forms affect the overall geometry of the building and by affecting also the structural traces in the main structural plan.

Micro modifications, refers to small modifications such as corner modifications. These small features seems to not affect the base form and shape of the building.

Structural Material: the structural material depends mainly to the selection process of the building structural system. The main structural materials used for multi-storey buildings are the reinforced concrete but also in recent years a new attention is paid in composite materials which offers the advantages of both steel and concrete. The statistical evidences show that the the reinforced concrete buildings represent approximately 45 % of all multi-storey buildings, the multi-storey buildings built with composite materials show a percentage of 30 % and in third place are listed the multi-storey buildings in steel material, only 15 %.

The most widespread structural system in high-rise buildings seems to be the diagrid system. This system is represented by a braced tube system. In some cases, the diagonal elements were not fully appreciated since they obstruct the outdoor viewing. Thus, diagonals were generally embedded within the building cores. The building core is composed by four single solid structural walls and it is mainly located in the interior of the building. The most representative building example of these system are the COR Building in Miami, O-14 Building in Dubai.

2.4.2 A brief history of high rise construction materials

One of main advantages of the industrial area is the invation of some construction materials as well as cast iron, steel, glass etc. In construction idustry, instead of the cast iron, was put into use the steel material. The steel material proved to had high values in tension although that it had little strength in compression. Regarding the cast iron, it proved the contrary characteristics. There can be found also some older High Rise buildings, mainly the frame system composed by columns and beams that used this material.

Refering to Glass material, in multi-storey buildings was used the float double glass or the tempered glass. There seems to be some advantages in terms of material installation, of the glass instead of concrete material. So some interesting facts are that a glass facade has a quicker fabrication process, a surface of 150 m^2 can be putted in the facade in a single day in contrary with a 70 m^2 surface of brick wall. A glass facade is eight times lighter than a brick wall facade and the construction site is more clean while applying the glass material. Structural glazing for high rise building leads to visual appeal, lightness, customization and flexibility.

Aluminium and P.V.C. (Poly Vinyl Chloride) are light metal and relatively soft. They are both used for non structural elements, such as claddings. The main disadvantage of aluminium its low structural stability compared to steel material. On the other hand, the P.V.C. material, it is widely used as a pipe material for waste and rainwater.

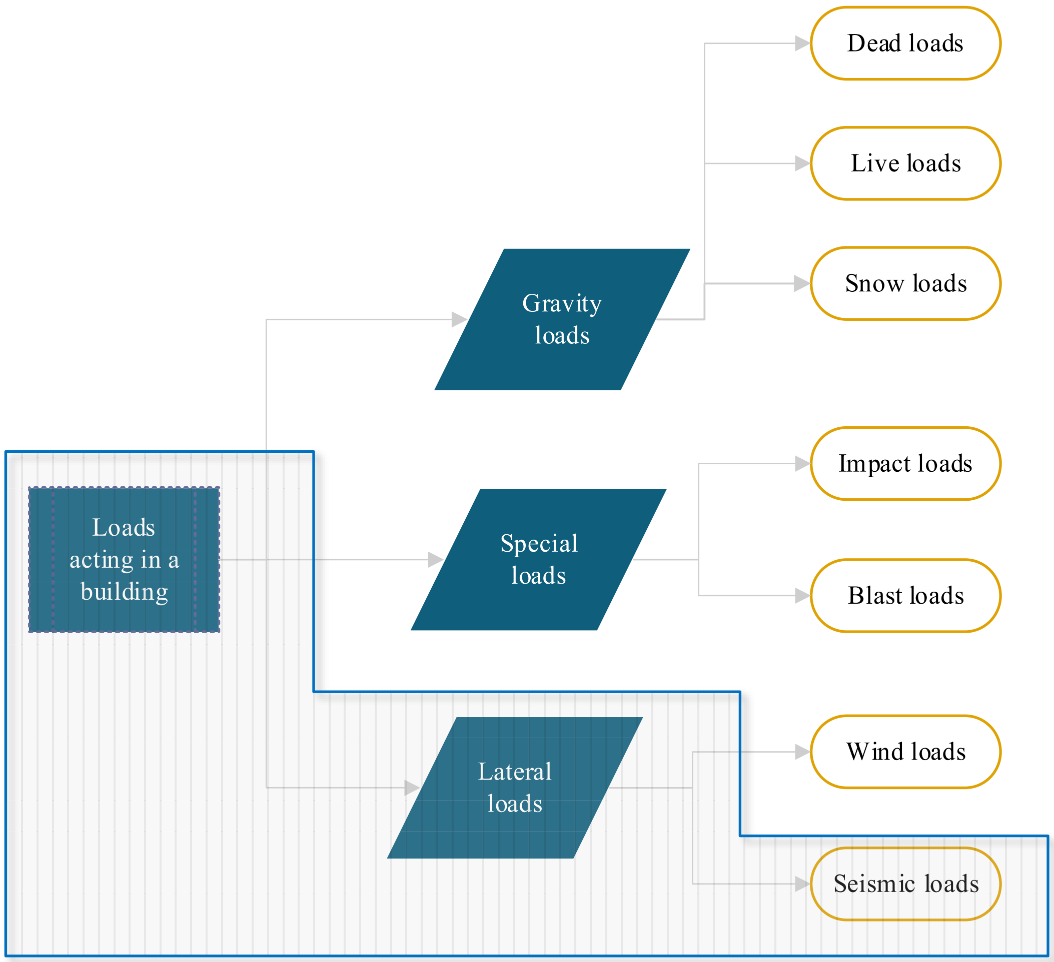
Reinforced Concrete: This material is a combination of the two single materials of concrete and steel. But the new development in regard to rise the material strength, is done by adding the fiber reinforcement instead of steel. The broad field in construction industry that use this technique is in the building retrofit.

The structural materials used in multi-storey buildings are typically one or a combination of above mention materials. The economic drivers affect the selecting process of the structural material for multi-storey buildings. There are distinguished several factors during the selection process such as material cost, materials availability, building form and height, design considerations, construction speed etc.

Elzner, in a 1904 article, has stated over the advantages that the concrete material has over the construction steel, saying that:

> "Concrete "'is considerably cheaper. Steel requires a great amount of capital and equipment and money to operate a steel plant. Long hauls and heavy freight bills are also involved". In addition, the schedule for completion was tight and concrete construction could begin well in advance of delivery of steel to the site." (Elzner, 1904)

Another important issue is determining the main loads acting on a given building. So the figure below aims in representing a simple chart of loads classification.



Graph 2.4.1. Main Loads classification acting on a building, (source: the author)

Designing a building or analysing a building is about combining different structural elements. First thing that an engineer probably do is look at each element, they first consider different types of loads acting on a building, that would be subjected to, vertical loads are some of the main loads, first of the things an engineer will look at.

Therefore, the vertical load would come from self-weight and from material itself, so building is made of concrete and steel or some other material that has a certain weight and the vertical load from that weight have to get down at the ground.

There are also the applied loads from people, furniture, everything that is in the building, obviously the equipment. Those again are vertical loads and in addition, outside in the building it may have snow, which is a big vertical load, rain that sometimes pull up on the roof.

So analysing the vertical loads would be first of all to figure out the load path, so the vertical loads would be either on the roof, on the floor levels so where the people are, generating the loads. Those would be applied directly to the beams so those beams will be analysed to make sure that are ok and those beams would carry loads to the columns and the column would carry loads downs to the ground. In addition, a process it is called vertical load flow, displaying the path loads to get from where they start to the ground in a safe manner. On the other hand, a designer has to deal with the lateral loads or horizontal loads, which are called the loads acting laterally or horizontally on a building.

Two main horizontal loads in a building are wind and earthquakes. So wind pushing at a side of the building, and earthquakes generation a ground motion. Another important element is the dynamic nature of wind-structure interaction. It is very important to analyze the wind force regarding the increasing height of the multi-storey buildings. The engineers should have in mind that more accurate analysis against high velocity of wind force at high level should be conducted.

So in general modelling the building as a single element is the methodology used for analysing the failure scenarios in multi-storey buildings. A shorter wider building would tend to fail in shear, whereas a tall, a slender building would tend to bend more, so have more a bending behaviour. In addition, it is important to look at the tension compression of that bending, check those columns can take that action in compression, and see if they can handle this tension.

The other two failure modes for overall building are overturning and sliding. Overturning is a failure mode due to tipping or rotating and sliding is a failure mode that results in the structure translating or moving horizontally or sliding along the base. Therefore, in general a designer has to make sure that the structure has strong enough connections to withstand overturning or to withstand any type of lateral sliding.

Regarding the structural behaviour of the multi-storey building, there are being distinguished two important load resistance systems: the gravity load resistance system and the lateral load resistance system.

Regarding the Gravity Structure, it is represented by all structural elements, which transmit the vertical load from the structure to the foundation. Slabs, beams and foundation plates are typically the main gravity structure elements of a typical multi-storey building.

There are very interesting studies by the author Kayvani, the first study in 2008 and then the second in 2011 on the Lateral Load Resisting Structure. Moreover, he states that:

> "The lateral load resisting structure also referred to as lateral stability system consists of all structural elements which form part of the load path (s) for transmitting the lateral effects of all loads (wind, earthquake, eccentric gravity effects, unbalanced lateral earth pressures loads) from their sources to the foundation in any direction. These elements typically include walls, beams, columns, floor diaphragms, and footings." (Kayvani 2008 and 2011)

Regarding the concept of providing greater stiffness of the building due to positioning the columns in its perimeter, he states that:

> "The general principle behind efficient design of lateral load systems of multi-storey buildings is to engage the perimeter structure (i.e., columns) with the core(s) within the constraints of planning and architecture. By effectively engaging the perimeter columns, the structural width of the lateral load structure and hence its efficiency is increased dramatically. In addition, as the perimeter columns are preloaded in compression due to gravity loads, they can resist wind-induced tensions (or, more accurately, decompression) very economically (with minimum need for tensile reinforcements). Adjacent cores are often engaged together with "header beams" (typically running across the lobbies,) allowing the core boxes to act in a compound manner in resisting the lateral loads, i.e., to develop "push-pull" couple over their cross-sections rather than simply bending independently. The perimeter columns can be engaged with the core(s) by either direct or indirect "shear linkage" elements. Outrigger walls connecting the core and the columns can provide the direct shear links. The indirect shear links can be provided by offset outriggers and the belt walls." (Kayvani 2008 and 2011)

2.4.3 Lateral Load Design Philosophy

The lateral resistance system, in the engineering theories represent a philosophy, the so-called the Lateral Load Design Philosophy. In contrary to the gravity system of the building, the lateral load values are proportionally increased from the bottom to the top of the entire structure. In this regard, the strength and the stability requirements of the structural elements are the key parameters for a multi-storey building design.

In satisfying these requirements, the designers pose two alternatives. Increasing the cross section dimension of the structural elements is the first way and changing the building form towards a more confined structure, is the second. There are several reasons on selecting the first or the second alternative, but in general, the first alternative is considered uneconomical and the second one, is considered a more elegant approach.

It is of great importance considering in this design theory, the effect of p-delta. This effect can cause even the collapse of the building while not considering and analyzing it. The effect of P-delta, represent the gravity load eccentricity, which can cause the columns failure due to axial loads. In this case the structure runs into a dynamic analysis by adjusting the stiffness in order to obtain the requested the natural vibration of the building. The natural vibration of the structure is represented by the design spectrum, which will be further more explained in detail.

The main output of this design philosophy are the Lateral Displacements between the storeys, the interstorey drifts and the Top Displacement, the maximum value of displacement in the top of the multi-storey building. Referring the Top Displacement, they should be considered regarding also the comfort of the inhabitants. The above two parameters, the interstorey drifts and the top displacements should be both be limited referring the building design code.

Another important consideration in this philosophy is the concept of ductility. This concept will be further explained in the chapters after, but to summarize it deals with the strength reserve of the building to undergo larger deformations during seismic event.

Referring to the literature on this topic, there are distinguished three main lateral structural systems: i) the classic frame system, ii) the structural wall system and iii) the framed tube system. This study refers to the second lateral resistance system by introducing an innovative structural wall element with different arrangement of openings, named the Perforated Structural Wall System.

Based on several studies, it was concluded that for a building 30 storey high with Structural Wall system and framed tube system, the top displacements are about 2% in difference within each other. On the other hand, the Structural Wall system tend to be more economical compared to the framed tube system. For the 40, 50 and 60 story high buildings, the framed tube seemed to be very much more effective in resisting lateral loads compared to the structural wall system.

2.4.4 Displacement Based Design Philosophy

Over the past few years, emphasis if being given to "performance" rather than "strength" in terms of seismic resistance. This realization has led to the development of alternative design philosophies based on deformation rather than force. These are labelled as Performance Based Design (PBD) philosophies. These philosophies consider the fact that the strength distribution throughout the structure is more important than base shear design. It was established that the response of the structure subjected to seismic attack will be further enhanced if it can be conceived the creating of the plastic hinges in beams rather than in columns.

Generally, the various procedures following this approach consist on small changes to existing design codes and only apply displacement checks in the end. It is concluded that the general approaches used are force-based approach with an addition to ensure acceptable performance levels. Displacement Based Design was first introduced by M.J.N. Priestley in 1993 and has been given much attention since then.

The concept used for performance based design modelling is driven from generating the main forces acting in a multi-storey building. Below it is shown a schematic example of the structural assumptions. Under the seismic excitation, the main forces acting on a building are inertia forces, which are shown with the black arrows. This inertia forces are lateral forces acting at each storey and applying at the mass of the buildings.

The mass is assumed to be calculated for each story depending on the story weights. For a simple building 10 story tall the lateral seismic forces apply as increasing from above to top stories. They will cause a lateral displacement of the frame building and there will be generated an internal force at the base of the system, the shear forces. Evaluating these parameters under the requirements of the design code, will ensure the structural stability of the given frame multi-storey building.

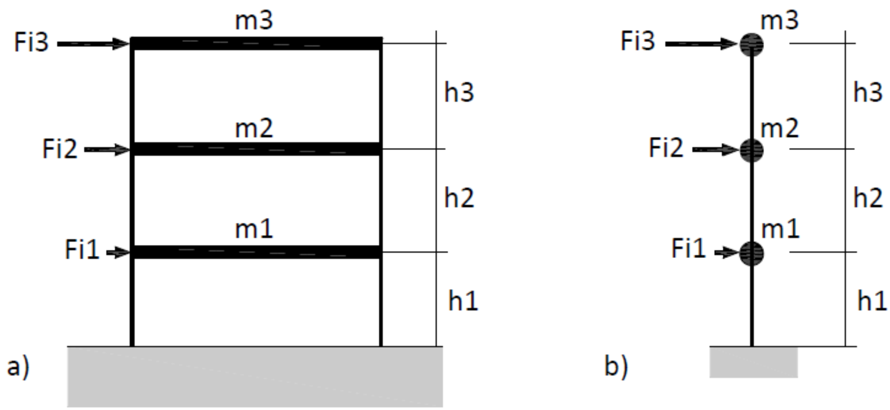


Figure 2.4.1. Seismic Design Force example (source: Llunji, 2012)

Another important parameter in this calculation modeeling approach is also the serviceability criteria. Referring to multi-storey buildings design, the serviceability criteria is represented by in the lateral deflection. On this topic Murty. C. V. R., et. al., 2012, has expressed in much more details as following:

> "New design approaches are challenging previous design norms, which allows greater freedom in choosing appropriate constraints for structural and non structural components. Whilst the subject matter is not new, the use of new design tools and processes leads us to re-examine rules of thumb previously used. Structural design of multi-storey buildings is usually dominated by lateral loading effects. In order to justify the performance of these buildings, it is essential to understand the nature of lateral deflections. One important system of a multi-storey building is the facade or cladding system. Cladding systems must be designed to accommodate the movements imposed upon them so as to maintain the structural integrity. The movements of concern to cladding are local deformations, not overall deflections. The relevant local deformations are affected by the arrangement and the design of the joints, but may be categorised broadly as vertical compression/extension and in-plane shear. All aspects of sources of deformation are of concern. These include:
>
> - Long term effects due to gravity loads, creep and shrinkage
> - Short term and dynamic effects (earthquake)
> - Maximum displacement joint size
> - Size of panels
> - Detailing of movement joints and connections
> - Ductility of panels
> - Relative vertical gravity between internal and exterior cores, walls and columns (Murty. C. V. R., et. al., 2012).

Occupant comfort is related to the perceived movement of buildings. Deflection checks should be used in assessing damage to buildings, and not occupant comfort. Murty in his study specificate according to the Hong Kong concrete design code (2004), a lateral "deflection limit" of H/500 and in, in extreme cases, the "slope" of a building may be noticed by the occupants as the building floor becomes non-horizontal. Perception might be triggered by even a small object putted on the floor.

Poland et. al are a group of author who have studied the main criterias for investigating the building motions. They stated as below:

> "Criteria for such phenomena have not been developed, as traditionally it has been "motion" that has governed. However, this may not be the case in future for buildings where human sensitivity to acceleration is lower and where slopes at the top of a building inevitably become relatively high. Normal design practice assumes that the structure will remain near-elastic for the ultimate load. ASCE 41-06 (2006) provides guidance on how different shear drifts relate to different damage levels." (Poland. C. D., & Mitchell. A. D., 2007)

> "... structural modelling of frame, typically, structural modeling is performed with the intent of calculating force distribution within a building. A conservative approach is made which often over deflections. Therefore realistic assumptions would need to made relating to items such as Non-structural elements, P-delta effects, Construction sequence, Cracking of elements, Stiffness degradation, Modelling of joints." (Poland. C. D., & Mitchell. A. D., 2007)

> "While there are numerous text books written on this subject, there is little standardized guidance. Seismic response is usually based on either the 475 or 2475 year event. Interstorey drift largely matches shear drift in this case. Damping is a big factor in determining the dynamic response, which will often contribute a significant proportion of the overall deflections." (Poland. C. D., & Mitchell. A. D., 2007)

The division of the maximum top displacement to the total building height, is defined as the overall drift ratio of the building. In a fist analysis, this parameter helps in the general perception of building stiffness and its structural behaviour.

On the other hand, the division of the lateral dispacement values to the height of a single story, is defined as interstorey drift. The building deformations are mainly defined using this parameter being limited to many structural design standards.

(Murty. C. V. R., et. al., 2012) invastigated more on deformations affecting the non-structural elements by stated as below:

“The slope may vary in each bay, depending on the relative vertical deflection of the columns or walls at each side of the bay. Panel deformation is a measure of the in-plane shear deformation of a wall panel. It is the difference between the interstorey drift and the local floor slope.

Whilst in framed perimeter structures the floor slope will generally mean the panel deformation is less than the interstorey drift, in some cases the effect of floor slope is additive (e.g. between a core and a perimeter structure). This is a measure of the deformation that would cause damage to non-structural elements.” (Murty. C. V. R., et. al., 2012)

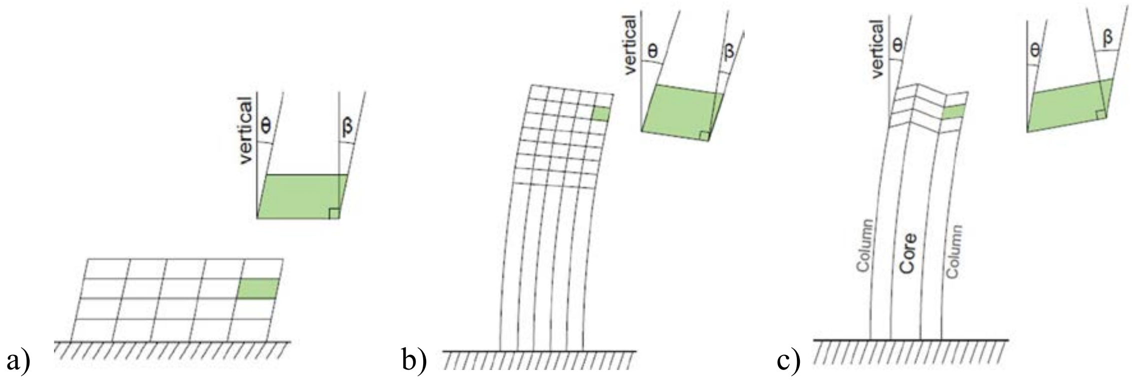


Figure 2.4.2. a/ Low-rise building – interstorey drift same as panel deformation b/ Tubular building – interstorey drift higher than panel deformation c/ Core building – interstorey drift can be lower than panel deformation

Comparing the figures b and c, it can be seen that in the case of the figure b, the interstorey drift is higher than the panel deformation. On the contrary, in the figure c, it can be seen that, the interstorey drift can be lower than panel deformation. The Pisa tower, is a good example in this case. In this building it can be seen that the slope of the floor and the interstorey drift is high, but there is no deformation of the panel. All the expected deformation is in the building foundation. This type of deformation cause the inclination of the building, also defined as the slope of building’s vertical elements.

Moreover, Murty in his study had also given some useful explanations over the concept of Displacement-Based Design. He explained in details that governing the analysis of the building deformations, contribute in considering the base problem of earthquake shaking of buildings as a fixed base problem.

The next steps refer to the analysis of the design of building subjected to displacements. The accelerations extracted from the response spectrum allows quick calculations in order to obtain the displacements values generated during the seismic activity.

It is important to mention the fact that in the first periods of time when designing buildings to resist earthquakes, the induced lateral force was considered a problem to the structure analysis. On the other hand, the designers noticed that the design of the buildings considering this parameter, significantly improved the overall structural performance of the building. In the framework of a preliminary calculation, they consider a lateral force of 10% of the weight of the building. This was considered too small in case of taller buildings.

Evidences of building behavior in many seismic evenets showed significant variations. Now even the lateral force which was given in function of the fundamental natural period of the building was no longer sufficient. Ductility was placed in the spotlight. Even introducing ductility was too prescriptive, it was very important in understanding various structural behaviour of the buildings.

The above mention factors corresponded to buildings collapse analysis. But it seems that either this assumption was not sufficient. Reffering to the buildings that after suffering a moderate or strong earthquake, were classified as not-usable, a new parameter came into light. This had to do with the concept of builing performance during and after the earthquake which bring a new direction of erathquake building design. The displacement design methodology presented really an effort in the research community and among the proffesionals.

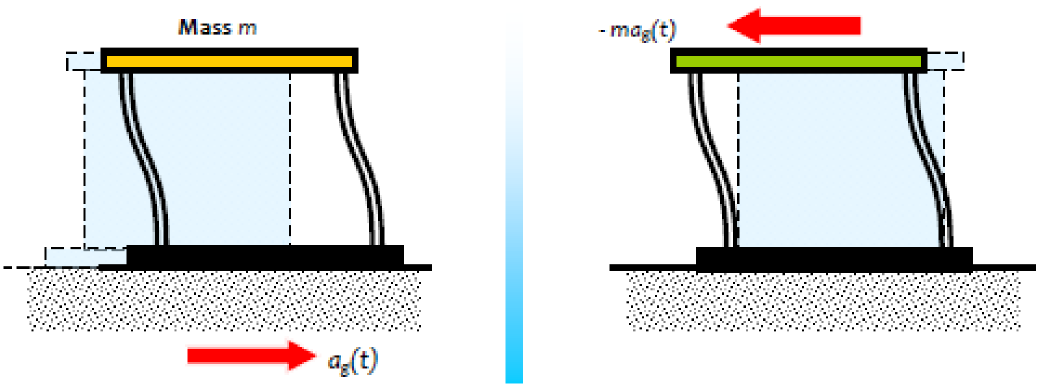


Figure 2.4.3. Acceleration time history at the base of a building: Converted to a force time history at the mass of the building with the base fixed (source: Ali and Armstrong, 1995, Curtis, 1996)

Refering some recommendations for criteria on drift limits, there can be distinguished several of them:

"For instance "The stability of multi-storey buildings" gives a table of racking tests. From this, it can be seen that typically first cracks in a masonry wall would occur at around H/400, although there is considerably more movement before ultimate load is reached." (Wood, 1958)

A paper by Freeman (1977) on plasterboard partitions, effecting the overall damping and building stiffness, indicated that:

"First cracks would occur around H/300 to H/400." (Freeman, 1977)

Also a review of the drifts is published by the Council of Multi-storey buildings and Urban Habitat in 1980. It was determined the limits for interstorey drift ranging from H/333 to H/666.

In the study of Wood in 1958 and in the study of Ellingwood et al. in 1986, are represented the effect of drift on structural to non-structural elements. All the data were given in the table below and as it can be seen, the damages would be seen to the values of H/500 to H/300.

Type of frame and infill	First visible crack: deflection/height	First crack: deflection (inches)	Ultimate deflection (inches)
Frame type 1 Horizontal girders 10 inch x 4.5 inch (I25) Vertical stanchions 10 inch x 8 inch (I55) (weak direction) 6 inch x 3 inch x 0.5 inch bolted cleat connections to top and bottom flanges of each beam			
Open bare frame	n/a	1.0	6.0
Encased frame	1/100	1.0	2.3
Encased frame with 4.5 inch brick panel	1/350	0.3	2.5
(repeat test) with 4.5 inch brick panel	1/400	0.28	2.8
Brick on edge in filling	1/400	0.27	2.0
3 inch hollow clinker block	1/450	0.25	0.8
(repeat test) 3 in clinker block	1/400	0.28	0.7
3.5 inch hollow clay block	1/275	0.4	1.5
3.5 inch brick	1/425	0.26	0.6
4.5 inch brick with door opening	1/1000	0.11	2.1
Frame type 2 (stiffer) Horizontal girders 13 inch x 5 inch (I35) Vertical stanchions 10 inch x 8 inch (I55) (strong direction) 6 inch x 4 inch x 3/8 inch bolted cleat connections to top and bottom flanges of each beam			
Encased frame	1/100	1.0	2.2
4.5 inch brick infilling	1/400	0.28	1.5

Table 2.4.1. Test data (source: author's redesign from Wood, 1958)

Deformation as a fraction of span or height	Visibility of deformation	Typical behavior
< 1/1000	Not visible	Cracking of brickwork
1/500	Not visible	Cracking of partition walls
1/300	Visible	General architectural damage Cracking in reinforced walls Cracking in secondary members Damage to ceiling and flooring Façade damage Cladding leakage

1/200 - 1/300	Visible	Visual annoyance Improper drainage
1/100 - 1/200	Visible	Damage to lightweight partitions, windows, finishes Impaired operation of moveable components such as doors, window, sliding partitions

Table 2.4.2. Serviceability performance levels published by ASCE (source: author's redesign from Ellinwood, 1986)

It was later in 1988 conducted a very interesting survey by the ASCE. In this survey participated several american structural engineering. The study focussed on their practises on multi-storey buildings drift. Typically, 41% of respondents, used to design to values of H/400 interstorey drift for the 50 year. This study was conducted for wind loads but the findings can be subjected also to seismic loads. There were a considered number of engineers that refered to different values of drift, between H/600 and H/200. In reality, a probabilistic approach is more realistic, by determining a deflection limit refering to the different design codes.

Reid and Turkstra (1981) wrote on damage limitation:

> "As has been discussed previously, overall deflection limits and interstorey drift limits can in general be a crude measure the functional requirements, and specific "performance based" approaches offer greater flexibility and make more sense particularly for very multi-storey buildings. In seismic zones construction details are modified to permit greater movement than normal without damage to cladding and fit-out." (Reid and Turkstra, 1981)

Also they explained why damages are more likely to occur in flexible buildings, if they are not detailed correctly, than in rigid buildings by stating that:

> "Deflections should be measured in appropriate panel sizes, which represent cladding panels or non-structural walls. Interstorey-drifts, even when considering the differing effects of shear and bending are fairly meaningless as they do not consider the internal deformation of the building. Quantitative criteria for occupant comfort are expressed in terms of acceleration, not deflection, and traditional deflection limits are not a good way of attempting to satisfy comfort criteria." (Reid and Turkstra, 1981)

2.5 Buildings Aesthetic Vocabulary

The building aesthetic vocabulary varies a lot from the compositional parameters of architect. The compositional parameters seem on the other hand that often govern the architectural form.

Describing the main compositional parameters, it should be address several compositional elements, such as controlling the visual depth of a given panel, its thickness, and the arrangement of opening.

The above mention analysis is conducted to the relative size of the elements, which is in relation to the entire size of the panel. While the compositional scale is attributed mainly to the variance of scale from fine to intermediate to monumental, completely distinctive features can identify each of them. Very large rings of a monumental scale walls achieve an atrium focal point. On the other hand, fine or intermediate scale walls allow light and more visual communication between spaces, by penetrating deeper from exterior windows. In addition, by using compositional elements, the panel visual depth can be father modified in order to create the optical illusion of depth.

2.5.1 Perforated screen as global contemporary architectural trend

Perforated building facade presents nowadays a global architectural trend. In Mediterranean region is referred to the traditional perforated patterns, such as “Mashrabiyya”, “Takhtabush” and “Qmariyyah” etc. Different studies have been conducted, describing the analytical comparison both technologically and behaviorally these patterns considering also the interaction between perforated models and occupants. Many authors have written about this topic and one of them is Waziri who in 2004 stated that:

> “The architectural and urban production of the old cities or villages stemmed from the nature of each society, and reflected the realistic image of life of each community.” (Y. Waziri, 2004)

More over Olgyay since in 1963 wrote on the relationship between the tradition and the everyday context, referring to climate and environmental aspect, stresses as following:

> “The relationships between the traditional cities and the socio-economic and socio-cultural contexts are also connected to the climate and to the environmental context Many examples showed that the urban fabric of the old cities was derived from the dynamic synthesis of environmental, social and cultural factors.” (Olgyay, 1963)

Salqini, 2004 attributed the above concepts in micro size, relating to the building. He stated that:

> "Furthermore, buildings were interlocked to each other as one system considering environmental role and socio-cultural connections. This was common in the tropical and in the temperate climatic regions, a thermal balance was obtained in the traditional buildings to provide a thermal comfort for occupants in hot summer and cold winter, during the day and at night. The balance was evidential in the flooring system, in the underground floor, and in the setbacks of upper floors." (Salqini, 2004)

It is important to mention the fact that the traditional perforated models in architecture enhance the integrative system, by providing at the same time the direct and indirect natural light, shade and shadows.

The perforation technique was seen as a functional response to the climatic conditions. However, other three different approaches were introduced:

- The first approach was during the 20th century. Examples of this techniques were "Notre dame du haut", "Unité d'habitation de Marseille", and "Maison de Jeunes" by Le Corbusier. The motives were used as a functional response but totally disconnected from the past.

- The second approach was represented by perforation interpreting the traditional forms, but also bringing these elements back to the current context of technological advancements. The "Dar Assalam" by Hassan Fathy and "Institute of the Arab World" by Jean Nouvel, are two basic examples.

- Thirdly, correspond to the beginnings of the 21st century. There were introduced significant techniques, technologies and materials. Some of the main structures were "Abbink X de Haas House", "Seville Ceramics Museum", and "San Telmo" Museum Extension. The digital technologies, made possible this new trend, which was perceived also as an architectural leap of perforation.

Several different authors, Germanà, M.L., et. al in 2015, elaborate more the concept of building envelope, by stating as following:

> "The contemporary concepts of buildings' envelopes reflect the complexity of themes focused not only on environmental design, where the external appearance of a building was recognized,

but also on the relationships between indoor and the outdoor environments. Accordingly, the connection between the contemporary trend and the traditional solutions has the opportunities to rethink of the future advancements in building envelope in terms of shape, form and performance." (Germanà, M.L., et. Al, 2015)

2.5.2 The distinctive models of perforations

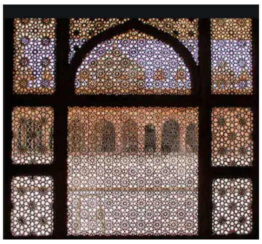
In an attempt to identify several perforated models in the traditional buildings, many references were used and are described as follows:

On "***Mashrabya"***, Zukelpee investigated more on this technique by stating:

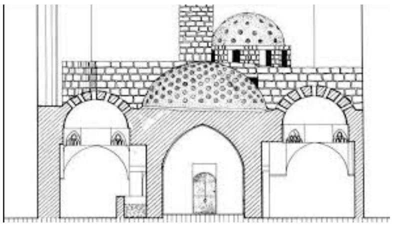
"Mashrabiya is one of the leading attributes of the Arab-Islamic architecture; it can be observed in the old cities of Baghdad, Damascus, Cairo, Jeddah, Tunis, etc. The 'Mashrabiya' has many functions; controlling the passage of daylight, controlling the natural air flow, cooling of the natural air, and assuring a considerable level of privacy that is essential in the conservative Islamic communities." (O. Zukelpee, et al, 2014)

"The perforations of 'Mashrabiya intercept the direct solar radiation, and soften the uncomfortable glare. The 'Mashrabiya' provides security and its form is considered as an aesthetic value. It is covered by a wooden lattice (a structure consisting of strips of wood crossed and fastened together with a certain shaped spaces left between them)." (O. Zukelpee, et al, 2014)

a) 

b) 

c) 

d) 

e) 

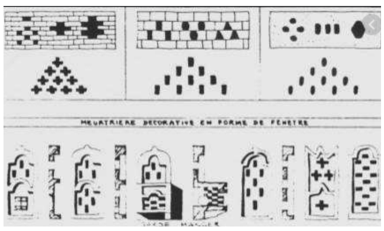
f) 

Figure 2.5.1. Examples of the perforated envelopes in different regions[1]. a)"Mashrabiya", b) "Jaali", c) "Takhtabush", d) "Qamariya" domes, e) "Qamariya", f) "Taqa" (source: https://www.pinterest.com/ author 07/20)

Shah investigated more on first evidences of this technique, he stresses:

> "The first evidences of which is seen in the Mediterranean, where the windows were divided into subparts. The span of lintels was reduced with latticework and provided security. A variation of jaalis in Egypt, Oman etc. is the Mashrabiyas. The term of Arabic origin means 'a place for drinking'. In the earlier phases, it was used to cool drinking water placed in clay pots. Winds would pass over the porous surface after passing through the shaded lattice screen and bring down the temperature of water inside by evaporative cooling." (Shah, 2009)

Then several authors investigated more on manufacturing process, such as Feeney:

> "Later mashrabiyas were fitted with beds inside, where the occupant could relax and it suited their privacy notions. However, unlike the jaali, they were typically carved out of wood. The artisans would patiently dovetail the pieces together without nails or glue to allow the wood to shrinks and warp under high temperature and adjust itself." (Feeney 1974)

Alternatively, the Mohamed who refers to different names in different countries:

> "Different names- Takhrima in Yemen, Shanashil or Roshan in Iraq and Saudi Arabia, with differences in design, materials, etc., calls them but the function remained the same as a climate control tool in the harsh deserts." (Mohamed 2015)

- [1] "Mashrabiya" is one of the leading attributes of the Arab-Islamic architecture; it can be observed in the old cities of Baghdad, Damascus, Cairo, Jeddah, Tunis, etc. (Germanà. M. L. et al, 2015)
- "Jaali" word means a net or a fine web. It is an ornamental perforated screen found in Indian, Indo-Islamic and Islamic architecture. (Kamath & Daketi, 2016)
- The 'Takhtabush' is a setting area between the house courtyard and the backyard (type of loggia), with perforated panels that provide shade and increase privacy in the semi-outdoor setting area. (Germanà. et al, 2015)
- The perforated roofs or domes are sometimes classified as 'Qamariya', but they were a perforation into the roofs or domes, by making small cylindrical holes, to enhance the passage of daylight to the interior spaces that require extra-lighting, without prejudice to the concept of privacy (e.g. Ayoubi Castle, Halab - Syria, & Turkish bath, Hebron - Palestine). (Germanà. et al, 2015)
- "Qamariya" is a sort of nearly semi-circular openings. The first use of 'Qamariya' was before 4000 years ago in the era of the state of Sheba in Yemen (T. M. Smith, 1997)
- "Taqa" is a small simply-shaped opening (rectangular, square, etc.). It was used in a linear, in a diamond, or in hierarchical arrangement at the end of the building's facades or above windows and doors. (J. Awad, 2012)

The word “***Qamariya***” comes from the Arab word qamar, meaning moon, meaning beauty. Therefore, in Arabic culture, this is said to let light reminiscent of the moon’s beauty into the house.

> “Qamariya is a sort of nearly semi-circular openings. The first use of ‘Qamariya’ was before 4000 years ago in the era of the state of Sheba in Yemen.” (T. M. Smith, 1997)

The Qamariya model was represented using a colored glass. This element was mainly located above the main openings of the building. The perforation technique of ‘Qamariya’ covers different shapes and colors. The Gothic architecture displayed several elements by this technique but in another context, playing the role in the symbolism of light.

Traditional Yemeni buildings, reflects mostly the perforation model of qamariya. It is obvious the colored glass formed the geometric perforated patterns.

Then in the study of Germanà. M. L. et al in 2015, it is very interesting the explanation on later application of this technique in several countries. They reflected as below:

> "The rise of the stained-glass qamariya began on a small scale during the Ottoman period, with traders bringing patterns and craft styles to Yemen from throughout the Islamic world, particularly Syria. Ottoman authorities encouraged traders to introduce colored glass to Yemeni architects. Today, the qamariya can be found in every city and village in Yemen. Even modern buildings that retain no other traditional features of Yemeni architecture include qamariya windows. All qamariyas are hand-made; there are no qamariya factories. The majority of qamariya production is done at small, family-run operations." (Germanà. M. L. et al, 2015).

Referring to Western Europe countries, they stated that:

> "During the medieval period, light was seen as an allegory to God’s presence. Therefore, colored light was an even fuller and more glorious depiction of the magnificence of God, hence the prevalence of stained glass windows in churches and cathedrals." (Germanà. M. L. et al, 2015).

“Taqa” is represented as a technique of using small simply-shaped openings. Mainly these opening are in regular shapes that in rectangular or square shape. Regarding the building element, it was used in a linear arrangement at the end of the building's facades or above windows and doors. The natural ventilation was facilitated a lot in this regard by an increasing passage of natural light into the building.

The ***"Takhtabush"*** provided shade using the perforated panel.

> "It is located between two open spaces while permeating a stream of natural air, which offers a comfortable setting area for occupants." (T. M. Smith, 1997)

Also on the ***perforated domes***, Smith states as below:

> "The perforated roofs or domes are sometimes classified as 'Qamariya', but they were a perforation into the roofs or domes, by making small cylindrical holes, to enhance the passage of daylight to the interior spaces that require extra-lighting, without prejudice to the concept of privacy (e.g. Ayoubi Castle, Halab - Syria, & Turkish bath, Hebron - Palestine). Sometimes, glass bottles or something else closed the holes, to prevent rainwater from going inside." (T. M. Smith, 1997)

On ***"Jaali",*** in 2009 Sorensen represented the ornament panel evolving in another dimension:

> "Jaali became highly popular during Mughal rule, they were used as partitions, railings, ventilators, windows, outer walls etc. Influenced by European art they evolved to contain flowers and vegetation, evident in Red Fort of Shahjahanabad. The Mughal response to European art was not slavish imitation but creative reinvention. The jaali can be metaphorically be equated to a shady tree branch, sheltering the person bellow from the sun, creating exquisite patterns of light on the plane…a poetry of nature. A jaali being fixed serves as picture windows, framing scenery within. They can provide better aesthetics along with maintaining view and climatic comfort, better than glass." (Sorensen 2009)

2.5.3 On patterns, repetition, symmetry and visibility

In Arabic culture, there are clearly noticed several distinctive shapes such as hexagon. The hexagon is in general combined with other shapes. Andani further explains the meaning of the hexagon. His judgment is extremely interesting by stating as following:

> "The hexagon represents the heaven, with 6 sides expressing 6 days of creation as per the Koran and the negative space, the 7th component is an expression of the 7th day or Sabbath, when god

> established his throne. The seventh component is not obvious but is integral to the composition, and allows for exchange of views. Another intention is to depict the shari'ah, which was delivered by the prophets and culmination of their cycles of philosophy on the appearance of the Natiq, who will bring in the 7th cycle of sacred history and reveal the spiritual meaning of all the previous prophetic revelations and faiths. The hexagonal shape is a mark of protection belief and faith of the followers." (Andani 2009)

The simple shapes that are combined, are mainly referred to circles geometries, squares geometries, rectangles etc. In addition, there was no specific reference to determine the arrangement of openings of the patterns. On the other hand, in contemporary design, it seems that the main reason behind determining perforation ratios is technological, as a result, by no longer being in themselves simple patterns without containing any function.

On the contrary, the traditional 'Mashrabiya' pattern is identified by its unity in the perforation ratio. The local identity is well represented in this context by this traditional pattern. In addition to this, all traditional perforated patterns tended to be created by a subtractive sculptural process. While several patterns are generated, using mathematic simple tools such as a compass or a ruler, this process is also very delicate and a special attention is required to not make mistakes.

Referring to the repetition process of the perforated patterns, Tavani referred to one of the traditional pattern, that of Jaali. He stated that:

> "Most geometric jaali patterns are made up of repetition of a module. However complex the pattern may appear to be, they can be identified to be made on a grid. The modules are composed of triangles, squares or hexagons. The continuity makes the eyes move over the composition. Infinity - Due to replication of a module over and over, they appear to continue beyond the physical boundary of the frame. It is difficult to identify the starting and the end of the patterns. This intentional repetition is symbolic of infinite nature of God. It is so because Muslims believe that human can't imagine a stable palace for God." (Tavani 2014)

Regarding the symmetry concept, these traditional patterns contain the mirror step of the basic unit. Achieving the symmetry of the panel is also attributed to the viewer perfection. The materials and the symmetry on the openings also emphasize the natural light. It often resembles a game played of shadow and light while providing a dynamic nature throughout the day.

The most useful materials are the stone, sandstone or marble. In the past, for ‘Mashrabiya’ and ‘Takhtabush’ were mainly used wood, and terracotta, while for other traditional models it depended on the main construction material used for the building facade. Another material used was the metal, especially as an additional layer for perforated building envelope.

From a technical point of view, the using of metal was considered enough rationale, but regarding other aspects such as, the economic or environmental aspect there were doubts. Also referring to different climatic zones, the usage of this material required also the use of insulation methods.

On the other hand, the visibility is a very important feature of the given perforated patterns. It Provides privacy due to the difference of light while maintaining also a visual continuity between the interiors and exteriors.

Nowadays the comfortable interiors are achieved by the advancements in technology. The mechanical air-conditioning is a representative of the above mentioning. Despite its extremely important role, it is often necessary to reconsider other possibilities to create similar effects as discussed above referring the using of perforated panels. A proper understanding of perforated patterns maybe evolved with technological advancements, helps in proper application of them in the design.

The provision of shades, the light control and the air ventilation are the environmental issues that the contemporary trend of perforation has bring in the center of design. In addition, as was mentioned above, the perforated patterns were designed in some cases, to be kinetic and moveable, not fixed.

As above, the perforation technique became an important feature in many manufacturing companies, due to the great interest in this architectural trend within building façade but also for building interiors. This study suggest using this technique but rather in a structural element, which will be further discussed in the following chapters. In the end of the research, this process will help in suggesting innovative patterns while improving the product, and by technologically propose economical design elements in the future.

2.5.4 The transitional phase of traditional perforated patterns

With the aim of technological advancements, there can be investigated several transitional phases of the perforated patterns, from fixed to moveable patterns. In the figures below are presented four of them. As it can be seen, there are four different countries in each photo where in some of them, the climate plays an important role in determining the perforation ratio. The tiny perforations are used in Brazil, Barcelona or Cape Town, whether the larger perforation is used in Austria where the weather is colder than the other countries. In any cases, within each model, the perforation enable the daylight interaction to the interior spaces of the building.

Figure 2.5.2. Examples of the contemporary transitional space in different cases

References from left to right:

B+B House, Brazil

http://www.archdaily.com/575463/b-b-house-studio-mk27/ (07/20);

Teresianas School, Barcelona

http://www.archilovers.com/projects/151609/teresianas-school-extension.html>(07/20);

Caldor Hotel, Austria

http://www.arthitectural.com/sohne-partnerarchitekten-caldor-hotel/ (07/20);

House in Cape Town

⇒ *http://aasarchitecture.com/2015/02/residence-in-cape-town-by-three14-architects.html (07/20).*

2.5.5 The appropriateness of perforation in the Mediterranean region

In the study of Germanà. M. L. et al in 2015, the traditional perforated patterns were considered in the Mediterranean region. Since some of these countries such as, Turkey, Spain, Italy, Egypt, Palestine, Lebanon, Syria, Tunisia, Morocco, Algeria, etc., include perforated models in their traditional architectures, the authors stated that this contemporary trend of perforation is more concentrated in these regions than others. In more details, they stressed:

> "For the case of Mediterranean region, it is known of many available conservative communities. Therefore, the necessity to provide privacy in the designed envelopes is evident and required. In addition, the environmental problems are still the focus of the world researchers. This means that the architecture of today did not meet yet the occupant's needs for a comfortable living. The selected cases have approximately no focus on social issues to be considered in the future design of the perforated envelopes." (Germanà. M. L. et al, 2015)

It is very logical for the above patterns to be used in Mediterranean countries, because it is an inherited style for this region. However, a more pronounced attention in this regard is given to research on materials that best suit certain patterns in certain places as well as the appropriate contemporary design methods considering also the sustainability of the panel itself, the aesthetic values and the social and economic needs.

2.5.6 Case Studies Analysis: Perforated RC Shell Element as primary structural system

In this study, the case studies are referred to mainly visual observations of the building facades in terms of architecture design and different patterns used the main design idea or inspiration behind them and at last, a very rapid survey on the structure element and its detailing.

Here are described several case studies for perforated shell element. The perforated shell façade element represent an exterior concrete element with different arrangements of openings. These buildings referees aim in getting a better understanding of perforated shell element performance. It is important to underline that in this study, it will be suggested different perforated patterns in terms of Perforated Structural Walls, which do not cover the entire building like in the building examples but rather are put in different positions in the building structural plan. Regarding the Structural wall location, it will be discussed in the following chapters.

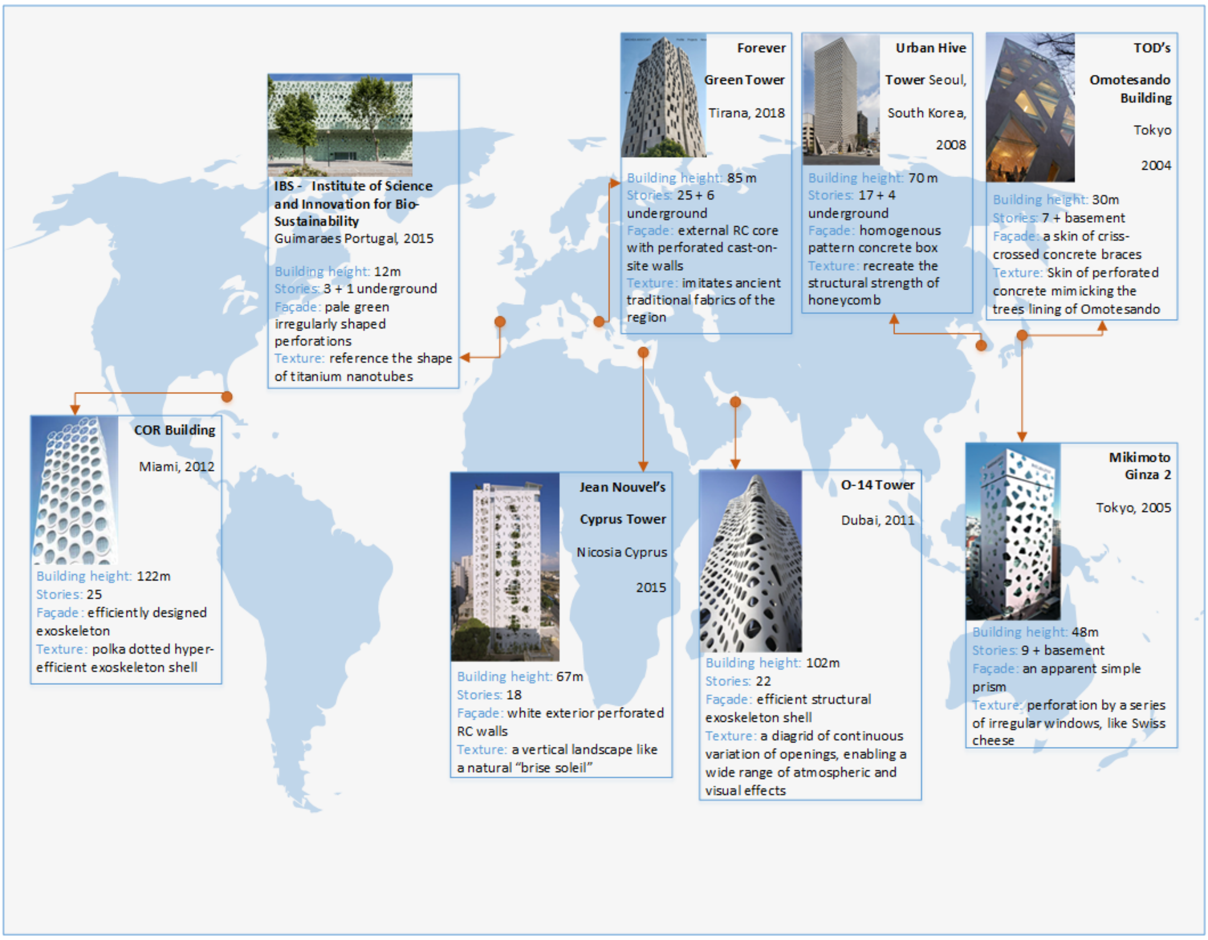


Figure 2.5.3. Worldwide Buildings with Perforated Shell, eight cases (source: the author)

	Architect	Design Idea	Example	Picture
1	RUR Architecture	Using technique as a constant. All parts of the building are nondecorative and functional	O-14 Tower in Dubai	
2	Oppenheim Architecture + Design	The environment as the main inspiration, new green tower in Miami	COR Building in Miami	
3	Toyo ITO	The presence of the structure as the base of design	Mikimoto Ginza 2 in Tokyo	
4	Toyo ITO	A skin of interlocking concrete supports and glass, mimicking the trees lining the street.	Tod's Omotesando Building in Tokyo	
5	In-Cheurl Kim of ARCHIUM	Hundreds of circular apertures designed to recreate the structural strength of honeycomb	Urban Hive Tower in Seoul South Korea	
6	Jean Nouvel	Creating vertical landscape working like a natural "brise soleil"	Jean Nouvel's Cyprus Tower	
7	Claudio Vilarinho	Openings that reference the shape of titanium nanotubes which are being investigated	IBS Institute of Science in Guimaraes	
8	ARCHEA ASSOCIATI	Inspired by the tradition of the masonry towers of the historical landscape	Forever Green Tower in Tirana	

Figure 2.5.4. Case studies, main design idea of building's architectural volume (source: the author)

As it can be seen from the graph above, there were selected eight different structures, mainly high rise buildings worldwide, except the case of building selection in Portugal. What they have in common, is the perforated structural façade. The main material used is reinforced concrete in different thickness, and above it there are distinguished several layering.

It is interesting also to bring into consideration a study conducted in 2019 where are described three building cases, The O-14 Tower in Dubai, the COR Building in Miami and the Mikimoto Ginza 2 in Tokyo. Furthermore, the author Rusi stresses:

> "The aim is perceiving through this cases the potential of perforated shell elements in enriching the aesthetic vocabulary of such buildings. With these tower typologies the structure and skin have flipped to new area of tectonics and space. The concrete shell provides an efficient structural exoskeleton as in case of O-14 that frees the core from the burden of lateral forces and creates highly efficient, column-free open spaces in the building's interior." (Rusi I., 2019)

Figure 2.5.5. O-14 Tower Dubai, COR Building Miami and Mikimoto Ginza 2 Tokyo

However, Jesse Reiser in his study in 2010 explores more on the virtual form of those buildings by stating that:

> "The perforation of shell seeks to attenuate the monotony, while still preserving a sense of the sublime. Modulation of pattern works like camouflage, becoming disruptive and de-materializing the tower block. The shell's pattern changes referring to viewer location and in conjunction with additional patterns of light and shadow which produces a sort of virtual form Because of the effects of his virtual form, the actual form of the building can be simplified and become subject to logics of designing methods of structural analysis and calculation." (Jesse Reiser, 2010)

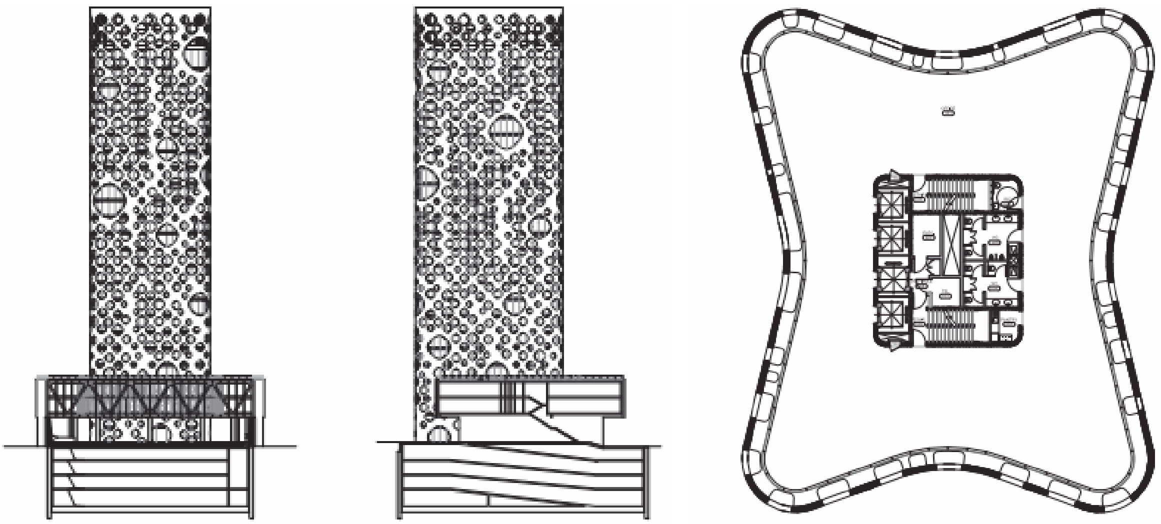


Figure 2.5.6. O-14 Tower in Dubai, elevation view and typical floor plan

In a report of Archdaily, referring the COR Building in Miami, it was written as follow:

> “The COR Building in Miami, represents a dynamic synergy between architecture, structural engineering and ecology. The building structure is composed of polka dotted of exoskeleton shell that provides thermal mass for insulation, shading for natural cooling and enclosure for terraces.” (www.archdaily.com, 2010)

Figure 2.5.7. COR Building, the parking level and the elevation view of perforated shell

Four thin structural walls compose “Mikimoto Ginza 2” building. The structural walls create a single system, the so-called a tube structural system. In the interior spaces of the building, there are few structural traces of columns. The façade design is composed of several triangle shapes, deriving the main geometry of the building openings.

Referring to the following source (openbuildings.com/buildings/mikimoto-ginza-2-profile):

> “This design follow a structural expressionist approach, becoming possible for the first time through the use of structural analysis technology known as the “finite element analysis method.” (openbuildings.com/buildings/mikimoto-ginza-2-profile)

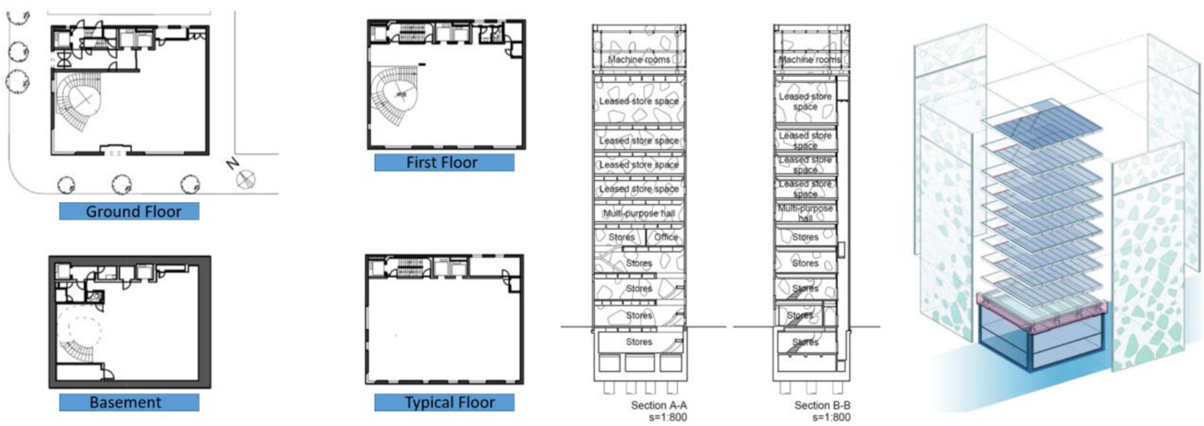


Figure 2.5.8. Mikimoto Ginza 2, the basement, ground floor, first floor, typical floor and the elevation view

TOD's Omotesando Building in Tokyo represent a skin of interlocking concrete supports and glass, mimicking the trees lining the street of Omotesando in Tokyo. The use of computerized algorithms continues to investigate the material qualities belonging to the world of organic forms, trying to obtain spaces capable of bringing the man to the natural environment.

In other words, Ito wants to show the way in which the flow of forces that support the weight of the construction follows the ramifications to discharge to the ground, as happens in real trees Toyo Ito himself says that his architecture has recently experienced a new direction of research. Starting from the design for the Serpentine Pavilion in London, unexpected geometries and patterns create a light architecture in which the structure is the materialization of a computer-generated fractal image.

Never since then has his architecture lived a long process in which models even on a real scale, lead to a continuous refinement of the architectural object. The building seems to be nothing but the three-dimensional materialization of one of the infinite frames developed during the process.

The new TOD'S store in Omotesando is designed as a segment of an infinite DNA whose structure is that of the Zelkova tree. Not the real tree, but its synthetic image, the one digitized and then re-synthesized by the computer, repeated and superimposed countless times to completely confuse the hierarchical contents. The intention is to go beyond modernism using the natural icon of the tree to obtain a dynamic geometry.

As modernism transformed pure geometries into architectural icons, so Ito in his most recent projects uses complex geometry, a transfigured natural image, to create new super modern icons.

Once more Ito seems to find a special relationship with the place, born of a silent contemplation of urban space. Walking on the pavement affixed, the real tree and the virtual one continually change the reciprocal perspective, but only for a few fleeting moments one of the "temporary and tense relationships" of which the architect is constantly searching is realized: one appears the exactly the other's shadow, the margins of the real and the virtual, the natural and the artificial are increasingly confused, an evanescent and ephemeral image is conferred to architecture, as to nature. In this case *"The new technology does not antagonize nature, rather* *it creates a new kind of nature, just as we are provided with two bodies: one real and the other virtual."* (Ito T., Tarzans in the media forest, 1997.)

At Omotesando, a synthesis between fluidity and geometric purity (expressionism and lightness) is achieved; in the TOD'S shop, it is realized in a single element: the pattern-structure-envelope, whose graphic two-dimensionality is even more accentuated by the co-planarity between glass and concrete wall.

The stairs on the façade between the second and third levels do not seem to look for internal spatial effects, but to highlight (as if it were one of the digital screens that decorate the city of Tokyo) the rite of luxury and shopping. Ladies of impeccable elegance, accompanied by distinguished sales men in white gloves, they descend and ascend the steps, with the awareness and the subtle pleasure of being looked at, projecting the umpteenth simulated image of themselves. A casing, in which the structure (concrete thickness of 300mm) is in the shadow of a tree delicate transfigured, projected on an iridescent glass volume.

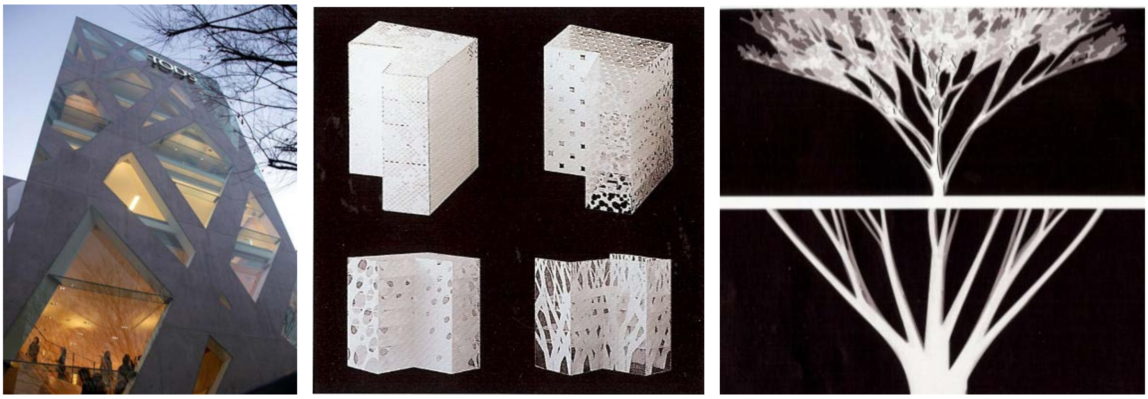


Figure 2.5.9. Architectural overview of TOD's Omotesando Building, Tokyo

Figure 2.5.10. Criss-crossed concrete braces skin of TOD's Omotesando Building, Tokyo

Urban Hive Tower in Seoul South Korea

The Urban Hive Tower was designed by Archium studio. Reinforced concrete walls with circular openings compose its façade. The entire façade is calculated from a structural point of view to withstand external loads as well as by its structural system, providing an interior space without columns. This possibility is a great advantage from the architectural point of view by organizing the interior spaces in the most functional way for the building.

"Urban Hive is an example of the skin and structure unification in a building and has been designed to maximise the flexibility of the space by excluding structural elements, other than the core, in the users' space," stresses the architect.

The wall thickness is of about 40 centimetres. The openings are positioned regularly, composing a flexible structure by creating the tension and compression zones inside it. This configuration of internal forces makes it possible to withstand the inertial forces generated during a seismic event.

Regarding the general assumptions on the perforated pattern of the building, the architect states as following:

> "In architecture, a building's structure and the skin has been treated as a separate subject. The embracement of new materials and advanced technologies has allowed the architects to design Structural Skin, which the surface of the building acts as the structure and vice versa. Urban Hive is an example of the skin and structure unification in a building; and has been designed to maximize the flexibility of the space by excluding structural elements, other than the core, in the users' space. This form of structure has excellence in safety towards the dead and live loads as well as the natural disasters such as earthquakes. In addition, it adds an advantage for creating a flexible spacing. This type of skin does not only act as the structure, but also contributes in formation of a dynamic space; and the punctured circular frames provide various views."

Figure 2.5.11. The dotted façade of Urban Hive Building in Seoul's Gangnam district

Figure 2.5.12. Internal view of the dotted façade of Urban Hive Building at the ground floor

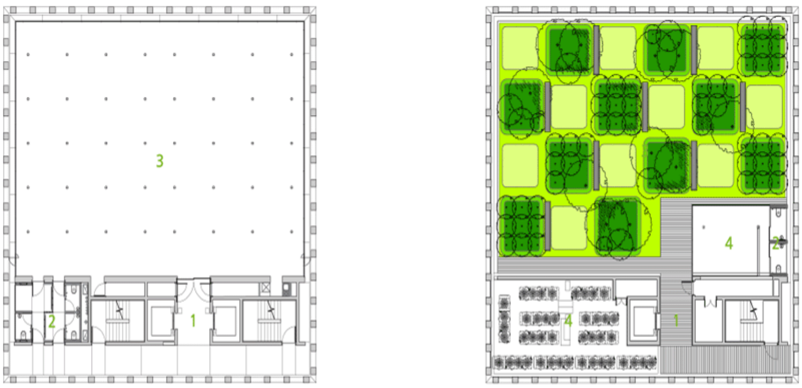


Figure 2.5.13. Typical Floor Plan and Roof Garden Plan of Urban Hive Building

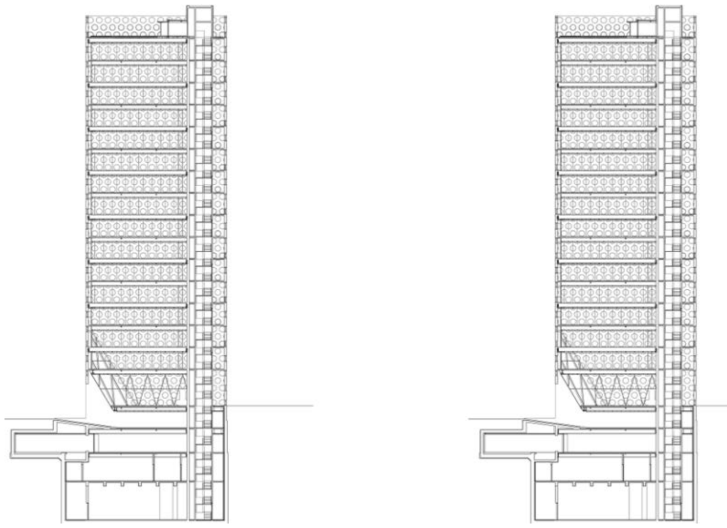


Figure 2.5.14. Vertical Sections of Urban Hive Building

As it can be seen from the above plans and sections, the aim was to have a simple and clear façade. The perforated concrete wall are considered thick and they do not close the space. In the two figures below, are shown the reinforcement bars and all details to the construction of perforated façade. It is very clearly observed that the also the reinforcement detail follows the main idea of the path of the internal forces, by creating the "X" form of two principal zones, the tension and the compression zone.

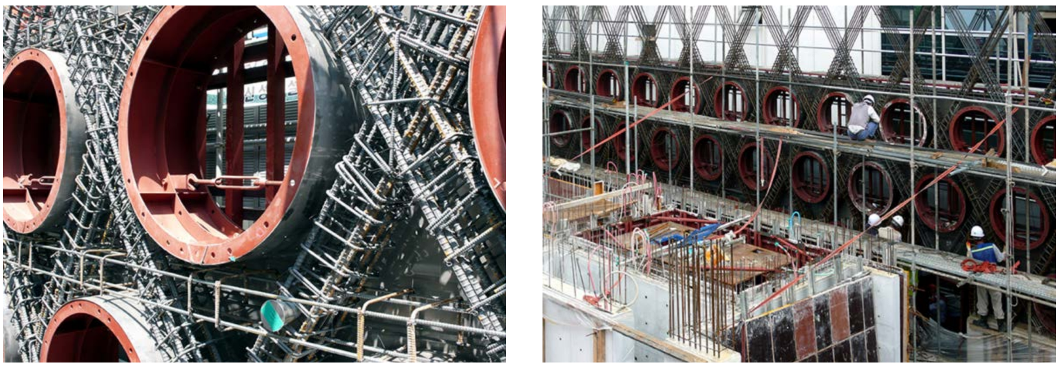


Figure 2.5.15. The detailed reinforcement of the exterior concrete wall of Urban Hive Building

Jean Nouvel's Cyprus Tower

The Jean Nouvel Tower in Cyprus represent an iconic tower, which bears the name of its own designer, Jean Nouvel. This 18-story high building is located in the center of Nicosia. Regarding some characteristics on the façade, the architect stresses that:

"On the south façade a vertical landscape covers approximately 80% of the building's façade area. This exceptional living environment is working like a natural "brise soleil". The plants will act as a natural sun control shielding the apartments and the offices from direct sun during summer while admitting a maximum of sunlight in winter. This "living façade" supports a variety of Cypriote climbing and spreading plants and will be continually transformed by the cyclic movements of the different seasons. On the top two floors of the tower, a duplex apartment is organized around a central court-yard inspired by the Cypriot traditional architecture."

On the north façade, the balconies extend out, toward the park and the city skyline. And on the east and west façade, there can be noticed a random arrangements of openings, determining interesting light and shadow throughout the exterior and interior space in relation to the different sun position of the day. The building represent a good example in the integration process of architecture and landscape by offering Nicosia a new architectural icon.

Figure 2.5.16. The exterior perforated concrete wall of Jean Nouvel's Cyprus Tower


Figure 2.5.17. Elevation view of perforated concrete wall of Jean Nouvel's Cyprus Tower

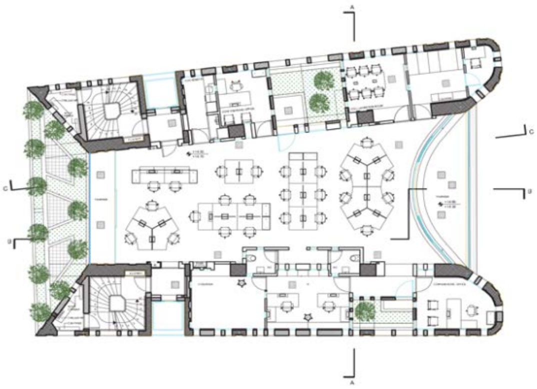



Figure 2.5.18. The ground floor plan and the vertical section of Jean Nouvel's Cyprus Tower

IBS Institute of Science in Guimaraes

This building in Guimaraes is the only low-rise building in the matrix of eight buildings selected worldwide. The reason for selecting this building is connected to the structural façade. This building represent a very important university research institute in Portugal and its façade is composed by an irregular arrangement of openings. The perforation technique is referred to the inspiration of the scientists by the tubular molecules that form solar panels.

Vilarinho, the architect, on purpose, intended to design a particular building façade where each surface was in pale green color, in order to interpret the titanium nanotubes shapes through the facades openings. The building form is that of a cuboid with an open section at the front of the ground floor. This removed part creates a cantilevered in the upper storey that shelters the main entrance. Moreover, Vilarinho stresses that:

> "We propose a building with a unique image for the campus. A building that breaks the existing grey monotony – referring not only about the pictorial issue of the campus, but also about the 'global crisis without end' – and that, at the same time, is able to captivate. Associated with recent discoveries, the titanium nanotubes have capacities for reuse and cheap production, becoming an inspiration for an architecture that seeks sustainability as an ideal."

In fact, unusual the other building examples taken onto consideration, this building the façade is comprised by the prefabricated panels. The prefabricated panels were cast from a cement composite material. In order to increase the strength parameter of the structural material, the microfibers were incorporated. This material tend to be resistant to corrosion and is suitable for moulding since it has a plastic quality. The pale green color was provided by adding some pigments during the process.

Figure 2.5.19. The exterior perforated concrete wall of University science institute at Portugal

Figure 2.5.20. Computer Digitized Perforated Front and Side Elevation of University science institute at Portugal

The purpose of selecting this building is related to the fact that also in Albania, as in all metropolises of the world, a series of high-rise buildings have been built in the last 20 years, as part of Tirana’s urban requalification plan. This building is 100 m high and it is intended for commercial and hotel business. Its façade is structural with in cast concrete and as it can be seen from the photos below, its pattern is perforated.

The texture of the façade is a clear interpretation of the ancient traditional fabrics of the region. The interior spaces are free from the columns and walls, since the high vertical structures exclusively consist only of an external reinforced concrete core. The floor slabs are also 40 cm thick, considering the high load intensity.

The 85-meter multi-storey building was designed by Archea Associati who stress that:

> “The building has a complex, varied functional programme: a six level underground parking lot, four levels of commercial space, seven levels of offices, and apartments on the top eight floors as well as a luxury hotel in a panoramic position at the very top of the tower. Entitled "4 ever green", was chosen above the others for the way it manages to fit the tower into its urban context and create public spaces by narrowing the base of the building. Rather than the glass and steel architecture of the contemporary skyscraper, we are inspired by the well-established tradition of the masonry towers of the historical landscape. The building's motion and skin reinvent tradition, inspired by the weaves of the traditional fabrics from the Tirana area, transforming them into a texture which gives the building's facades a vibratile, ethereal nature.”

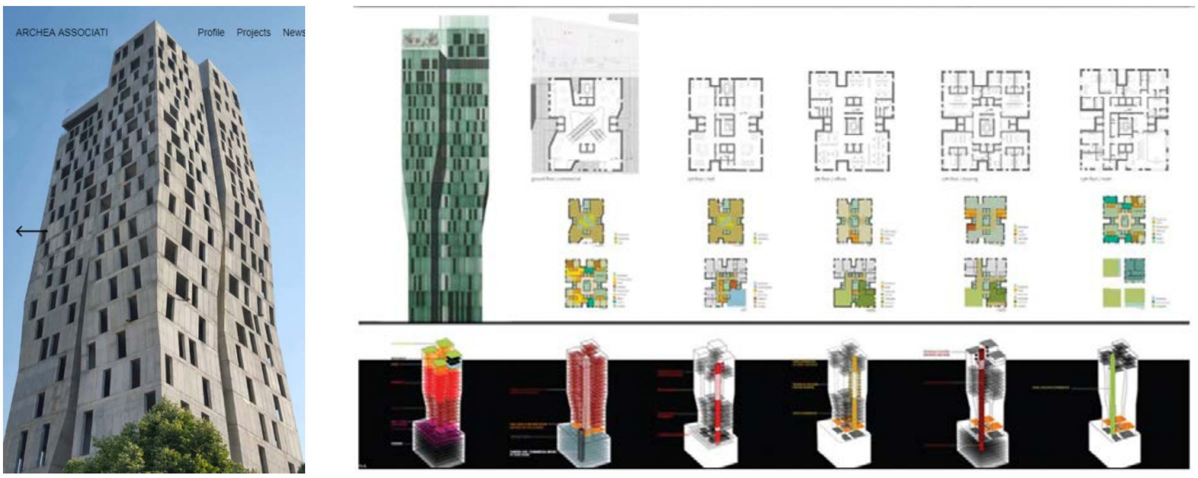


Figure 2.5.21. Computer Digitized floor plans, elevation and 3D view of Forever Green Tower in Tirana

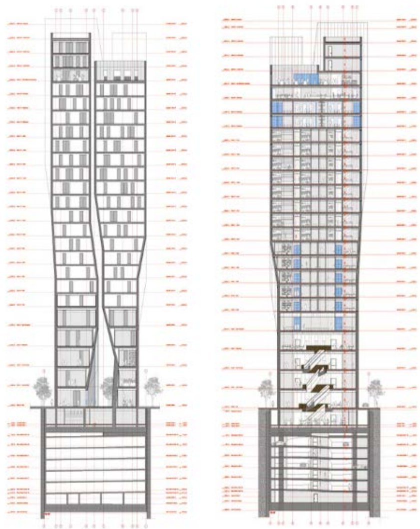


Figure 2.5.22. The vertical sections of Forever Green Tower in Tirana

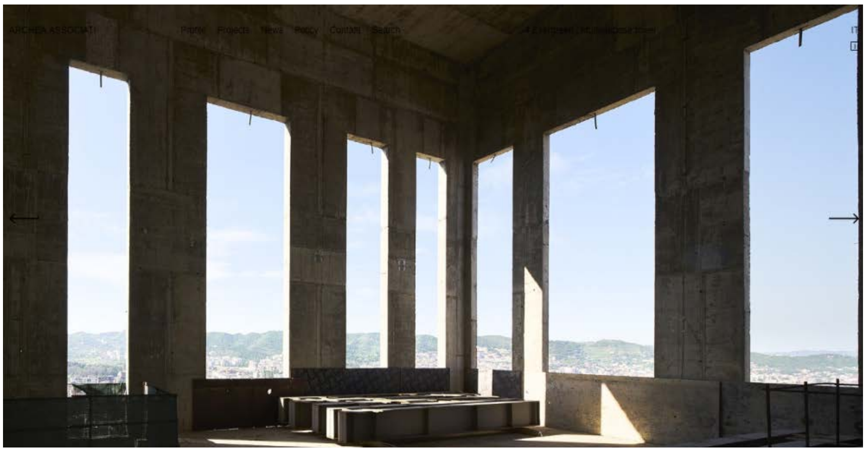


Figure 2.5.23. The exterior concrete walls from the inside of the building

Figure 2.5.24. The texture of the façade of Forever Green Tower in Tirana

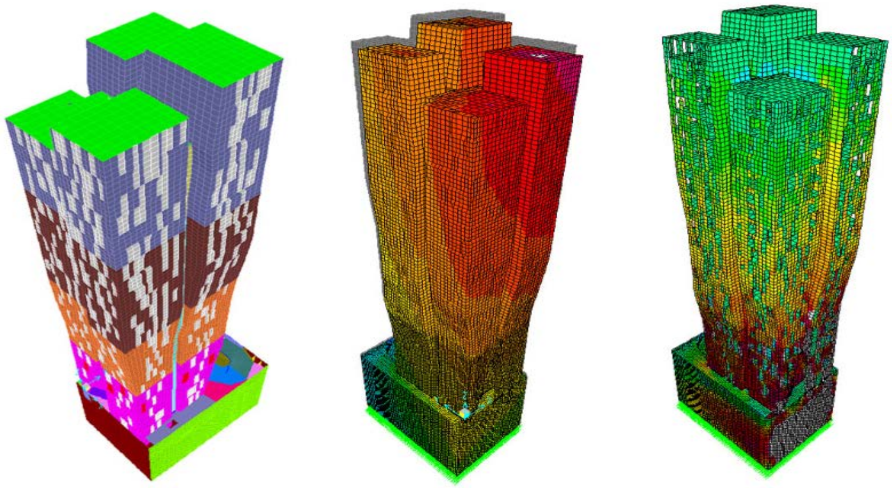


Figure 2.5.25. The stress-strain analysis and internal forces diagrams of Forever Green Tower in Tirana

2.6 Summary

In this chapter is being discussed the assessment of perforated structural walls located in the perimeter of a multi-storey building, towards increasing the general knowledge related to these typology of architecture.

Moreover, it addresses the optimization of structural element to fulfil the low cost criteria. By at the same time offering the possibility to enrich the architectural aspect of multi-storey buildings via perforated structural wall panels.

The main purpose is that this vertical structural element to be recognized as architectural and structural values of multi-storey buildings façade and by means of a co-design process elaborate an appropriate design in terms of architectural and structural aspects.

The methods used are through case study, which give a better understanding of perforated shell performance on multi-storey buildings and get inspiration for perforated panels as structural wall elements.

There have been identified eight cases of multi-storey buildings worldwide and for each of them have been presented the main design idea, architectural plans and details regarding the perforated facade. All of these buildings at their façade have exterior concrete skeleton that frees the core from the burden of lateral forces, and at the same time is the primary vertical and lateral structure for the building itself.

On the other hands, this element creates inner spaces without columns, maintaining minimal structural traces by at the same time possessing the opportunity to create a wide range of visual effects on structures.

CHAPTER 3

Multi-storey Buildings | Exposed Structural Systems | Structural Wall with Openings

C H A P T E R 3

3 Types of Structural Systems

3.1 Introduction

In this chapter will be discussed the various structural systems of multi-storey buildings. In a broader perspective, construction has been one of the main directions where the human mind has tried to design even often unrealistic buildings. All these buildings hide in themselves what is called the Structural System of construction. Shape, dimensions, method of construction, materials used, etc. are diverse, from the simplest to the most sophisticated where the human imagination can go. But it should be noted that in all cases what precedes, are the calculation methods of these structural systems.

According to the type of construction and the way of applaying the external forces, it is chosen also its calculation scheme. The calculation scheme should be associated with the main and basic hypotheses. These are based on the classical principles of structure theories and take into account the type of materials used as well as the way the structure reacts.

It is clear that the fewer hypotheses made, the closer the constructive solution is to the real reaction of the structure. But this in turn will require increased computational work. With the development of informatics today, using powerful calculation methods, several structural schemes are solved, considering that only a few years ago several of those schemes were considered unthinkable to be practically realized.

In this study, from the many types of structural systems, are studied those types of structures which in the literature are called Dual Systems, Structural Walls combined with moment resisting frames both rigid or flexible frames. Due to the very large stiffness in the horizontal direction of the structural wall which can reach up to 90-95% of the stiffness of the whole structure according to this direction, this will be the main supporting element for the system against the action of these types of loads.

These elements are generally made of reinforced concrete and do not change cross-sectional dimensions throughout their height. To avoid the effects of torsion as much as possible, these vertical elements are usually placed in such a way that they have the smallest possible eccentricity. The eccentricity is defined as the distance between the center of mass and the center of rigidity of the structure. This means that for structures with a more or less regular shape in the plane, the core[2] is placed in the center of gravity of the plane cut, accompainig with the structural walls in their perimeter.

3.1.1 Historical and bibliographic notes

Detailed theoretical studies based on laboratory research on the reaction of the reinforced concrete walls under the action of external forces, have received scope and have provided solutions to many design-related problems of these types of structures.

During the years of 1950 until 1970, there were given some special aspects in the dynamic reaction intertwined with the seismic one even that the research in this field had a sporadic character and small volume. After the 1970s, with the even wider spread of structural systems using their advantages in the realization of earthquake-resistant constructions and external horizontal forces, experimental research was intensified in many countries of the world, especially those interested in problems of anti-seismic design (USA, Japan, Romania, New Zealand, etc.). In this regard, more emphasis has been placed on the reaction of different structural schemes in the specific conditions of seismic action and especially in the post-elastic stage.

In this period has begun to pay more attention to the study of reaction of solid structural walls and structural walls with openings, under the specific conditions of seismic action of loads especially in the post elastic stage. Survey experiments on models have also been conducted in the direction of another category, the stresses caused by the concrete shrinkage and shrinkage of temperatures. Due to the massive character of the structures with these types of stresses, it is important to compare to frame structures. Based on these theoretical predictions is further specified the dimensioning of structural wall.

[2] Core is referred to Core Wall, a group of three or four single structural walls which form a shape of the letter U or the shape of a rectangular in plan. In general these walls are solid, unless for functional requirements of the designers, openings are present in them.

It has been ascertained that the fracture pattern as well as the determination of the bearing capacity in eccentricity compression can be adapted for walls with large length and is being determined the method of calculating structural walls in shear force is defined.

Referring the vertical structural elements with openings which are part of a frame type structure, theoretical and experimental research in several research papers and technical papers have proved that special attention should be made to the calculations on the static scheme of the structure taking into account the specificity of the structural wall elements and in particular that of connecting beams.

Qualitative experimental stage of these types of structural walls in the 80s have been those of structural behaviour in the post elastic stage up to failure under the seismic loads. It is been also observed the behaviour of the connecting beams and their failure mechanism.

In these studies, it is reached the conclusion that there is a large increase in rigidity if the connecting beams are constructed in such a way that absorbs the shear force without considering the contribution of the concrete.

The realized structures based on anti-seismic concepts and norms and dimensioned at a sufficient level to the horizontal forces dynamic calculation, have withstood the forces born during powerful earthquakes.

An approximate orientation on building safety is the acceptance of the active cross section required to absorb the shear force. This applies to especially for structures with structural walls in particularly difficult working conditions, such as; those sparse walls, with reinforced concrete core wall, or with a longitudinal wall. It has been concluded that for the buildings above 10 floors, if the total wall section is approximately 80% of the total floor section, no significant expectations from seismic action are observed.

Defects have been found in the slabs of the structures with sparse walls and those with core walls, from the stresses arising in the horizontal hinges, as well as of the difference of the rotational positions in the vertical plane of the wall with that of intermediate frames.

Laboratory research and experiments performed on the reaction of structures with core walls, have led to safe design against the dynamic action of horizontal loads for buildings with various configurations and with great height.

3.1.2 Basic hypothesis and classification of structures with rigid core wall

The building design under the action of horizontal loads (Wind, Seismic Loads, etc.), must contain the required strength of its composing elements to withstand the internal stresses deriving from the static or dynamic action. The structural systems that are most useful to resist this type of forces, are those who have supporting elements such as structural walls and core walls. These systems are generally more economical for buildings which do not exceed 100m in height. Excluding the industrial buildings, the frame systems are not recommended due to large deformations and consequently to high construction costs.

"Tube" or "Tube within Tube 'systems should only be used in those cases when it is necessary to reduce the horizontal deformations of the building including the rigidity contribution of structural elements located on the facade. This may be necessary in the case of very high rise buildings or in those areas with a high seismic activity.

Together with the inter story slabs, the structural walls and the core walls form one three-dimensional hyper static system. Horizontal loads in general are considered to be applied at the level of inter story floors. In each floor the loads are being transmitted through to the structural walls and core walls through the slab which works in horizontal direction as a plate supported in an elastic manner in the structural wall and core wall. The forces **Sij** resulting in different structural walls and core walls are equal to the building reactions, so they are proportional to their rigidities.

These elements can be either be in cast concrete or prefabricated. As it can be stated, the difference between them lies in the fact that the prefabricated elements are produced industrially in specialized firms and are interconnected to the building by casting the "Connection Joints". These joints are considered parts of the structural system. It is clear that the existence of such areas "connections" in the structure will affect the reaction of the structure as a whole, and the request for additional calculation and construction procedures. It is worth mentioning the fact that due to the construction of prefabricated structures in such areas, the cast in place structures are more preferable since they behave much safer under the action of dynamic forces.

When designing these types of structural systems should be taken into account some basic hypotheses and requirements where the main ones are the following ones:

1. The behavior of the system is accepted to be Elastic – Linear.

2. The rigidity of the partition walls and non-retaining elements is neglected.

3. The inter story slabs are accepted as diaphragms with infinity rigidity in their own plane.

4. The rigidity of diaphragms and slabs outside their own plane is neglected.

5. The deformations from shear stresses in the "thin" elements (1 / h> 3) and their torsional rigidity is neglected.

6. The surfaces and rigidities of the sections are based on concrete sections.

7. The joints between the elements are considered absolutely rigid.

8. The rational distribution of vertical elements. These are required to be placed in a more symmetrical shape related to the main floor plan axis, to avoid the emergence of torsional effects in structure.

9. The structure rigidity in its height to have continuity, which is realized through the continuity of the vertical elements throughout the height of building. Lack of one or more vertical elements on any floor can bring dangerous concentrations of strain.

10. Axil deformations values of the elements are neglected.

11. Second order effects are neglected.

Hypothesis (**1**) of the linear-elastic reaction is generally correlated. A detailed nonlinear analysis may be required in very high buildings where the axial deformations of the columns and the effects of the second order (P-Delta effect) are important.

Hypothesis (**5**) is acceptable for those vertical elements which are considered “isolated” (one element = one diaphragm). For an ensemble reinforced concrete walls which form a rigid core, the stiffness in his twisting can not be in neglected.

Undoubtedly, the above requirements do not oblige to not design structures with different geometric configurations or such to be take also in consideration the flexibility of the slabs of the inter story slabs. The problem lies in the fact that by deviating from these basic requirements, one must operate with theory rectified and “structural model” choices, to approach the real behavior of structures. These lead to the use of more complex calculation procedures with a large volume of work.

A big impact of the Industrial Revolution on 19th century architecture was the production of iron and later steel in considerably quantities and it became an economical building material and a game changer in architecture. Even today it seems to be hard to overstate the importance of it in modern life.

The steel application expanded the structural capabilities of existing materials, and created new ones. Steel has tremendous strength to weight and allowed to engineers to design increasingly bigger, lighter, more open spaces. The first major applications of steel occurred in public works, namely railroads and bridges which quickly made the best use of steel. For example a humble steel truss bridge required very little material and the architectural intervantions were just in adding some sort of decoration on the portal frame facing the viewer.

During the twentieth century, the presence of steel in architecture has assumed roles that are certainly not secondary, roles that involve the whole building components, from the supporting structure to the covering panels, from the skeleton to the leather. Like in the ancient Vitruvian canons of Firmitas, Utilitas, Venustas, the formal identity of a building is still linked to it and also from an engineering point of view to research technology of materials and construction systems.

The feasibility of multi-storey buildings has always depended upon the available materials and the development of the vertical transportation necessary for moving people up and down the buildings. The ensuing growth that has occurred from time to time may be traced back to two major technical innovations that occurred in the middle to the end of the nineteenth century: the development of wrought iron and subsequently steel, and the incorporation of the elevator in high-rise buildings. The introduction of elevators made the upper floors as attractive to lease as the lower ones and, as a result, made the taller buildings financially successful.

During the last 120 years, three major types of structures have been employed in multi-storey buildings. The first type was used in the cast iron buildings of the 1850 to 1910, in which the gravity load was carried mostly by the exterior walls. The second generation of multi-storey buildings, which began with the 1883 Home Insurance Building, Chicago, and includes the 1913 Woolworth Building and the 1931 Empire State Building in New York City.

Category	Sub category	Material	Maximum number of storeys	Advantages	Disadvantages	Building Examples
Rigid Frames		Steel	30	Provide flexibility in floor planning. Fast construction.	Expensive moment connections. Expensive fireproofing.	860 & 880 Lake Shore Drive Apartments (Chicago, USA), Business Men's Assurance Tower (Kansas City, USA), Seagram Building, (New York, USA)
		Concrete	20	Provide flexibility in floor planning. Easily moldable.	Expensive formwork. Slow construction.	Ingalls Building (Cincinnati, USA)
Structural Wall - Frame Interaction System	Braced Rigid Frames	Steel Shear Trusses + Steel Rigid Frames	40	Effectively resists lateral loads by producing shear truss - frame interacting system.	Interior planning limitations due to shear trusses.	Empire State Building (New York, USA), Seagram Building, 17th to 29th floor (New York, USA)
	Structural Wall / Rigid Frames	Concrete Structural Wall + Steel Rigid Frame	60	Effectively resists lateral loads by producing Structural Wall - frame interacting system.	Interior planning limitations due to Structural Walls.	Seagram Building, up to the 17th floor (New York, USA)
		Concrete Structural Wall + Concrete Frame	70	Provide flexibility in floor planning.	Slow construction.	South Wacker Drive (Chicago, USA), Cook County Administration Building, former Brunswick Building (Chicago, USA)
Outrigger Structures		Shear Cores (Steel Trusses or Concrete Structural Walls) + Outriggers	150	Effectively resists bending by exterior columns connected to outriggers extended from the core.	Outrigger structure does not add shear resistance.	Taipei 101 (Taipei, Taiwan), Jin Mao Building (Shanghai, China)
Tube	Framed Tube	Steel	80	Efficiently resists lateral loads by locating lateral systems at the building perimeter.	Shear lag hinders true tubular behavior. Narrow column spacing obstructs the view.	Aon Center (Chicago, USA)
		Concrete	60	Provide flexibility in floor planning.	Slow construction.	Water Tower Place (Chicago, USA)
	Braced Tube	Steel	150	Efficiently resists lateral shear by axial forces in the diagonal members. Wider column spacing possible compared with framed tubes.	Bracings obstruct the view.	John Hancock Center (Chicago, USA)
		Concrete	100	Provide flexibility in floor planning.	Slow construction	Ontarie Center (Chicago), 780 Third Avenue (New York, USA)
	Bundled Tube	Steel	110	Reduced shear lag.	Interior planning limitations due to the bundled tube configuration.	Sears Tower (Chicago, USA)
		Concrete	110	Provide flexibility in floor planning.	Slow construction	Carnegie Hall Tower (New York, USA)
	Tube in Tube	Ext. Framed Tube + Int. Core Tube	80	Effectively resists lateral loads by producing interior shear core - exterior framed tube interacting system.	Interior planning limitations due to shear core.	West Madison Street (Chicago, USA)

Diagrid		Steel	100	Efficiently resists lateral shear by axial forces in the diagonal members.	Complicated joints.	Hearst Building (New York, USA), 30 St Mary Axe (London, UK)
		Concrete	60	Provide flexibility in floor planning.	Expensive formwork. Slow construction.	COR Building in Miami , Mikimoto Ginza 2 in Tokyo , Tod's Omotesando Building in Tokyo
Space Truss Structures		Steel	150	Efficiently resists lateral shear by axial forces in the space truss members.	Obstruct the view. May obstruct the view.	Bank of China (Hong Kong, China)
Superframes		Steel	160	Could produce supermulti-storey buildings.	Building form depends to a great degree on the structural system.	Chicago World Trade Center (Chicago, USA)
		Concrete	100	Provide flexibility in floor planning.	Slow construction.	Parque Central Tower (Caracas, Venezuela)
Exo-skeleton		Steel	100	Interior floor is never obstructed by perimeter columns.	Thermal expansion / contraction.	Hotel de las Artes (Barcelona, Spain)
		Concrete	60	Provide flexibility in floor planning.	Expensive formwork. Slow construction.	O-14 Building (Dubai)

Table 3.1.1. A Structural systems classification of high-rise buildings.

Source: (Shawkat. S., 2017), (Ali. M. M., 2010), (Kayvani. K., 2014), (Mufti. A. A., Bakht. B., 2011), (Goldsmith. M., 1953), (Taranath. B. S., 2010), (Ali. M. M., Moon. K. S., 2007), (Azizi. M., Torabi. Z., 2015) (Revised by the author)

In the table above is presented a classification of structural systems with material used that of concrete and steel. The classification is based on the studies of eight different research papers and authors. The structural systems were divided into main categories and subcategories, the efficient height and for each of them there are also given the advantages and disadvantages.

The invantion of elevator and steel frame structure are obvious two technological developments that enhanced the increasing in height of buildings. On the other hand, providing the required stiffness, ductility and strength is the main aim of the design team besides their insiprations to build higher structures. An important factor to consider in this aspect is related to the maximum top displacement of the building due to an eventually seismic motion.

The main types of structural systems observed in high rises and in contemporary design are: Structural Wall System, Braced system, Hybrid System, Moment Resisting System, Trussed

Tube, Bundled Frame Tube etc. Below it is intended to give a brief explonation for each of them.

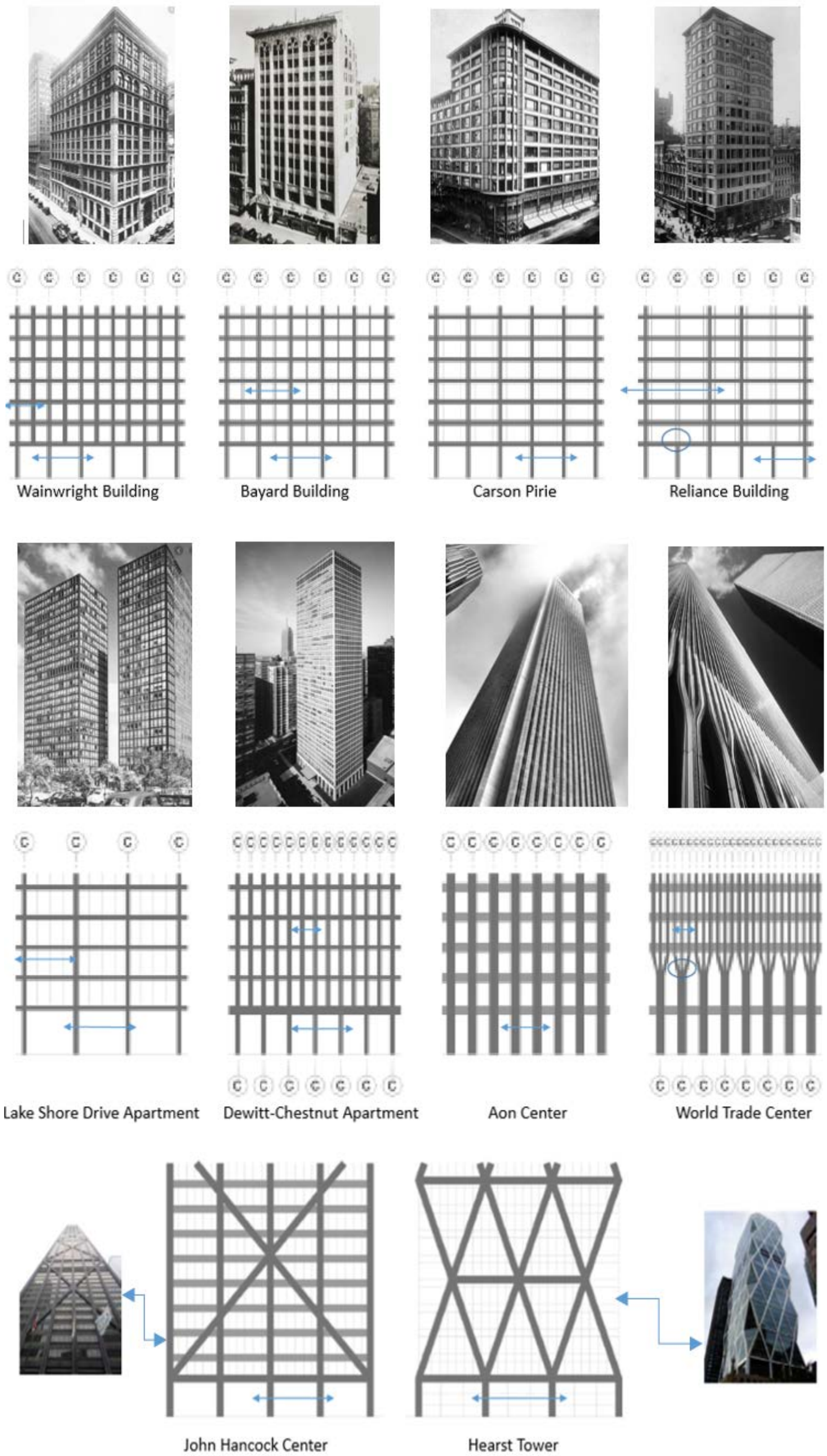


Figure 3.1.1. Simplified diagrams of moment resisting frames.
Source (Ali, M. M., and Moon. K. S., 2018); Illustration by the (author, 2019)

3.2 The exposed structural system of multi-storey buildings

The three main structural systems of multi-storey buildings are:

⇒ Structural Walls,

⇒ Braced Frame,

⇒ Moment Resisting Frame.

Structural Wall System is considered a rigid frame construction. The Structural Wallcan be either in steel materila or in reiforced concrete material providing greater lateral rigidity. This system use to show resistance of both horizontal and vertical loads. The most common loads acting on this element are the wind and the earthquake loads. It is preferable that in the aplication of the multi-storey buildings, with the increasing of the structure size, the cross section of the wall itself should increase proportionally.

Braced System Frame are composed as cantilevered vertical trusses. Their primary resisting system are related with the lateral loads. The steel bracing works in tension scheme providing the required stiffness while subjecting to lateral loads. This system tend to be more economical in terms of resulting in the end a very stiff structure.

Moment Resisting System, has a definition related to the basic behavior of moment resisting Frames, Beam-to-column connections: before and after Northridge, Panel-zone behavior, AISC seismic provisions for moment resisting Frames: special, intermediate and ordinary. A moment resisting frame allows visual the exterior but is considered one of the least stiff options, braced frames tend to be more flexible and Structural Walls stay in the middle: are very stiff but tend to use more materials.

So every building really needs to have some type of, one of those three systems and sometimes they have multiple systems and designers are looking out how stiff, how they are gonna resist the applied load coming from earthquakes or from wind. So you probably found that braced frame was pretty stiff so use a truss system, tends to be very stiff also very efficient.

Structural Walls can also be very stiff but they tend to use more material so theres pro and cons there. From a single degree of freedom if we experiment with a single degree of freedom model, stiffnes is not always better but there are pro and cons.

Sometimes designers need stiffnes when they get buildings that are very tall and they are not stiff enough there are to much motions and their are not comfortable especially at the top of the building. And if the beams are not stiff enough they deflect to much. So it has to balance.

Stiffness is one peace of the puzzle but there are other reasons. A moment-resisting frame tends to be the choice for a lot of buildings because it allows visual the exterior, it allows windows, so it permits a lot more open space from windows, it is one of the least stiff options but it provides other things that are useful. Structural Walls are the opposite, no options for windows in Structural Wall but we often use them in the core of a building so around elevators and staircases and they are very stiff.

But engineering is all about these competing criteria so its not just stiffness, is also strength but is aesthetics, functionality and cost is a big factor. So how you pick different systems would depend on all these citeria. So putting all these pieces together, how structure is changed over history.

So talking a little bit about early structures in stone which are very strong in compression who does a great job with arches, vault domes but is very weak in tension, people did use them for buildings but the span tend to be very small, very short again because it doesnt have very much tension capacity and those beams rely on both tension and compression.

So considering a plan view of ancient buildings so an example would be the Parthenon, the temple of Zeus, one of large stone structure, if you look at the plan view you see lot of coloumns very closely spaced throught the building, that is because stone, if it used for the beams can not span very far.

It span little bit farther when they started using arches and vaults in many of chatedral so the span get little more greater and the height got more heigher but still it was limited by the material. It was until 1700 with the advent of steel and iron so we started to get more open space, we started to get taller buildings.

So one of the first examples of a steel moment-resisting frame which are more common systems used in early buildings, was the Wainwright Building in St Louis. If you remove the outer skin of the building, you see steel coloumns and beams. It was designed by Louis Sullivan and Dankmar Adler.

Around 1900s, an unofficial skyscraper competition began that was mainly New York and Chicago compiting, trying to get the tallest structure. So the Woolworth Building is an example of that. It was commissioned by Franklin Woolworth, the entire goal was to build the tallest building so he paid 13.5 million dollar in cash for the building, it was completed in 1913, it was 241.4 m tall and it was the tallest building in the world until 1930. It was designed by engineers Gunvald Aus and Kort Berle.

Again as early buildings it was used a steel moment-resisting frame and it was gained to get a lot of windows. It also was the first building that include an elevator which is the key for making buildings got taller. So if you want to get building taller you will started to have to think about fires and possibility in getting people in and out.

The next building which was completed in 1931 was Empire State Building which was the tallest building in the world until 1972, was designed by the architect William F. Lamb and the engineer Homer G. Balcom. One of the key points about this building is the speed which it was built.

It was designed and built in 20 months, so it began the phase for construction to use a sampling line approach. It is an iconic building and it was designed in an art-deco style, propably began the famous skyscraper around the world. Internally is using a steel moment-resisting frame to resist those lateral loads.

Next building is the John Hancock Tower it introduced a new type of frame infrastructures that actually helped structures in general become taller. So it is introduced the tube structure, so up until then, buildings were traditionaly very regular, all the volloumns were spaced regularly, the John Hancock Tower uses a truss tube so if you look at the exterior, you will see axes on outside. It was designed by the engineer Fazlur R. Khan with the help of the architect Bruce Graham. It was completed in 1969 and is 344 m tall.

Fazlur Khan describe the Engineering as a science which is about competing criteria of stiffness, aesthetics, functionality and cost. Fazlur R. Khan is a famous enginner, he is known as the father of the tube structure. He is a bangladeshian american engineer. So started from the traditional grid of coloumns placed very regurlarly throughout the building, he moved everything to the outside of the building, not everything most the coloumns and lateral forces resisting system was moved to the outside.

This tends to be more efficient and economical, it has to do with the stiffness if we compare with beams, moving a beams mass away from its center increases its moment of inertia, that why we use I beams, forms that have everything moved away from the central axes. It is the same in buildings.

Tube framed approach increases overall buildings moment of inertia. Fazlur Khan also designed the Willis Tower (formely now is the Sears Tower) is again a tubed frame system, not with the truss but still tube frame everything in the outside. It was completed in 1973 and it was the tallest for almost 25 years so the Burj Khalifa in Dubai is currently the tallest building in the world. It goes a height of almost 830 metres which is huge, it is 3 times the height of Eiffel Tower to give a prespective. Another way to give a prespective is the weight of the concrete that was used. The weight of the concrete in the building is equal to weight of 100 000 elephants.

He initiated the classification of structural systems in multi-storey buildings considering height, structural efficiency and material used. Khan, known as the father of the tube structure, moved most the coloumns to the outside of the building, and lateral forces resisting system was moved to the outside.

This tends to be more efficient and economical, moving mass away from its center increases its moment of inertia like in I beams. The figure below shows a very simple structural plan following the idea of Khan moving all stiffness in the perimeter of the building.

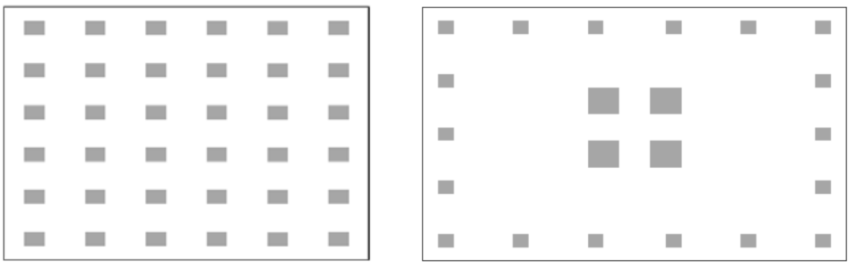


Figure 3.2.1. Plan view of a traditional grid of columns placed regularly (left) and a tube framed structure (right) (source: author, 2020)

Following the concept of Khan, the three main structural systems have been emerged further or combined to each other like in the case of mixed systems which is better described in the book of Andrew Charleson "Seismic Design for Architects. Outwitting the Quake". He use to emphasize with simple diagrams the structural behavior of each system under seismic excitation and identificate the mixed system as the best one.

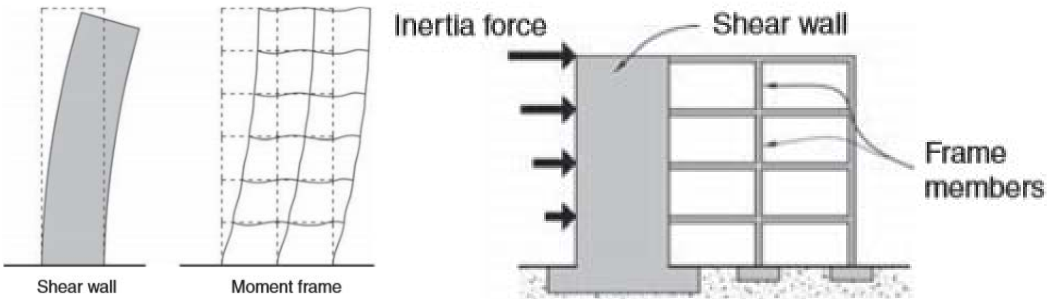


Figure 3.2.2. The different deflected shapes of a shear, a moment frame resisting seismic forces and a mixed system (source: Charleson, 2008)

He states that Structural Walls and frames in combination provide the required stiffness and strength to withstand lateral loads in multi-storey buildings although the fact that in certain cases the Structural Walls are much more stiffer than the frames and thus take most of the lateral load. For this reason, the participation of the frame in resisting lateral load is often ignored especially in lower stories. The goal is to try to figure out the pro and cons of different system and specifically to look at their stiffness so which of them is stiffner, which deflected less as you try to push on them.

Another interesting statistics was 12 000 people worked on Burj Khalifa during the construction. The Burj Khalifa was designed by the engineer Bill Baker and the architect Adrian Smith. It is interesting to read about the design which is based on a flower and it is also using a bundle tube construction but it got this three arms so it got very strong core and as it goes up less and less it tappers somewhat like the Willis Tower.

The reason it has those three arms is that it can resist the wind in any direction, so it has these three arms of a nice moment of inertia at the base, so it has this strong core and this three arms that extend out to give it some stiffness. So as it tries to bend it got stiffness in any direction, in similarity with beam theory and the moment of inertia. It is an extensive wind tunnel testing that was done, models of the Burj Khalifa and all the details in computer analysis. It is just an amazing feature that brings all the systems together.

The building in the above figure consists of a tube in tube structure. In the perimeter, it can be identified structural walls while the internal are positioning the braced frames. For diagonal bracings are used prestressed steel bars. This system contain also braces with wide elastic range which helps a lot in resisting the acting forces on the structure.

- *Hybrid System* is composed by two or more of basic structural schemes appicated in the entire structure or even in a single part of it. Its lack of torsional stiffness requires that additional measures be taken, which resulted in one bay vertical exterior bracing at a considerable number of level of perimeter.

Architect	**Nikken Sekkei ltd**
Structural engineer	**Nikken Sekkei ltd**
Year of completion	**1968**
Height	**110.06m**
Number of stories	**26**
Stories below ground:	**2**
Frame material	**steel**
Material	**steel grade 490 mpa**

Figure 3.2.3. Kobe Commerce Industry and Trade Center, Japan

- *Trussed Tube* interconnect all exterior columns to form a rigid box, which can resist lateral shears by axial in its members rather than through flexure. This system introduce a minimum number of diagonals on each façade and making the diagonal intersect at the same point at the corner column. The system is tubular in that the diagonals not only form a truss in the plane, but also interact with the trusses on the perpendicular faces to affect the tubular behavior. Relatively broad column spacing can result in large clear spaces for windows which is also a particular characteristic of steel buildings. The façade diagonalization serves to equalize the gravity loads of the exterior columns that give a significant impact on the exterior architecture.

Figure 3.2.4. John Hancock Center, Chicago

- *Bundled Frame Tube*, the concept allows for wider column spacing in the tubular walls. The space make it possible to place interior frame lines without seriously compromising interior space planning. It also has the ability to modulate the cells vertically can create a powerful vocabulary for a variety of dynamic shapes.

Figure 3.2.5 Willis Tower, Chicago

- *Framed Tube*, is a system composed by a very stiff moment-resistant frames. The frames consist of 2-4m between centers, joined by deep spandrel girders. Gravity loading is shared between the tube and interior column or walls. When lateral loading acts, the perimeter frame aligned in the direction of loading acts as the “webs” of the massive tube of the cantilever, and those normal to the direction of the loading act as the “flanges”. The tube form was developed originally for building of rectangular plan.

Figure 3.2.6. Dewitt Chestnut, Chicago

Structural Walls are primarily lateral load resisting element. They provide lateral resistance through virtue of geometry and moment of inertia generated of the whole system in plan. In order to efficiently utilise this phenomena, providing Structural Walls at periphery increases the lever arm for moment of inertia and higher value of it is achieved.

From historical precedents, a number of high-rise buildings are “tubular” structures with the main Structural Walls at the center. In addition, this for two main reasons:

- ✓ Periphery needs more openings for aesthetics (windows);
- ✓ Elevator (lift) walls are useless (non-revenue generating) and have no openings on three sides, so are excellent choices for Structural Walls.

Structural Walls further from the geometric center of the building will resist torsion *better*. This is why it is more *efficient* to place Structural Walls at the exterior perimeter of the building. However there is more to life than efficiency, thus sky scraper designers place a greater importance of the view that the efficiency of the lateral system. If you can compromise efficiency without sacrificing safety then you are free to do so. *“It has been proven that this system provides efficient structural system for multi storey building in the range of 30-35 storey’s”* (MARSONO & SUBEDI, 2000). “*In the past 30 years of the record service history of multi-storey building containing Structural Wall element, none has collapsed during strong winds and earthquake”s* (FINTEL, 1995).

In the seismic design of buildings, reinforced concrete structural walls, or Structural Walls, act as major earthquake resisting members. Structural walls provide an efficient bracing system and offer great potential for lateral load resistance. The properties of these seismic Structural Walls dominate the response of the buildings, and therefore, it is important to evaluate the seismic response of the walls appropriately. It is very interesting to investigate on the different location of the structural walls in a multi-storey building plan. In addition, optimum percentage of Structural Wall seems very important to be determined with respect to perimeter of the buildings.

Structural Wall are one of the excellent means of providing earthquake resistance to multi-storey reinforced concrete building. The structure is still damaged due to some or the other reason during earthquakes. Behaviour of structure during earthquake motion depends on distribution of weight, stiffness and strength in both horizontal and planes of building.

In modern multi-storey buildings, Structural Walls are commonly used as a vertical structural element for resisting the lateral loads that may be induced by the effect of wind and earthquakes, which cause the failure of structure. Structural Walls of varying cross sections i.e. rectangular shapes to more irregular cores such as channel, T, L, barbell shape, box etc. can be used. Provision of walls helps to divide an enclose space, whereas of cores to contain and convey services such as elevator.

Regarding the strategic position of Structural Wall openings, both authors Marsono and Subedi have declared in their study as above:

> "Wall openings are inevitably required for windows in external walls and for doors or corridors in inner walls or in lift cores. The size and location of openings may vary from architectural and functional point of view. The use of Wall structure has gained popularity in high rise building structure, especially in the construction of service apartment or office/ commercial tower. It has been proven that this system provides efficient structural system for multi storey building in the range of 30-35 storey's." (Marsono and Subedi, 2000)

Another statement that comes from Fintel in his study in 1995 on the importance of walls as below:

> "In the past 30 years of the record service history of building containing Wall element, none has collapsed during strong winds and earthquakes." (Fintel, 1995)

Abolhassan Astaneh-Asl (2001) presented in his study the effect of using composite Walls in seismic design. This composite Walls composed by steel plate and reinforced concrete material tend to improve the structural behaviour of the element itself and the impact that this element, gives on the general structural behaviour of the structure under study.

Kevin B.D.White & Gupta (2009) represented in their study a very different aspect in the design that by using wood frame Walls. Moreover they states that:

> "It was found that partially anchored subduction zone earthquake tests caused wall failure modes consistent with monotonic and cyclic tests. Fully anchored subduction zone tests caused wall failure modes consistent with cyclic tests. Fully anchored monotonic tests did not cause screw fracture or nail withdrawal and therefore did not have failure modes consistent with subduction zone earthquake tests. Energy dissipation was most similar to cyclic tests rather than monotonic tests." (Kevin B.D.White & Gupta (2009)

P.P.Chandurkar states on structural wall position regarding four different seismic areas as below:

> "A paper in determining the Wall location of four different types of models varying with earthquake load with zones II, III, IV, V as per IS: 1893: 2002. It was found that Structural Wall in short span at corner in model 4 was economical and effective in high rise buildings."

On the other hand, P.V.Sumanth Choudhary and Pandian made research on different positions of Structural Wall in a rectangular building. It was found that, in high seismicity areas, providing Structural Walls in the perimeter and the centre of the building tend to reduce the total deflection in horizontal translation movement.

Varsha R. Harne analysed the stability of multi-storey building with Structural Walls at different locations. Also compared these models considering different load combinations. It was found the most critical combination, that of (1.5DL+1.5EQX).

Venkata Sai Ram Kumar & Maruthi Krishna conducted an experiment in their study, by increasing each floor height above the seven floor. The structural system of the building under analysis is composed by reinforced concrete Structural Walls and from the structural analysis, were derived the main capacity curves. The active load applied in the structure were considered the wind loads. From their study, some interesting conclusions were derived related with the structure drifts, internal forces of shear etc.

The authors Ugale Ashish B. and Raut Harshalata R. who took in consideration a six story tall building frame presented a similar study. The building was situated in the third seismic zone, designed considering the Indian code of 1893:2002. The structural analysis was conducted using the software of STAAD PRO, and the structural Wall used was that of steel plate.

By working out the actual requirement of Structural Wall in projected rectangular shaped plan for a normal building, it is found that minimum 5% length of perimeter of plan is used as Structural Wall for the purpose of Vertical Circulation such as Lifts etc. Therefore, additional 5% Structural Wall is provided as the base of project and its percentage is increased in steps of consecutive 5% as 10% Structural Wall, 15% Structural Wall and 20% Structural Wall with respect to periphery of the plan.

3.3 Concrete Possibilities

This study deals with multi-storey buildings, which have as main constructive system composed by reinforced concrete frames. As were stated in the introduction of the thesis, a key element of the frame in the multi-storey buildings is the structural wall. The structural walls are made of reinforced concrete material. Since the focus of this study is on the generation of perforated patterns, it is important to provide in more details the possibilities offered by the concrete material itself to bring an innovative element in the design. Herewith, concrete proves its transformation ability and great potential for innovation.

Over the last 150 years, concrete was used in the construction industry with a wide range of application. Increasingly, many architects and engineers recognize that this material had an enormous potential in creating attractive surface design by using creative formability. Then several modern manufacturing methods allowed in building concrete structures even with innovative cross sections.

An impressive manner of many aspects of the concrete material it was demonstrated more and more. New unusual approaches for sustainable buildings were also demonstrated. So it becomes clear that architectural design vocabulary could be expanded following correctly the technical requirements. New surprising ideas for the use of the building material concrete were introduced, documenting at the same time unconventional thought experiments within architects thinking outside the box. On the other side, many imaginative engineers could produce new structural schemes following the designer inspiration.

By mentioning concrete, one has the picture of a massive, grey and cold material in his mind. The buildings with this material are usually associated with brutal, massive and depressing architecture. There is also a fact among others, that over time this material has not been investigated, there were no new developments and no innovation. It is generally used utilizing its positive sides as a building material or some positive features such as great load bearing capacity, high fire resistance, large thermal mass etc.

However, several developments have been over the last decades: ultra-high performance concrete, with performance capability as similar to that of steel, self-compacting concrete, allowing greater reinforcement by simultaneously providing better-controlled surface qualities. In addition, for even ductile constructions, there have been produced a combination with stainless steel or glass fibre reinforcements.

This new material allows thinner structural elements in a building. Other investigations area were those related with embodied energy and carbon dioxide storage in concrete, energized by sunlight. So looking at the material developments it becomes obvious that with a material, strong like steel and ductile, the structural schemes could become light in the sense of its weight due to the limited load and light in the sense of its appearance, the material is able to concentrate forces in a single point similarly the typical skeleton structural schemes.

Consequently, it is important to provide designers and engineers to a new understanding of concrete. It can be light and do provide more functionalities then just massively and load bearing capacity. Further investigations with focus in developing potential technologies for future projects should be conducted to find technical driven design results for future inspiration. A fundamental role in this process may be towards experimenting as the key instrument to ensure technical possibilities as well as functional results.

Research on concrete material becomes even more important whenever it is evidenced in massive elements in the facades of buildings such as the case of structural walls in multi-storey buildings. In this regard, it is always an attempt to investigate more on new technologies, performance development and innovation, being tested in designs and experimental buildings.

Being part of possible future façade development, there have been conducted several information sessions, symposium and workshops, sharing knowledge and experience. In the academia field, there are dozens of pursued PhD studies, investigations mainly in the fields of "Climate, Comfort and Energy", "Construction, Product and Material", Production and Assembly" and "Design Tools and Strategies", financed via various resources ranging from industry research, national and international grants as well as individual interests.

A very interesting research is presented in the research field "Production and Assembly" and is partly financed by a grant of the Deutsche Forschungsgemeinschaft (DFG), the scientific German grant agency for fundamental research for the project. It is part of the Schwerpunktprogramm "Leicht Bauen mit Beton", which is a special research program "building light with concrete" (Knaack, U., et al 2015). Within this environment, the authors collaborate closely with several staff of TU Darmstadt in Germany on adjustable moulding technologies and fabric formwork.

According to research within the Façade Research Group as mentioned above, the topics related on physical performances of the building envelope are of a great importance. The main question is linked with the service components. It aims in selecting the proper components for a massive building envelope and the question would be on how to integrate them towards improving the overall façade function.

In a more advance discussion, in the case of elaborating the free formed constructions, there is a need to solve correctly the principle problem by bringing efficient moulding systems compared to framework constructions. So in this regard, related to the research within the group, technologies are sketched that will provide reusable free form moulding solutions.

A particular element putted in the façade is the Flying buttresses system. By either identifying maximally stress loaded systems; the flying buttresses system was developed to split the functions. There are recognised the carrying structural loads, separating inside and outside where were served by two different building elements. This can be perceived as one of the first preparation for the separation of functions. The separation of functions became even more radical with the development of steel and its wide application in the building industry in the beginning of the 20th century.

Then changes occurred to the thermal requirements of facades. A lighter material was added since solid materials such as brick or concrete have poor thermal resistance. This insulation layer needed to be protected from weather conditions, which made an additional layer necessary.

Solid wall constructions although integrate more functions still appear monolithic. There are being explored new technologies on the material level and more and more, there are promising new functions and solutions for massive walls by changing the way the material is used. New technologies that have been introduced for concrete walls are for different wall functions.

Maintaining monolithic appearance of concrete walls and exploiting its functionality needs to be pursued for future applications. It can be by changing the material composition, and in this case, the material itself gains an extra function.

Another form is by adding extra components or systems to the massive layer. In this, case the components work together in order to allow the addition of functions. Another form is changing the shape of the massive layer to gain an extra function. The common perforated blocks are an example for this type of measure. By adding voids in the massive block, the layer gains insulating properties without changing the material composition or adding extra components.

Speaking about the building façade it is important to conceive a high functionality by applying simple systems. High performance facades are mostly realized by multi-layered facades. The facade needs to work as one coherent and smart system. Further steps will include integrating not all but a limited amount functions to a monolithic appearing system. Maybe the integral wall will start with the application of complex components layered in the facade, like a multi layered facade covered with a monolithic shell. This will help further to simplify the production process.

The history of concrete is closely linked with the development of concrete formwork. The first steps date back early in time when clay bricks where formed with wooden forms. These are considered the first known formwork. Knaack, U., et al 2015 in their series track some stages. They ascertain that during the second century the Greeks began constructing using the technique of cast masonry, in Greek language, the so-called “emplecton”.

So there were not used anymore the stacking bricks and mortar. This new technique consisted on two wall shells made of ashlar, which is the finest stone masonry unit or on wooden boards as formwork. In this way, stability was ensured of permanent walls, which are closely related to concrete constructions nowadays.

Unlike the Greeks, the Romans used to develop this technique further by creating the first permanent binding material so changing the first composition. As stated by the authors, “Opus Caementitium” was the new material, which provide the possibility to be to harden under water and therefore at the same time be stronger and weather resistant.

By combining this technique with new concrete material, the Roman master builders invented the arch construction of approximately 2000 year ago. Coliseum and the Pantheon in Rome are built with this technique, which are buildings that still exist today. On the other hand, the knowledge of Opus Caementitium began to vanish after the collapse of the Roman Empire.

Another interesting fact is that for almost 1500 years, this material was not used not before the transition from Renaissance to Baroque. In the 17th century there were given some alternatives for wood and clay buildings given that the demand for these types of constructions was higher. Thus the binding material was further developed.

This is where the moment begins for further research on binding material, the so-called cement today. As the most representative case of the first use of this material is the Basilica of St. Peter's in Rome.

John Smeaton, a British engineer who discovered a new composition of the material, which did harden also under water apart of hardening when exposed to air, introduced another type of binding material at the end of the 18th century. This new binding material was named 'Roman cement'.

However, concrete was named for the first time not early than 18th century when sand and crushed rocks were added to cement. One century after, stated the authors Knaack, U., et al in their study in 2015, Portland cement seems to be the main product used today and for which a patent was applied since 1824:

> "Again in Great Britain, a building contractor from the city Portland harvested clay and limestone from natural resources; burned them together and then ground the result." (Knaack, U., et al 2015).

Based on the characteristics of the concrete material, concrete used to assimilate high compressive forces but showed weak under tensile loads. On the other hand, iron and steel cope very well when absorbing tension. It was not later than in the 19th century when these two material were combined together forming the so-called reinforced concrete. The inventor of reinforced concrete material is considered the Frenchman Josepf by producing flower buckets made of concrete and bead wires since 1849.

In addition, as stated by the author of the series of concretable, that time Monier discovered that those buckets were extraordinary durable. At the second world fair in Paris in 1867, Monier presented his bucket and registered his first patent during the same year. His term on rebar steel is still used today. In addition, for the first time it was documented on paper that cement protects iron from rusting (Knaack, U., et al 2015).

Since that period, there have been other attempts at mixing the material. Various concrete products have been developed over different period. Already in 1874 an earlier patent was applied for intermix metallic waste in improving the concrete's behaviour but the term steel fibres was only introduced later at the end of the '60.

Today, a variety of fibres is available used as reinforcement such as carbon fibres, synthetics and many more. In '70 was established glass fibres by glass producer Pilkington Brothers Ltd. In England. This type of fibres proved to be resistant against the alkaline of concrete.

The invention of high-strength concrete in the beginning of the 20th century, used to improve further the capabilities of concrete. This type of concrete provided the possibility of designing curved surfaces as in the case of shell structures by showing higher initial strength. Knaack, U., et al 2015 have evidenced that the concrete producer Dyckerhoff & Widmann, had developed a technique to apply this product on a shell formwork.

They used to shot concrete into the formwork by forming in this case the so-called shotcrete. This development established the era of concrete shell structure and the most relevant representatives are the buildings designs by well-known designers as Pier Luigi Nervi, Felix Candela, Heinz Isler, etc.

However in the building sector shotcrete decreased in relevance. As to mention that, today it is most commonly used to consolidate rocks, repair and maintain concrete components.

After the industrial revolution, with the aim of technological progress and especially the need for new buildings stimulated concrete construction to be in its peak phase. After that, a special attention is paid to cost and labour reduction. In this line of thought, it was introduced the recycling concrete. The technology of producing this new material enabled economically efficient construction. In the beginning in the '90ies there was developed a variety of concrete products.

The main material components were changed time by time. From a concrete made out of the three components: cement, aggregates and water it developed in to a five-component system: cement, aggregates, water, admixtures (fly ash) and liquid admixtures. All the chacteristic of the concrete components allowed new performance capabilities such as self-compression and extraordinary strength. These two parameters, the composition and the framework, are the most relevant factors for the production process and the concrete's qualities today.

On the other hand, even small changes in the mix design; reflect directly in the main characteristics of concrete material. The exact measurements need to be maintained and the production conditions need to be controlled. This leads to high requirements during the production process, which seems to be very important factor. The concrete is delivered to the site in liquid form. The production of five-component concrete is an engineering task and requires a high level of accuracy.

Nowadays are used several types of concrete reinforcement, such as steel, glass or plastic fibres. However, since fresh concrete is highly alkaline only alkali-resistant fibres can be used. In the manufacturing concrete process, are defined the properties of the resulting material. Also are defined the mechanical properties, the geometry, as well as the quantity of added fibres and their orientation.

Similar to the case of fibre concrete, concrete can be reinforced also with textiles. For textile reinforced concrete are used the technical textiles such as glass and carbon fibre. The main advantage of using textile reinforced concrete deals with the presence of the cover layer. In this case, there is no need do provide a cover layer since the phenomenon of corrosion is not present unlike the classic reinforced concrete material.

By increased powder, content it is produced another variant of concrete, named the Self-compacting concrete. In this case, there is no need to vibrate the concrete. The final surface is a clear one unlike in the case of the reinforced concrete and it is obvious that a considered amount of money is been saved in this case. The self-compacting concrete is very appropriate while dealing the free formed structure geometries. However, has a negative aspect that of consistence deviations. In this regard, concerning the component of water. If the self-compacting concrete is too stiff, formwork might not be filled homogenously, and if it flows to easily the structural stability decreases due to possible demixing.

The use of concrete material is very efficient. Since the concrete is liquid during the production process, is very easy to produce and to be applied onsite. The change of state of the material enables the designers to form concrete into any desirable shape by the same time customized to the individual force flow of a building.

In the ‘20, Nervi investigated the force flow and generated construction that guides the force by using only the minimally necessary amount of material. Several patterns and various configurations were generated. Complex constructions were made possible by constructing simultaneously the formwork for different structural elements of the buildings, which has to be assembled individually for each part. It is obvious that reducing the labour costs the reduction of material will result in the overall costs of the building.

The authors in their book present a simple cost estimate by analysing the case of an intermediate slab of a building. They stated that the results in a cost distribution for a concrete slab is composed of 80 % for the formwork and 20 % for the material itself. On the other hand, the high formwork costs lead to simplified profiles like in the case of ripped slabs, which tend to be more material efficient but the formwork is too complex in terms of designing and constructing them on construction site.

A very positive effect on structural elements of a building but also on the entire construction, have shown the lightweight concrete. However, of course these types of constructions are not widespread. On the other hand, the load bearing construction can be reduced with a lighter weight slab construction. The authors mention the case of the Design School of Essen. The vertical loads were optimized with the Bubbledesk slab. The walls tend to be more slender since the structural requirements were reduced.

Another approach to optimize weight and loads was to reduce the slab thickness while improving the materials structural abilities. Here it is introduced the Ultra Hard Performance Concrete following significant developments made.

The formwork, however, still required high manual effort. Coated wood panels helped optimization but did not essentially change process as slip form enabled faster construction but did not increase simplification.

The perception of concrete material was further changed by the awareness of ecological dimension and of the cycle of materials. Prefabrication process is also very important dealing with multiple series of the element. It is obvious that the factory conditions are of a great importance towards customizing the production process and to enable qualitative products.

The potential for optimization comes not only from the production process but also from reusing of the material. It is known that waste from mineral material accounts for the highest share of building waste. The reuse potential of prefabricated elements can be higher compared to in place concrete building elements as the grid helps the disassemble process. This is a very good approach for optimizing the effect on nature. However, on contrary, this debate do affect the concrete as a material that offer the potential to become increasingly important.

As it is known, the construction of a building has several individual functions and it is very important to identify correctly each of them. Under the topic of structural design, it deals with structure weight, sustainable, thermal expansion, vertical & horizontal stress, mentioning the construction method; one has to consider the process, production and construction, for climate control.

It is important to have knowledge's on several climate parameters, under the topic of sustainability, one should consider the embodied energy, storage capacity/usage energy, recycling and consumption of resources, and for usability, the knowledge required are for aspects on safety, climate and maintenance, as well as on appearance topic, one should consider the urban context, exterior and interior surface perception. All these parameters can help to to improve the functionality of the construction and at the same time to sketch the potential areas of future development.

3.4 Structural Wall Design

High rise building is an important direction of vertical city development in the future, application of new type of Structural Wall in high-rise is of great significance to sustainable development of structure design. Application of perforated Structural Wall, greatly improve the seismic performance and efficiency of structure. A Structural Wall is a vertical structural element and also is part of the lateral resistance structure system and tend to support the effects of lateral load acting on the structure.

The main lateral loads acting on a structure are considered the wind and the seismic loads. The missing walls under the above mentioned active loads, has shown several damages in the building and on the contrary, their presence, lower to a considerable scale the building's damages. A very interesting study has been conducted by the author Rusi. A., related with the importance of using the structural walls in the building design. Moreover he states that:

> "In this case it is seen that the damages have appeared from the establishment of stirrups, mainly in the spaces between them. An effective reinforcement of a Wall would bring a very good seismic performance of the building to the earthquake. In conclusion, we state that Wall is a key element in the designing of buildings in seismic places." (Rusi. A., 2014)

Murty, on the other hand, states according the constructions using the structural walls by adding:

> "This type of construction has been practiced since the 1960s in urban regions for medium- to high-rise buildings (4 to 35 stories high). Wall buildings are usually regular in plan and in elevation. Structural Walls are the main vertical structural elements with a dual role of resisting both the gravity and lateral loads. Wall thickness varies from 140 mm to 500 mm, depending on the number of stories, thermal insulation requirements. In general, these walls are continuous throughout the building height; however, some walls are discontinued at the street front or basement level to allow for commercial or parking spaces. Usually the wall layout is symmetrical with respect to at least one axis of symmetry in the plan." (Murty 2004).

Figure 3.4.1. Building in Nagano, Japan, with vertical extension - unusual Structural Walls (source: Llunji, 2012)

It is important to emphasize that structural walls are considered only in the context of reinforced concrete buildings. This is important because Structural Wall system is also commonly used in masonry buildings, but that is not the scope of this thesis.

3.4.1 The effects of seismic loads in Structural Wall buildings

In the figures below are demonstrate various pictures of demolishing buildings affected by seismic events. The lack of structural walls is considered one of the buildings collapse cases. There have been concocted so far, a dozen of reports and studies, considering the very important role of structural walls due to their good behaviour in the resistance of an earthquake.

Some of the reasons in the weak behaviour due to earthquake oscillations, both in the cases of Chile and Mexico City is referred to insufficient wall density in plan, the lack of wall proper reinforcement, and the lack of confinement in the boundary elements.

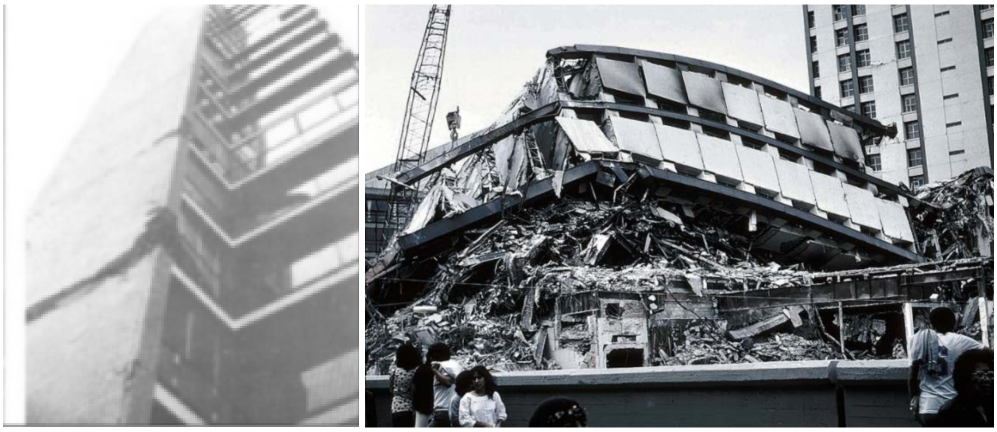


Figure 3.4.2. March 3rd, 1985 earthquake, Left: Viña del Mar, Chile, (source: Moroni 2002) and Right: Mexico City

Figure 3.4.3. Left: Building collapse in 1977 Vrancea earthquake, Romania (source: Moroni 2002), Right: Alto Rio Edificio Building collapse in 2010 earthquake, Chile

In addition to that, other common reasons in the building collapse cases of the above pictures are related with weak seismic performance due to:

- soft story and weak story mechanism;
- reduced wall density;
- neglected torsion effects;
- short column phenomena;
- column – beam joints experiencing high values of shear forces etc.

In support of the above reasoning, it is of interest to research the effects of earthquakes in some of the seismic countries of the world. A summary of this panorama is given in the study of Moroni in 2002:

> *"In Chile*, thinner walls are used in recent years and buildings are characterized with a smaller wall density. Also, some Walls are reduced in length at the street or basement level to accommodate a commercial or a parking space. (Moroni 2002).
>
> *In Colombia*, there is a tendency to use very thin walls with only one layer of reinforcement in new buildings; this can generate stability problems and cause buckling failure at the wall compression zone." (Moroni 2002).

Moreover, he represent in his study the main indicators that may be used in order to characterize the multi-storey buildings with the main structural system of Structural Wall. He states that mass distribution of stiffness either in plan or elevation, is very important. And referring to other additional parameters, he stresses that:

> "The quantitative parameters have been used, such as the ratio of the total building height (H) over the fundamental period (T) (H/T), story drift, P-Δ effect, top floor displacement, coupling index, redundancy index, and ductility capacity. All these parameters have been derived from a modal spectral analysis or a pushover analysis. Wall density indicates the magnitude of lateral stiffness of Wall buildings. It can be determined as a ratio of the wall area in each principal direction to the floor plan area." (Moroni 2002)

Regarding the density of structural walls in plan, Rusi. A., has collected data for some of the sites categorized as seismic regions and is expressed as follows:

Country	**Wall Density**	**Wall Density**	**Wall Density**
	Both directions	*One direction of the wall density in the other direction*	*Each direction*
Kyrgyzstan	15%	70-80%	NA
Turkey	NA	NA	4 (2 - 6%)
Chile	NA	NA	> 1.5% (average 2.8%)
Romania	NA	1.4% compared to 4.8%	6.6 - 7.2%
Colombia	3-5%	70-80%	NA

3.4.1. Values of the Structural Wall density in several seismic countries

Refering to ED.ICH in 2002 on H/T ratio, refering also to the table below of this paragraph:

"The ratio of the total building height over the fundamental period (H/T) also indicates the rigidity of a building. For example, buildings with H/T < 40 m/sec are considered to be flexible, whereas rigid buildings are characterized with H/T > 70m/sec. From the observed structural performance in past earthquakes in Chile, the relation between H/T and the type of damage has been developed." (ED.ICH 2002)

H/T (m/sec)	**➢ 70**	**50 - 70**	**40 -50**	**30 - 40**
Building behaviour	Very rigid buildings	NA	NA	Very flexible building
Reported damage	None	Non structural damage	Light structural damage	Moderate structural damage

Table 3.4.2. H/T vs damage relation, Structural Wall buildings

3.4.2 Types of Structural Wall, their form in plan and elevation

In the structural design criteria for evaluation of structural wall buildings, it is of interest to share some knowledge's on several types of structural walls, their cross section in plan and in elevation. In this regard, both the authors, Paulay and Priestley, divide the above mention information into three main steps, described as following:

First step is the definition of the dimensions and its shape, according to the stiffness, building geometry, bending plan and the shear force.

Second step is the definition of foundation below the Wall, knowing that Wall will transmit big overturning moments to the foundation and this one will transmit it to the earth under the building. For this in the Euro Code, there are specific definition that should be taken into consideration along the designing of the foundation against seismic effect.

Third step the boundary elements are very necessary for the edge of the wall. Boundary elements are the zones in the end of the cross section of the wall and it's reinforced as a column because the stress is in its maximum value." (Paulay and Priestley 1992)

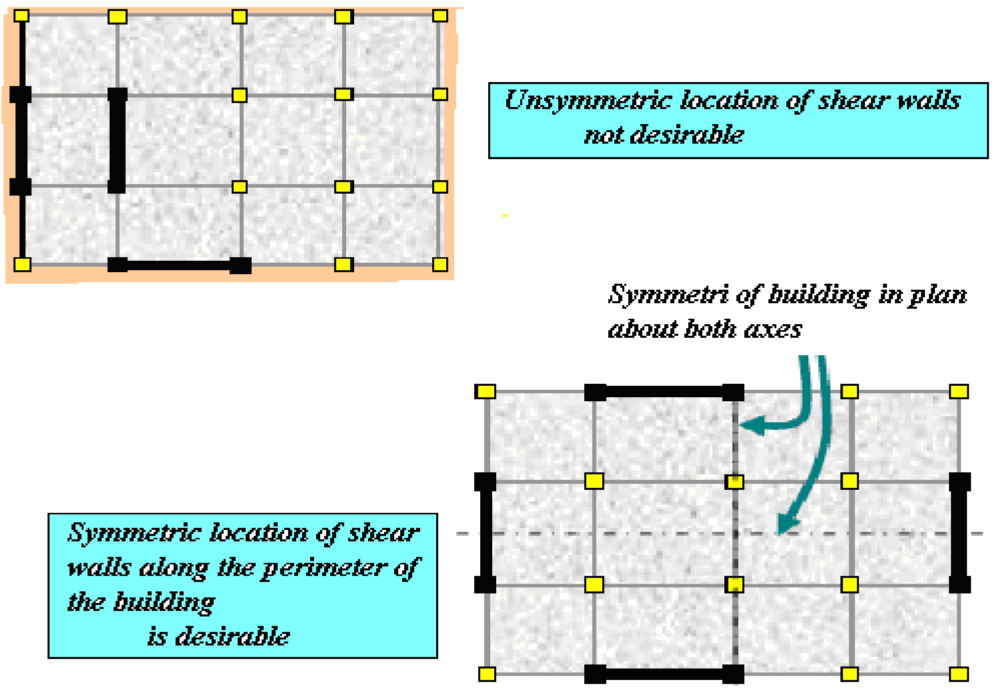


Figure 3.4.4. The plan distribution of Structural Walls (source: Murty 2004)

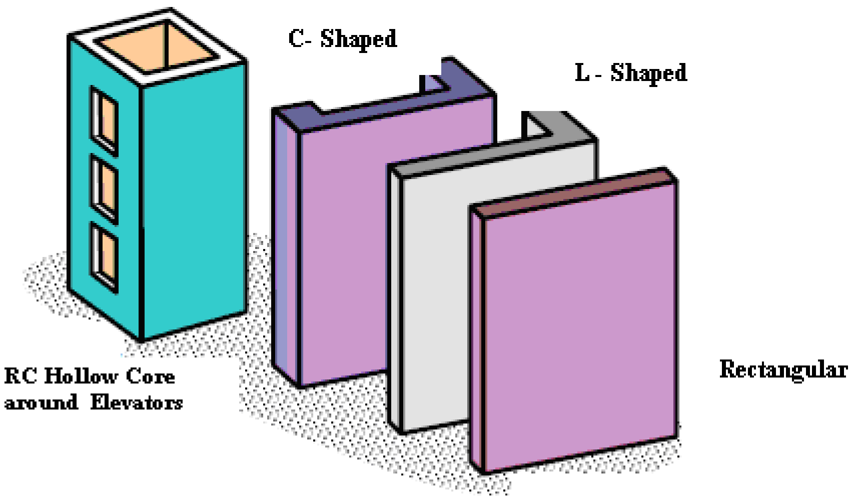


Figure 3.4.5. Different geometries Structural Walls in RC building (source: Murty 2004)

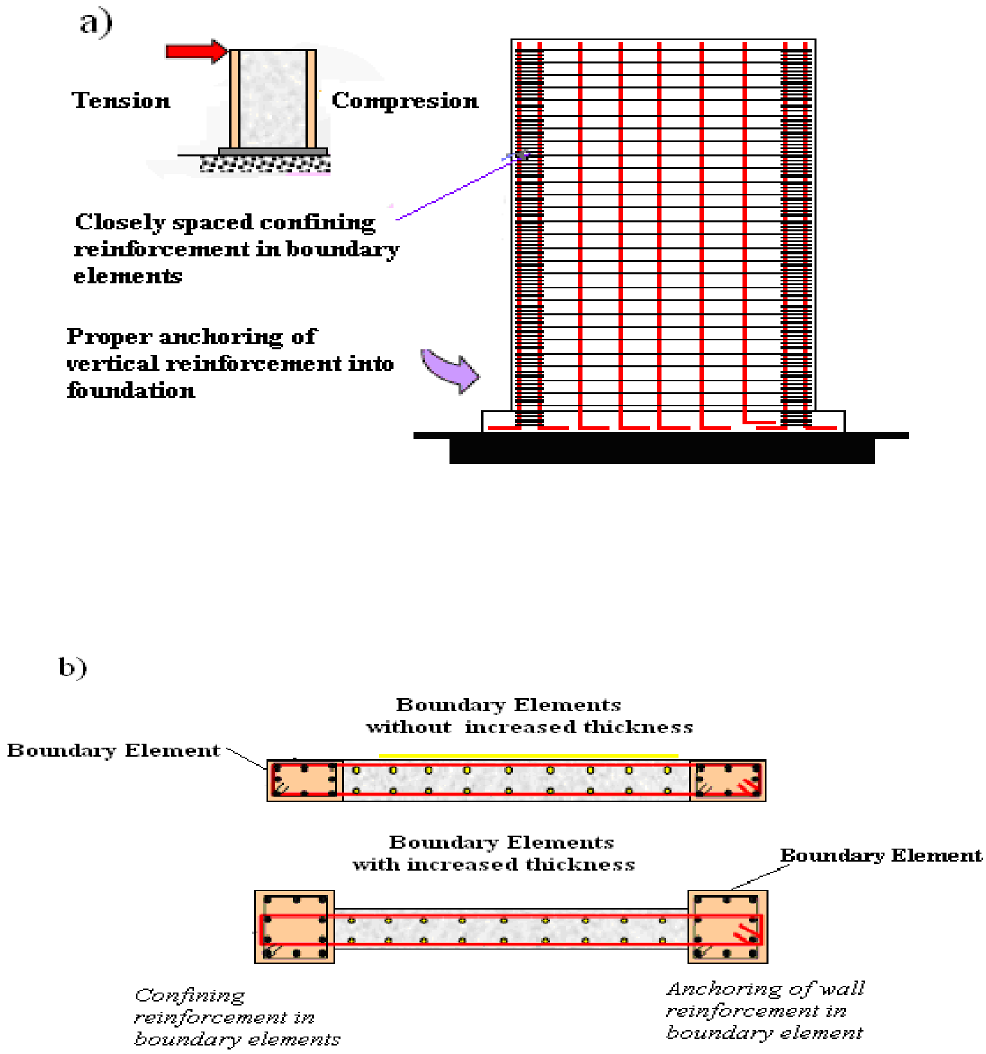


Figure 3.4.6. Layout of main reinforcement in Structural Wall (source: Murty 2004)

A creative process is in the base of selecting the final configuration that balances with aesthetic, functional and safety requirements. In this sense, it is linked directly with the requirements of functionality and the desire for aesthetic and is one of the key factors in the seismic response of objects.

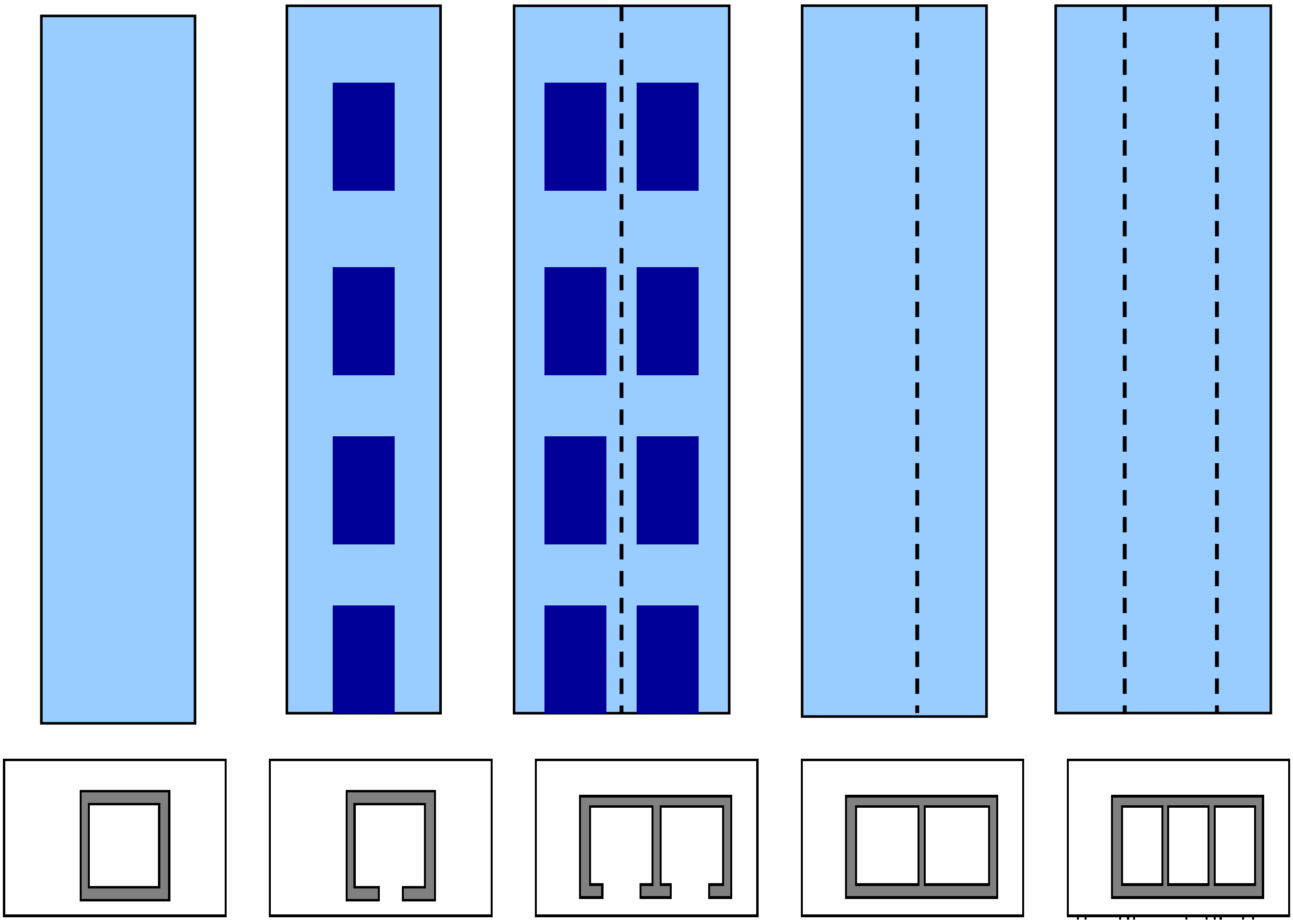


Figure 3.4.7. Basic type of Structural Wall (source: Anwar. A., & Yahyah. M. Q., 2009)

Mentioning the term configuration of a building is linked indirectly with the architectural decision of the designers, by indicatinge both the size and positioning of structural elements. This extension of the configuration definition is necessary precisely in the seismic response because of the interaction between different parameters. The building configuration can be influenced by urban conditions (the requirements for the height of the building, adaptation of the given environment, etc.), by the functional aspect of the building and, of course, from the aesthetic effect specified by the main design idea.

3.4.3 Structural Models Configuration

In this section, it is given a summary on different structural plan configurations emphasizing their key role in providing seismic protection. So for example, in tall buildings in order to provide seismic protection, as it is shown in the figure below, the building from the structural perspective it is modelled through placing an enlarged concrete service core in the center and a design of a frame lateral wings of building with the effects of torsional response in relation to the motion of the building as a whole, the so-called hull-core or framed-tube-with-core structure.

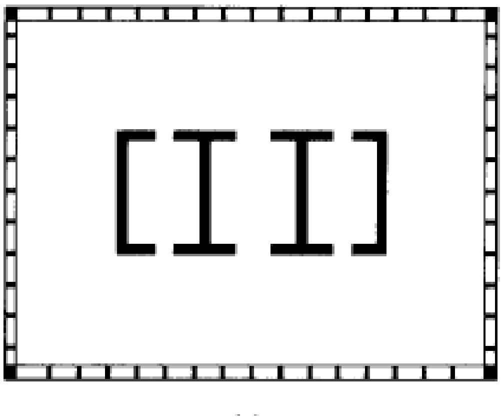


Figure 3.4.8. Frame tube with core structure (source: Mark Fintel 1985)

For buildings of moderate height, to provide seismic protection, refered to the following figure, the structural model is being realized by placing of a smaller concrete service core in the building center and by placing also of an enlarged frame-shear wall to the peripheral parts of the builidng.

The introduction of shear walls will generally be dictated by the need to limit the drift or lateral deflection under wind as well as earthquake loading to safe the tolerable values.

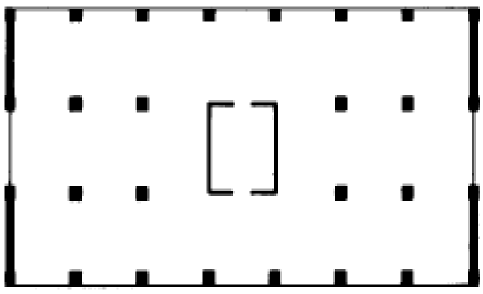


Figure 3.4.9. Frame- shear wall strukture (source: Mark Fintel 1985)

Such systems, due to the concentration of resistance forces of buildings only on some specific concrete structural walls, often require an increase in the transverse dimensions of the concrete structural walls, as for the increased requirements for flexural strength (flexture strength) due to the lower values of vertical forces against to the bending moments, as well as for the realization of the required shear by shear strength by fulfilling the condition for Nominal Shear Stress (vi) due to the concentration of shear forces on the structural walls of the building as explaining more in detail below.

Nominal Shear Stress for convenience of shear strength is commonly quantified in terms if a nominal shear stress vi' defined as:

$$vi = Vi/bwd$$

Because of the additional and unwarranted computational effort involved in evaluating the effective depth, d, in structural wall sections, it is customary, as in the case of column sections, to assume that d = 0.8lw and hence the average shear stress at ideal strength is :

$$vi = Vi/0.8bwd$$

To ensure that premature diagonal compression failure will not occur in the web before the onset of yielding of the web shear reinforcement, the nominal shear stress needs to be limited.

Recommended limitations are :

1. In general

$$vi \leq 0.2f'c \leq 6\ Mpa$$

2. In plastic hinge regions of beams, columns, and walls

$$vi \leq 0.16f'c \leq 6\ Mpa$$

When the computed shear stress exceeds the values given above, the dimensions of the member should be increased, additional resistance may be derived, through the realization of structural models with a close grid of the columns of the building, as shown in the figure below,

In dual systems of multi-storey buildings, with a more harmonized distribution of the columns grid and concrete walls, and the centrally positioned sufficient large core to provide torsional resistance for seismic protection.

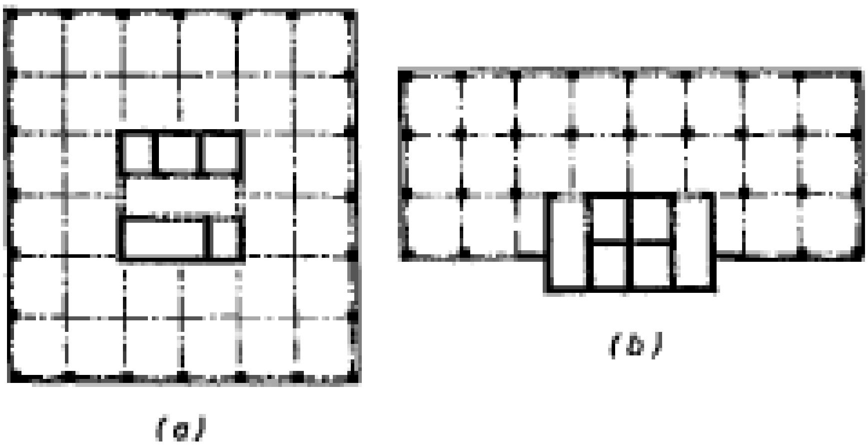


Figure 3.4.10. Lateral force resistance provided by reinforced concrete cores (source: Paulay and Priestley, 1992)

In the above figure (building case b), are being developed the cases of building design with extension in one direction, in the configuration form of a rectangular plan shape. These type of building plan configurations have brought also the solution to accommodate the concrete service core close to one of the building boundaries.

Eccentricity placed position of this service core lead to gross torsional imbalance. In order to provide torsional balance for this case, if it is not achieved through the applied scheme of frame system with a dense grid of coloumns and beams with significant cross section dimensions, it will be required to put adittional structural walls along the other three sides of the building.

In this regard, it is very important to identify by the design team those configuration variables that affect the distribution of seismic force. These variables are explained in the literature as irregularities, or deviations from the forms, regular and optimal configurations in terms of seismic force concept. The irregularity in the configuration follows the irregularity in the action of seismic forces which can produce different responses in the object.

3.4.4 Evaluation Criteria for structural wall with openings

With simple diagrams, Anwar in his study, summarizes the concepts wall positioning in different plan layout, as in the figure below, while mentioning that:

> "Different building that contains this structure elements must complete the regularity conditions in plan and elevation. Below are shown some figures of buildings with reinforced concrete core. The third picture is the best way in this kind of plans. It is divided by a fuge." (Anwar, 2009)

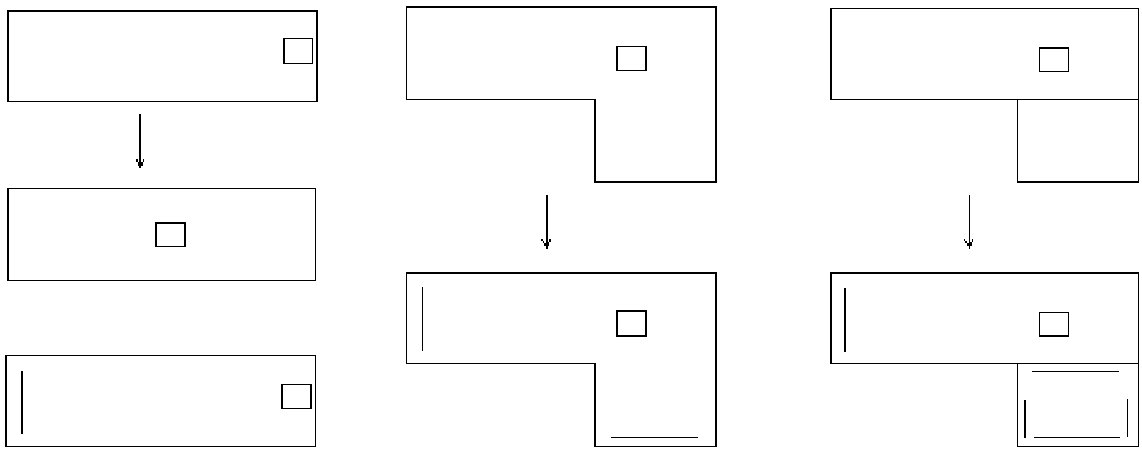


Figure 3.4.11. Structural Walls in plan (source: Anwar. A., & Yahyah. M. Q., 2009)

Elevator shafts and stair wells lend themselves to the formation of a reinforced concrete core. Traditionally, these have been used to provide the major component of lateral force resistance in multistory office buildings.

Individual walls may be subjected to axial, translational, and torsional displacements. The extent to which a wall will contribute to the resistance of overturning moments, story shear forces, and slory torsion depends on its geometric configuration, orientation, and location within the plane of the building.

The study on the strategy of the structural wall element is well explained by the authors Paulay and Priestley in 1992. They also refered in their study the wall systems stability against torsion phenomena which was further examined with the aid of the Figure below. They stated that:

> "The study on the strategy of the structural wall element is an important issue in improveming the lateral resistance scheme of the multi-storey building. As it was stated before, the proper lateral resistance scheme of a building, affect the force ressitance of single structural walls. But on the otther hand, an important parameter to be considered in this analysis is the torsional stability of structural walls." (Paulay and Priestley, 1992)

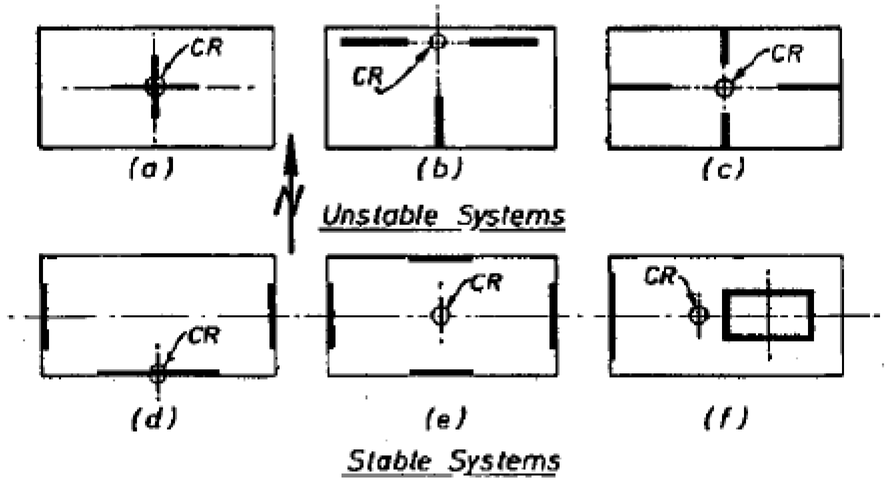


Figure 3.4.12. Examples for torsional stabiliti of wall systems (source: Paulay and Priestley, 1992)

Moreover, they explained that:

> "Many structural walls are open thin-walled sections with small torsional rigidities. Hence in seismic design it is customary to neglect the torsional resistance of individual walls. It is seen that torsional resistance of the wall arrangements of Fig55.(a) (b) and (c) could only be achieved if the lateral force resistance of each wall with respect to its weak axis was significant. As this is not the case, these examples represent torsionally unstable systems. Fig.55 (d) to (f) show torsionally stable configurations." (Paulay and Priestley in 1992)

Adding perimetric structural walls is of a great importance to provide the torsional stability for inelastic wall systems. Refered to different building structure models as in the figure below, the horizontal force *H,* in the longest direction can be resisted efficiently in both systems. While for seismic force action E to the shortest direction at scheme (a) ne drejtimin e shkurter ne skemen (a) because of a significant eccentricity between the center of mass (CM) and the center of rigidity (CR) as well as the lack of structural walls in the longitudinal direction, the wall at point B can reach the yield earlier causing excessive floor rotations and the structure becomes torsionally unstable.

While in scheme (b) due to the placement of the structural walls in the longitudinal direction the system remains torsionally stable.

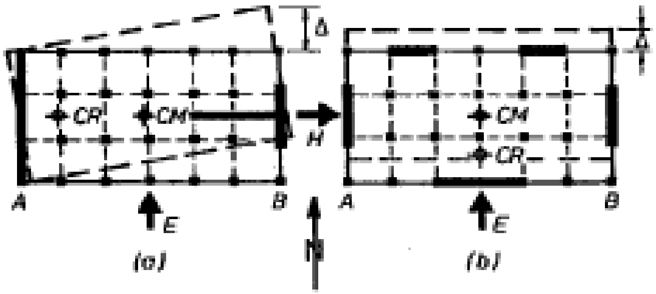


Figure 3.4.13. Torsional stability of inelastic wall systems (source: Paulay and Priestley, 1992)

A creative process is in the base of selecting the final configuration that balances with aesthetic, functional and safety requirements. In this sense, it is linked directly with the requirements of functionality and the desire for aesthetic and is one of the key factors in the seismic response of objects.

As above, as a more opportunistic solution on which the suggestion of this research topic is based, in the following paragraphs are being examined the primary effects for vertical structures of structural walls with openings based on the arguments of both the authors Paulay and Priestley.

3.4.5 Structural Walls with Openings

In many structural walls a regular pattern of openings will be required to accommodate windows or doors or both.

Regarding the wall openings, the author stress that:

> "Openings are sometimes arranged in such a way that an extremely weak shear fiber results where inner edges of the openings line up, as shown in Fig. 56 (a). It is difficult to make such connections sufficiently ductile and to avoid early damage in earthquakes, and hence it is preferable to avoid this arrangement. A larger space between the staggered openings would, however, allow an effective diagonal compression and tension field to develop after the formation of diagonal cracks Fig. 56(b). When suitably reinforced, perhaps using diagonalreinforcement, distress of regions between openings due to shear can be prevented, and a ductile cantilever response due to flexural yielding at the base only can be readily enforced." (Paulay and Priestley, 1992)

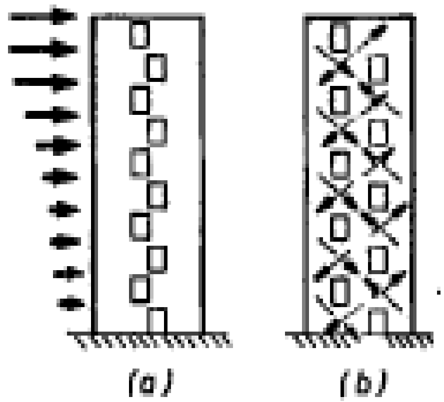


Figure 3.4.14. Shear strength of wall as affectet by openings (source: Paulay and Priestley, 1992)

Cases of structures modeling are also being explained by these authors refered to the following figure, in the cases when openings are arranged in such a way that the connecting beams are stronger than the walls.

A story mechanism is likely to develop in such a system because a series of piers in a particular story may be overloaded, while none of the deep beams would become inelastic.

Such a wall system should be avoided because a soft-story sway mechanism would result, with excessive ductility demands on the hinging piers.

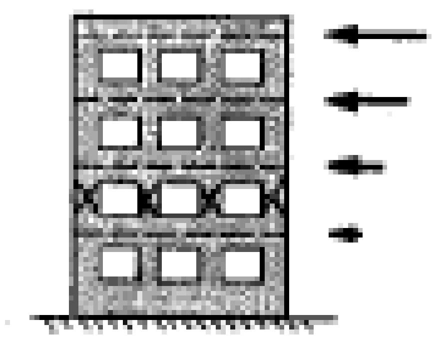


Figure 3.4.15. Undesirable pierced walls for earthquake resistence (source: Paulay and Priestley, 1992)

3.4.6 Framed Squat Wall Panels

The study and use of such squat walls has also strongly influenced the modelling in Japan of the behavior of multistory cantilever walls. The behavior of such squat walls, of the configuration is shown in the figure below. It is more interesting to bring in some basic concepts that the authors use while describing them in this paragraph.

Structural walls are traditionally provided with substantial boundary members appearing as both beams and columns.

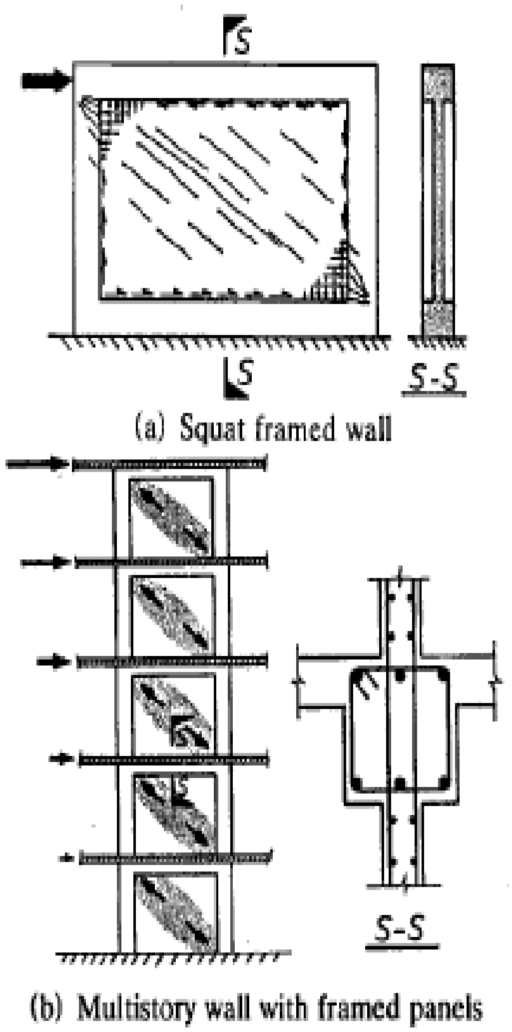


Figure 3.4.16. Framed structural walls (source: Paulay and Priestley, 1992)

Frame action of the boundary members combines with the shear strength of the web, which provides primarily a diagonal compression field, as suggested in the above figure (scheme a).

The vertical boundary members, reinforced in the same fashion as columns, are intended to prevent a sliding shear failure, but due to the overturning moment the reinforcement in column members is not expected to yield. After the breakdown of the web due to diagonal tension, the column members are expected to provide shear resistance.

Wall elements in each story of the structure shown in the scheme (b) of the above figure, are expected to behave much like the squat unit shown as in the scheme (a). The horizontal beam element at the slab wall junction is assumed to act as a tension member of a truss while the web portion provides the corner-to-corner diagonal compression strut, as suggested in schem (b). The mechanism suggested of scheme (b) would imply significant diagonal compression stress concentrations at corners and also inefficient utilization of the horizontal reinforcement in the web of the wall.

It is unlikely that the additional concrete and reinforcement in the beam element, shown in the scheme (b), would improve the strength or the behavior of such walls. Such beam elements would only be justified to provide anchorage for flexural reinforcement in beams, which frame into such a wall.

3.4.7 Evaluation Criteria for Squat Walls with Openings

The seismic design of walls with significant openings, such as shown in the following figure may readily be undertaken with the use of "strut and tie" models.

In this case, the authors have studied the structural behavior of a panel with dimensions 7x8m with openings in chess board shape with dimensions 2x2m.

It is very interesting to bring in some key concepts that the authors have underlined in this regard related to the panel configuration.

The two schemes of the following figure (a) and (b) investigate two distinguished models of a squat wall with openings. Each model is suitable for the seismic response corresponding with lateral forces in a given direction to be considered.

Critical magnitudes of tension forces can be derived from statics. Compression forces to be transmitted in struts are seldom critical.

If ductile response is to be assured, the designer should choose particular tension chords in which yielding can best be accommodated. A similar exercise will establish forces as it can be seen in scheme (b) generated in the other model during reversal of the earthquake forces.

Compression strains in concrete struts are likely to remain small. They should be kept small because in general these members are not suitable for energy dissipation.

A significant fraction of the inelastic tensile strains that might be imposed on members are recoverable because upon force reversal both members become struts.

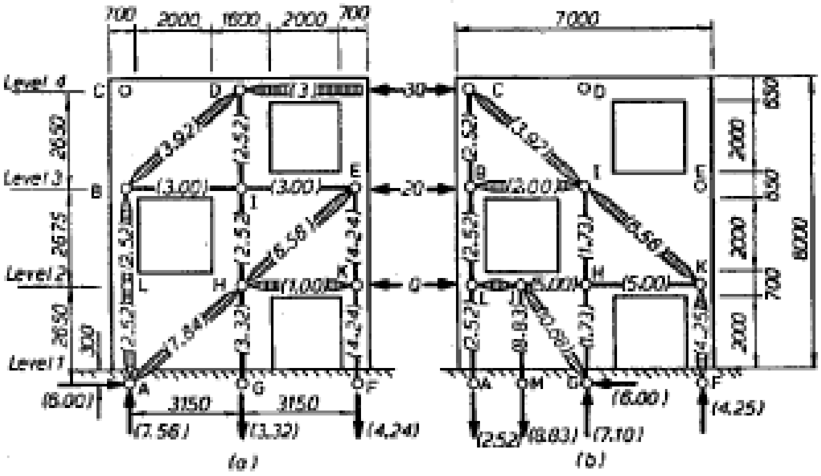


Figure 3.4.17. Strat and tie models for a squat wall with openings (source: Paulay and Priestley, 1992)

Such a study will confirm the appropriateness for the choice of "ductile links" in the "chain of resistance" and will assist in the identification of areas where special attention of the designer is required to aid energy dissipation.

With a rational design strategy, accompanied by careful detailing, significant ductility capacity can be built into these structures.

It is worth noting that designing for frame-shear wall interaction tends to eliminate yielding of the columns at the top stories.

Finally, to simplify the main approach to the object of this research thesis, it is worth noting that designing for frame-shear wall interaction, must be simplicity to make the best possible contribution of the structure wall, in a dual system.

For this in the paragraph below are being elaborated some further details about these systems.

3.5 Detailing for Dual Systems

Dual systems may combine the advantages of their constituent elements as for reinforced concrete ductile frames and for ductile structural walls.

When lateral force resistance is provided by the combined contribution of frames and structural walls, it is customary to refer to them as a dual system or a hybrid structure.

In addition to this, ductile frames, interacting with walls, can provide a significant amount of energy dissipation, when required, particularly in the upper stories of a building. On the other hand, as a result of the large stiffness of walls, good story drift control during an earthquake can be achieved.

Under the action of lateral forces, a frame will deform primarily in a shear mode, whereas a wall will behave like a vertical cantilever with primary flexural deformations, as shown in the following figure, scheme (b) and (c).

Compatibility of deformations requires that frames and walls sustain at each level essentially identical lateral displacements, scheme (d). Because the preferred displacement mode of the two elements shown in scheme (b) and (c) is modified, it is found that the walls and frames share in the resistance of story shear forces in the lower stories, but tend to oppose each other at higher levels.

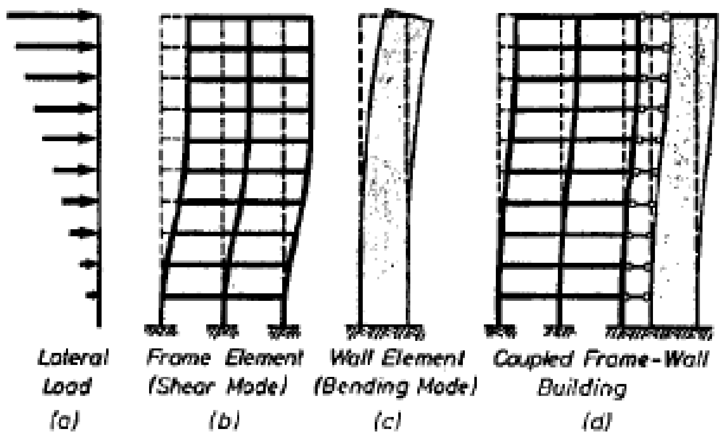


Figure 3.5.1. Deformation patterns due to lateral forces of a frame, a wall element, and a dual system (source: Paulay and Priestley (1993).

On the effect of design assumption on distribution of lateral loads between frame and shear Wall, the author Mark Fintel in his Handbook of "Concrete Engineering", have stated that:

Uniform Building Code provision requiring the frame to be designed for (at least) 25% of the total lateral force.

In this way, in determining the operating forces in the perforated wall it has been accepted an approximately range of values to 70-75% of the total lateral force.

Another important element for these systems is the determination of the self vibration periods of seismic oscillations based on the Stiffness Modeling of their structural elements, resulting from the computer analysis.

Under seismic actions, it is important that the distribution of member forces be based on realistic stiffness values, and that member lateral forces are reasonably uniformly distributed through the frame-wall system.

In the composition process of these models, it is impractical to evaluate the properties of several cross sections in each member of a multi-storey building, and a reasonable average value should be adopted as in the table below.

	Range	Recommended Value
Rectangular beams	$0.30–0.50I_g$	$0.40I_g$
T and L beams	$0.25–0.45I_g$	$0.35I_g$
Columns, $P > 0.5f'_cA_g$	$0.70–0.90I_g$	$0.80I_g$
Columns, $P = 0.2f'_cA_g$	$0.50–0.70I_g$	$0.60I_g$
Columns, $P = -0.05f'_cA_g$	$0.30–0.50I_g$	$0.40I_g$

[a] A_g = gross area of section; I_g = moment of inertia of gross concrete section about the centroidal axis, neglecting the reinforcement.

Tabela 3.5.1 Effective member moment of inertia (source: Paulay and Priestley (1992).

Whether for structural walls these values are being estimated in range **0.5-0.8*I*g** and referring the American Design Code the recommended value is considered **0.7*I*g**.

3.6 Summary

The third chapter deals with the structural walls in multi-storey buildings. The term “structural wall”, is elaborated in detail in this chapter by focusing more at the engineering aspect. Emphasizing the fact that, in the literature review, as well as the previous chapters, the structural facades are emphasized more as in the eight case studies. Those eight buildings are composed by the structural schemes of shell element that covers their entire facade. Meanwhile, as it was pointed out in the introduction of the thesis, this thesis deals with the typology of a multi-storey building and not of a high-rise or tall building (skyscrapers).

Consequently, the case studies, some of them represent high-rise buildings, are in the framework of examples and not analytical, though simply inspiring for evidence on the facades of the objects of structural elements. On the other hand, a representative element of multi-storey buildings is the structural wall element. The main aim as stated in the first chapter is generating innovative patterns for Structural Wall element with openings.

The advantages of positioning the structural elements in the facades have been described in the previous chapters, as well as in this chapter this argument is emphasized, qualifying it to contribute in a general improvement of the structural behaviour of the multi-storey building.

After elaborating the above arguments, this chapter clearly highlights the role of the structural wall element as well as the strategies in its positioning in multi-storey buildings.

There are being specified several geometries of structural wall cross section, in the form of concrete service core or individual structural walls adapted to the main building plan configuration such as following cases:

The case of tall building representing a tower, modelled through placing an enlarged concrete service core in the center accompanied by a large lateral frame system providing the effects of torsional ressitance from the seismic loads.

For buildings of moderate height, to provide seismic protection, the structural model is being realized by placing of a smaller concrete service core in the building center and by placing also of an enlarged frame-shear wall to the peripheral parts of the building.

Specifically are being elaborated the modelling cases of buildings with asymmetric location of service core in the configuration plan of buildings.

In these cases, to ensure the resistance to torsion, it becomes even more imperative to place individual walls in the perimeter contours of the facades of these buildings.

Also of interest are the cases of systems stability, which although they are modeled with the same walls, due to their position in the plan are divided into unstable systems when the walls are located inside the building and stable when the walls are located on the perimeter of buildings.

The structural model of the objects fig.3.4.13 is specified as a special case, which although it is balanced in the elastic phase of the reaction of the vertical supporting structures, due to the lack of walls in other parts of the perimeter, loses stability in its inelastic phase.

To justify the selected structural system using perforated structural walls placed in perimeter of objects, it is necessary te clarify some concept with structure walls with openings, building their adequate structural models containing the mentioned structural elements.

Thus, in paragraph, 3.4.5 are reflected the cases of wall openings for doors and windows in which the unfavorable cases of their openings are specified and the cases of openings are recommended which leave intact the areas of development of diagonal stresses in compression and tension as well as minimize the effect of the development of shear forces on the structural walls.

In paragraphs 3.4.6 and 3.4.7 are given the construction of similar structural models for multi-storey buildings with frame squat panels, and the elaboration process towards obtaining the squat wall with openings based on "strut and tie" model.

Finaly, in paragraph 3.5, details are given on the contribution of frame and structure wall in dual systems as well as on the equivalent modulus of elasticity value in determining the rigidity of these elements, values that are very necessary in defining individual models of perforated panels and their participation as a constituent element of the composition of the structural models of the buildings.

CHAPTER 4

Perforation Technique | Panel Configuration for Perforated Structural Wall Element | Structural Stability Check

CHAPTER 4

4 Generating examples of Perforated Structural Walls

4.1 Introduction

"Executions of concrete Structural Wall panels along the exterior perimeter of slender high rise buildings enhance the efficiency of such buildings to resist the seismic forces. Also there do exist uncertainties referring the demandable architectural openings in the exterior views of such buildings" (Hamdy H. A). However, this topic seems to be of great interest in co-design practices. There is also interest to investigate more on seismic behaviour of perforated Structural Walls since this element it is intended to be used in the exterior perimeter of multi-storey buildings.

Some definitions on structural walls are represented in several studies. Referring to Ji:

> "Structural Walls are efficient, both in terms of construction cost and effectiveness in minimizing earthquake damage in structural and non-structural elements. Structural Walls provide large strength and stiffness to buildings in the direction of their orientation, which significantly reduces lateral displacements of the building and thereby reduces damages to structure and its contents." (Ji, et al 2007)

More over Kyoung Sun Moon in his study in 2018 has stated that:

> "The emergence of multi-storey buildings in the late 19th century was possible by using new innovative materials and also by separating the role of structures from the traditional load-bearing walls. While traditional masonry structures on the building perimeter did the dual roles as both structures and façades, the skeletal structures performed only as structures. Therefore, façades in skeletal structures were supported by the structural frames, and this newly developed façade concept began to be called curtain walls.
>
> With these new concepts of curtain wall façades overcoming the limitation of the traditional masonry structures for multi-storey buildings, the new building type has evolved rapidly. Among the walls freed from their structural roles, façades are of conspicuous importance as building identifiers, significant definers of building aesthetics, and environmental mediators." (Kyoung Sun Moon, 2018)

First attempts towards representing the perforated structural wall panel, was begun with a research paper presented in the International Conference TAW 2018. There it was stated that:

> "Without the technological breakthrough of skeletal structures and curtain wall concept, the emergence evolution of multi-storey buildings would not have been possible. Many different types of efficient structural systems for multi-storey buildings have been developed since the invention of the early skeletal structures in conjunction with the advancements of structural materials and other related technologies." (Rusi. I., 2018)

Moreover,

> "Façade systems for multi-storey buildings have evolved from the early primitive curtain walls to today's dramatically advanced systems including double skin façades of various configurations. While these two key technologies have continuously been evolving, architectural design of different nature than technologies has played crucial roles in how to integrate these two. Today's multi-storey buildings are still designed and constructed based on the original concept of skeletal structures and curtainwalls." (Rusi. I., 2018)

Referring to the author Dario Trabucco, he does recognise the evolution of multi-storey buildings, naming in his journal papers as "An evolution still in progress". This topic represent the analysis of the history of the service core in high-rise buildings. It is obvious that, the design team tend to use the construction materials in a more effective way. In this regards, the structures of high-rise buildings evolved even more, mainly after the first skyscrapers that appeared in New York and Chicago.

In addition to this, citing Trabucco in his study of 2010:

> "Therefore, the author believes that the structural schemes for multi-storey buildings may be divided into internal and external structures, according to the position of the elements that carry the lateral loads. The historic analysis of the evolution of the service core of multi-storey buildings presented in his study is the introduction of a more comprehensive analysis on this part of a skyscraper. The service core is a distinctive feature of a multi-storey building and its design plays an important role in sustainability of the whole structure." (Rusi. I., 2018)

4.2 Perforated patterns as a technique of adding and cutting material

The last decades have been seen an emergence of several architectural shapes and some of them with geometrical complexity of patterns. Furthermore, the available tools dissociate shape and structural behaviour, which adds another complication. As a result, the modelling of patterns have in core the different geometry shapes. Geometry is a science used by both architects and engineers to generate harmonious and efficient structural configurations. In this regard, it is proposed a quick and critical overview of the existing literature on the stereotomic architecture and as well as tectonic architecture of complexly shaped multi-storey buildings.

Mesnil et al, 2019 explain better in the case of shell structures the challenges derived by the complexity of architectural forms. In the building industry, the fabrication of elements relies on mass production and standardisation. The five platonic polyhedral represented in the figure below are indeed the only polyhedral to have a unique vertex, face and edge. Beyond these shapes, the designer has to make compromise between repetition of elements and formal freedom.

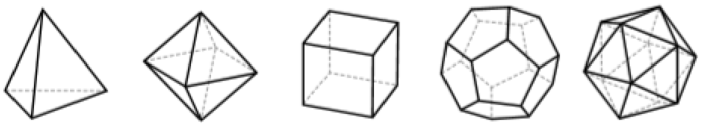


Figure 4.2.1. The five platonic polyhedral: tetrahedron, octahedron, cube, dodecahedron and icosahedron. (source: Mesnil et.al, 2019)

Below are shown some examples of different perforated patterns putted at the façade of buildings. As it can be seen, the transforms of surfaces and spaces of built architecture and the viewers experiences, were made possible thanks those exposed structures.

Figure 4.2.2. Examples of exposed structure and perforated surfaces. (source: Pinterest, 2018)

However it is important to state that it is not been advocated the necessity of having an exposed structure into a building, whether it presents a potential task for incorporating also different exciting architectural element. Building form, on the one hand, and structural expression on the other, offer the chances for the design concept to be an integral process. Following the above-mentioned concept, also in the case of multi-storey buildings design, it is of great importance a fully integrating process of structural system and building architectural volume.

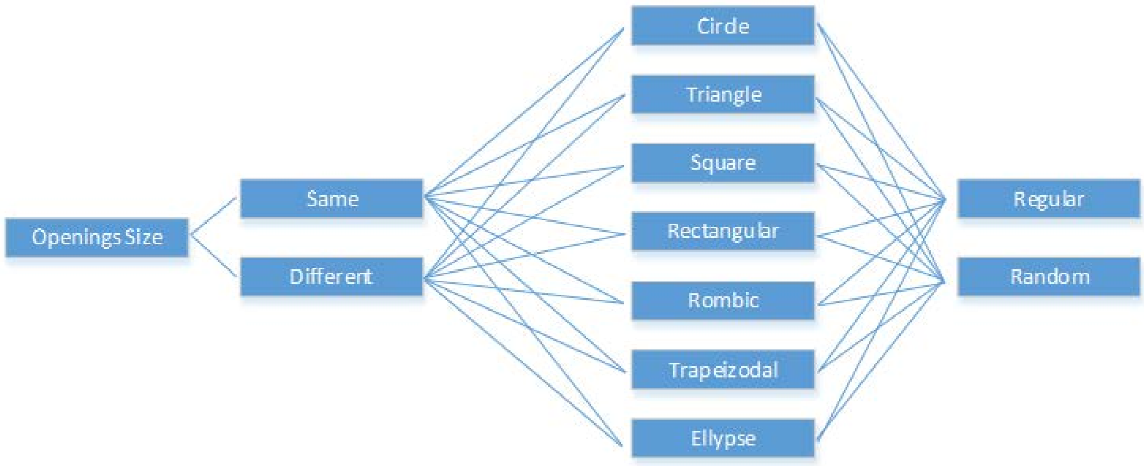


Figure 4.2.3. Openings size (source: the author)

To the concept of form based on repetition, it is a very interesting theory described in the book "The function of form" by the author Farshid. She propose repetition of several elements as a new theory form building form generating. She stated that this attitude on moving the architecture from the essentialism helps in considering two main aspects of materiality, the physical and non-physical one.

They are attributed both in the building form generating. In this regard, a conceptualisation of the built forms function is made possible by applying multiple inputs, using the same principles of a function equations used in mathematics.

"Form follows function", putted forward by Louis Sullivan in the nineteenth century, function was understood in terms of its cultural and social role. In that period, different building types were associated with different types of materials, including all things, organic and inorganic, physical and metaphysical, all true manifestations of the mind, stated by Farshadi.

She continues stating that for the modernists who adopted the dictum in the twentieth century, function was narrowly defined as the use or utility of a built form, an interpretation that has provoked disagreements among architects and theorists ever since.

In her book, she distinguishes several forms, starting from:

- *Unmediated forms*, which considered built forms as utilitarian objects.
- *Mediated forms*, a way of mediating between object (built form) and subject (people, environment).
- *Novel forms*, which overcomes the conventional split between concepts and precepts, opening the design process to the different ways in which they can combine to develop forms that allow people with different views and sensibilities to develop an affective relationship with their environment.

4.3 Practical approximations for modeling structural walls

Modelling of Structural Walls is an important step while dealing with the static and dynamic analysis of the structure. In order to introduce the finite element method in modelling, different techniques are used, applying both the "shell" element and the "frame" element.

The "shell" elements consist of two degrees of freedom, one according to the plane (membrane) and one outside the plane (plate).

A very challenging element for engineers has been considered for many decades, the element of membrane element. The element of membrane, mainly is combined with the plate elements, forming the so called "shell element" which consisted of an element with 6 degrees of freedom in each node and 1 degree of rotational freedom in its plane, comparable to a finite element type beam in three dimensional.

This approximation was successful, thus being embraced by a series of application programs. In engineering practice some limits of the above approximation were observed, where although drilling rotations allowed the introduction of external loads in the form of drilling moments, the analytical results dictated a discrepancy and a sensitivity in determining the size of the meshes and loading conditions.

(Kubin, J., et al., 2008) in their study, have considered different approximations in the modelling of structural walls of structural analysis of buildings. In regions with high seismicity, the use of structural walls in the resistance of horizontal forces is necessary in practical engineering.

The structural walls are modelled with both frame elements and mesh elements. Modelling with frame elements was mainly used in those linear or nonlinear analyses, referring to the design provided by the application program itself. The introduction of modelling with shell elements coincides with numerous studies, especially of the last three decades, in formulations versus models with the latest three-dimensional elements.

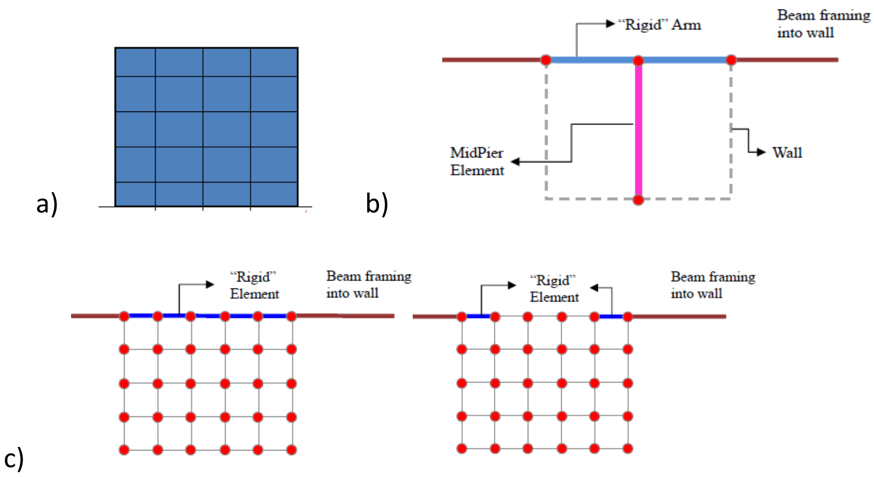


Figure 4.3.1. Examples of three different ways to model a single structural wall with frame elements in engineering analysing software's; a) modelling with shell elements, b) modelling with frame elements, c) modelling with rigid beams in the upper strip of the structural wall (source: Kubin, J., et al., 2008)

Below are given some descriptions regarding the specifics of each modelling according to the three cases, referring to the authors.

4.3.1 Modelling with shell elements

A method has found efficient use in structures with structural walls. The shell element is considered with six degrees of freedom for each node and with a degree of rotational freedom in its plan, thus making it comparable to models with finite elements of the three dimensional beam type. According to Wilson (2002), it is worth mentioning the fact that for obtaining the field information of the displacements of this quadrilateral element, the functions of the bilinear shape are used.

Thus, modelling requires a sufficient discretion of the mass, to obtain information and realistic behaviours of the structural element in the study. The advantage of this method consists in the fact of the ability to model big and complex structural elements in accordance with the three dimensional model.

The optimal mesh sizes and their impact on internal moments and loading conditions are presented in the following numerical example. Also in this example will be studied the effects of beams (through bending moments according to its own plan) in the structural walls connected to them.

4.3.2 Modelling with frame elements

Several frame elements are being used while it is modelled with this method. A mid-pier frame is applied which represent the most common technique. Further on there are presented the vertical element, which it is usually used while referring to a wall rigidity, and the horizontal frame or the so-called rigid arm. The rigid arm is very important to set the right connections with a beam element in case of a sudden interruption.

The focus of the structural analysis for horizontal frame element is linked with the determination of its rigidity. The bending moment can increase immediately while the upper frame element possess an infinite rigidity. This phenomenon is more visible in the connection sections between the beam and the wall.

However, in the case of structural walls analysis with cracks, the above-mentioned procedure is considered a little difficult. Considering also different configuration of structural walls with openings, these analyses seem to be more complicated to investigate the proper working model of the walls.

4.3.3 Modelling with rigid beams in the upper strip of the structural wall

This modelling is referred to positioning the rigid beams in the upper section of the structural wall. The cross section of rigid beams are represented by the torsion constant and moments of inertia (J, I2, I3). The beams cross-section parameters, positioned next to the wall, are being used also for the rigid beams.

In the study of **(**Kubin, J., et al., 2008), it is reached the value of the moment M3 for both the wall as well as for the beams. Mesh division with dimensions 160x160 cm gives only a 5% - 10% difference from the most detailed mesh.

In addition to these three different types of modelling that were mentioned, other types of modelling are also used which come more as a combination of the above cases. Some of them are specified below.

- **Modelling with rigid beam shell elements that traverse only one mesh partition.**

Rigid beams penetrate the wall only the length of a single mesh. As can be seen from the results obtained, this type of modelling gives good results for large mesh separations, while for small discretization of the structural element (20x20 cm) the difference of M3 for the wall and beams according to the main direction, goes to 15%.

- **Modelling of structural walls using frame elements**

In this analysis, different characteristics of cross sections of rigid elements are obtained. The thickness of these rectangular rigid elements can be taken as the thickness of the wall itself.

The models considered, considering several widths of the rigid element, are different: half floor height, full floor height, two-floor height and ten-floor height. The results dictate a change in the moment value of the M3 of the beam adjacent to the wall (on its side). The rigid beam that extends inside the wall, gives a result comparable to the models with shell elements for one floor height.

As a conclusion, the study of the authors **(**Kubin, J., et al., 2008), seems to insight more on the numerical results for the analyses performed regarding the models of buildings with structural walls. They stated that in the modelling of structural walls with shell elements, the bending moment of these structural elements as well as the beams bending moment, connected to the wall according to the plan, is conditioned by the discretization of the mesh. For a fine mesh, these values are reduced up to 10 times.

Considering the upper strip of the wall through the rigid elements brings about a significant stabilization in the results of internal forces. The introduction of the rigid element along the wall brings good results for a great discretion. For a slight discretion, the difference in the values of internal forces does not exceed 15%.

The dimensions of the shell elements have significant effects. A mesh division by 160x160 cm generally gives a difference of 5% -10% from the smallest mesh division. The ideal measurement for the concrete example varies from 50 cm to100 cm.

In modelling structural walls with frame elements (MidPier Model), the change of the characteristics of the cross sections of the rigid elements, regenerates a change of 5% -15% in the values of internal forces. Significant changes were also observed in the bending moment of the beams adjacent to the walls, approximately more than two times, in the smallest direction. As well as the rigid elements (rigid arm) as wide as the height of the floor, giving results more reasonable and comparable to modelling with shell elements.

All the conclusions of the above authors are of a great importance, to proceed further in the selection of the proper modelling of the innovative element that is suggested in this topic, that of the structural wall with openings.

4.4 Generating architectural patterns of Structural Walls

4.4.1 Software modelling of differently perforated Structural Walls

The finite elements method is a very common used analysis in nowadays while modelling a building structure in three-dimensional. To get a more realistic behaviour for Structural Wall modelling, the process includes a surface division into mesh.

> "The advantage of using shell elements is the ability to model very long, interacting and complex Walls within the three dimensional model. As it is mentioned before, Wall can play a significant role to reduce the earthquake force.
>
> The methodology of the study is based on the purpose with the focus in revealing that perforated Wall panels behave very much close to Wall elements without openings in dual systems. For this case, it is obtained a 14-storey vertical structure in elevation, a combined system of frame and Wall. The design and analysis is performed by using ETABS Ultimate 16.20.0 software." (Rusi. I., 2018)

In the analysis are considered four different models of structural walls. *The first model (A1)* represent a Structural Wall without openings; Structural Wall in Tetris shape represent *the second model (A2)*, a pattern Structural Wall in small squares shape is *the third model analysed (A3)* and *the last model (A4)* represent a Structural Wall with vertical line opening system.

Each wall is part of a dual system, maintaining the same cross section for each of the other structural elements such as columns and beams. The behaviour of this system is observed, under the effect of a design spectrum, while analysing the differences between the models.

The overall structure height is 14-story building and their structural behaviour are limited to the Euro Code requirements for structure self-vibration period and its lateral displacements.

The values of the stresses and forces at the base of Structural Wall were the first parameters checked for the structure and displayed in a graphical view. In this regard, some perceptible data are obtained from this study. Other data according to the study are listed as below:

> "Data and key parameters that are going to be extracted in order to be analysed and compared to corresponding results are (Rusi. I., 2018):

- ✓ The natural period of vibrations;
- ✓ Displacement at the top of the structure;
- ✓ Shear Forces and Stress values at the base of Wall

4.4.2 Data gathering information

As was stated in the above paragraphs, the Structural Wall is an integral part of a 14 story high structure. This structure is considered a dual system, composed both by concrete frame and perforated Structural Wall panel.

> "All other useful information regarding structural elements of the building are considered as below (Rusi. I., 2018):

- Type floor height -- 3 m
- Height of first floor -- 4 m
- Number of spans, to x axis direction ------------------------ 4 m
- Typical span --- 5 m
- Wall thickness -- 30 cm
- Cross section of columns ------------------------------ (60x60) cm
- Cross section of beams ---------------------------------- (30x50) cm

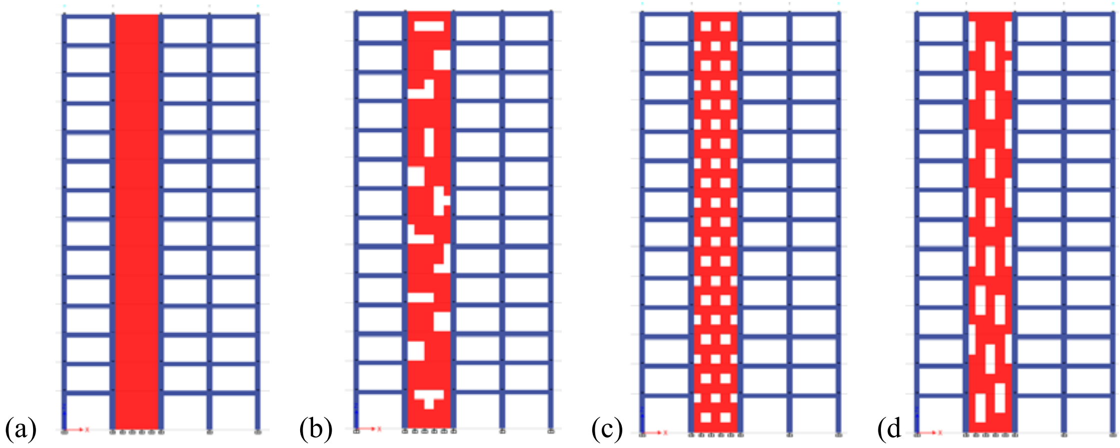


Figure 4.4.1. Models of dual systems (source: Rusi. I., 2018)

***a)** The model without opening (A1);* ***b)** The model with opening system no.1 (A2);*

***c)** The model with opening system no.2 (A3);* ***d)** The model with opening system no.3 (A4)*

Regarding the models shown in the above figure, there was no attention been paid to the size of the openings relative to the total wall area but the main aim is referred to the creation of some simple geometries of openings to get some preliminary data.

4.5 Comparison of Structural Performance of perforated Structural Walls versus solid Structural Walls

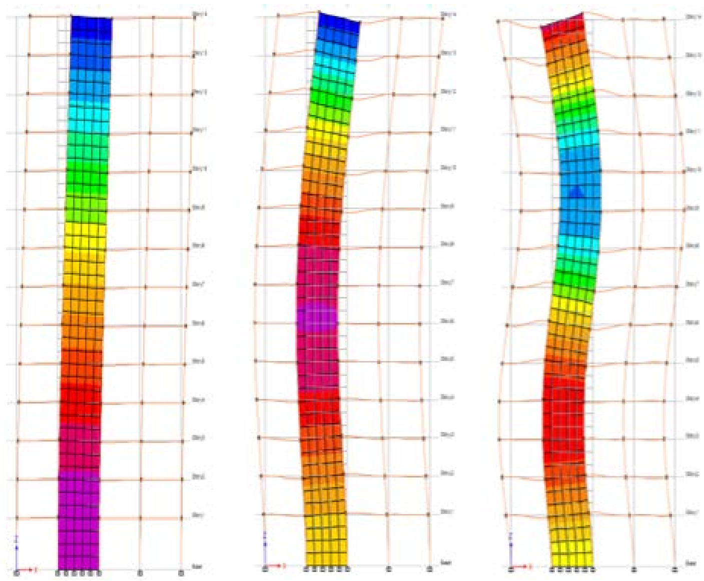
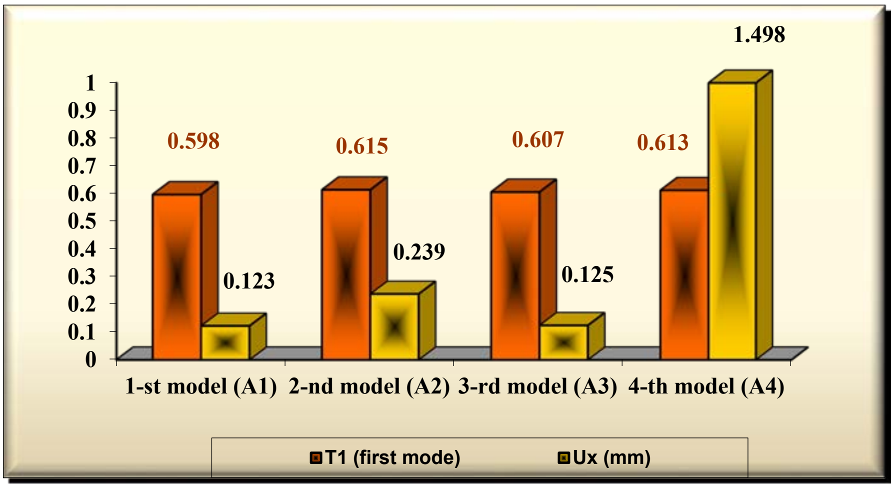


Figure 4.5.1. The first three periods of the natural vibration of the structure – Structural Wall without opening system (A1) (source: Rusi. I., 2018)

So according to the study, there were identified the first structure self-vibration period for each model. Of course, it is a very important parameter to judge over the structural scheme as well as the "rigid" or the "flexible" structural system. The linear analysis is used so far while defining also the lateral forces acting on each floor. However, for the the four patterns of the Structural Wall, were presented all the main three self-vibration periods.

As for conclusions, below are summarized some of them:

> "For the first period, as it is apparent from the chart below, the biggest difference that is observed between the models (between model A1 and A2) does not exceed 2.8%. There is also a relevant value between models A2 and A4. For the second period and the third one, the difference goes to 9.8% and 15.5%. It should be concluded that the values are fairly close to each other considering the fact that the maximum value does not exceed 3% for the first vibration period of the structure." (Rusi. I., 2018)



Graph 4.5.1. Vibrations periods for four models of the Structural Wall system (source: Rusi. I., 2018)

Where: **Ux** is the lateral top displacements in mm corresponding to each self-vibration period of the modelings.

> "Referring to Design Codes (Eurocode 8), to the topic of the self-vibration period calculation for a given structure shall not exceed the following value:

$$T1 = Ct \times H^{3/4}$$ where:

Ct - is a coefficient that depends on the type of Structures and Ct = 0.05 for dual-systems;

H - is the total height of the building from the foundation up to the top. (In this case, H = 43m)

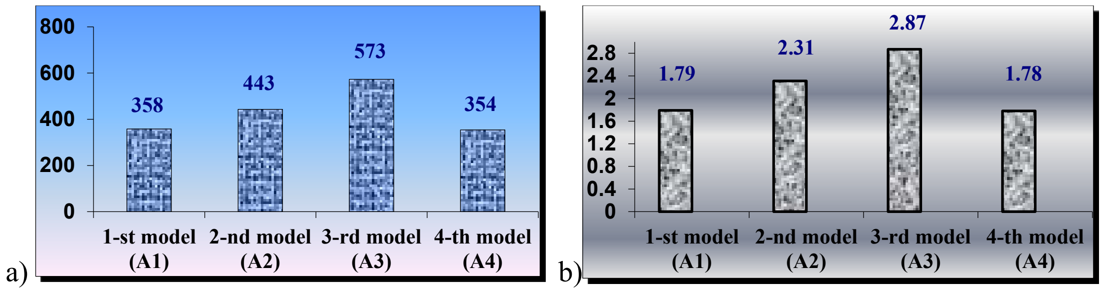
Replacing these values in the above formula:

$$T1 = 0.05 \times 43^{3/4} = 0.8396 \text{ sec}$$

The conclusions by the author are presented below:

"Another check is done referring to the values of internal forces (shear forces and shell stresses) at base of Wall panels. The values of internal forces is generated by spectral analysis. Results are shown in the following graphs.

The conclusion that can be drawn from the comparison of these data is that the models A1 and A4 show approximately similar values. The same it can be said for the other two models. The models with the closest value to model A1 (Wall without openings) are the model A2 and A4. In terms of relative differences expressed in percentage, the difference between model A1 and A2 is 23.4% for the shear forces at the base of the wall and 29.5% for the shell stresses also calculated at the basis of the wall. The values for the comparison of two model A1 and A4 are 1.3% for the shear force and 0.6% for the stress. It can be concluded that the fourth model (Wall with openings in vertical lines) show the best results." (Rusi. I., 2018)



Graph 4.5.2. Resultants of a) Shear forces (values in kN/m) and b) maximum shell stress (values in MPa) at the base of the Structural Wall for the four models (source: Rusi. I., 2018)

The higher value of stress was observed in third model, reaching the value of 2.87 MPa or 292 T/m^2. As stated also by Pojani, the higher values of stresses, are expecting at the base of the structure, a requirement that was also satisfied in the above study (Pojani 2003).

Moreover, some interesting conclusion points are listed below:

"It can be stated that, based on the results obtained from the analysis that has attended the structure, model A4 shows a relevant value to the model A1. In addition, the models A2 and A4 show almost similar values between them. Moreover, the staggered arrangements system of openings has slight effect on the resulting base shears in the Walls compared with that induced in the Walls without openings.

The effects of shear forces and shell stresses are bigger at the bottom section of the wall. Ground floor and the connection of the wall with the foundation are considered as critical areas. For this reason, it is given great importance to the areas that are taken into consideration during the designing. Based on results, further investigation in this field should be done in better arrange the opening system. Based on results and discussion over them presented in this paper, it is recommended to use a solid Wall panel without openings in the lower floors and perforated Wall panels in the upper floors of the building. " (Rusi. I., 2018).

4.6 While exploring the Structural Wall perforation

Starting from the fact that the architect generally use software's for their design which are mostly limited to the building geometry, while the engineer tend to use software's which adapt specific structural tasks, it is interesting to investigate more on mutual tasks that can both satisfy the designers. Parametric design seems to be one of them. According to White:

"Parametric design is a combination between mathematical thinking and new digital tools that with high efficiency can be used in the design process. It is done with the aid of parametric models, which is a computer representation of a design constructed with geometrical entities that have attributes that can vary or are fixed. Parametric design therefore gives the designer free rein to design structures and enables creation and analysis just by changing the parameters in the parametric model." (White, 2020)

On the other hand, Holzer states that:

"The increased specialization within their individual domains has also led to a big gap in the understanding between the structural engineers and the architects. When working on a common project, both entities need to cooperate to reach a final result where both parts often have different theories and objectives. By linking parametric design to the structural analysis, both entities can explore design in the conceptual design phase through informed geometry alterations and therefore save a lot of time." (Holzer. D., 2008)

In this chapter will be investigated several perforated Structural Wall patterns, using parametric design tools. This new methodology aim in integrating both professions in a single co-design process, resulting to a more effective process in the early stage of multi-storey building design.

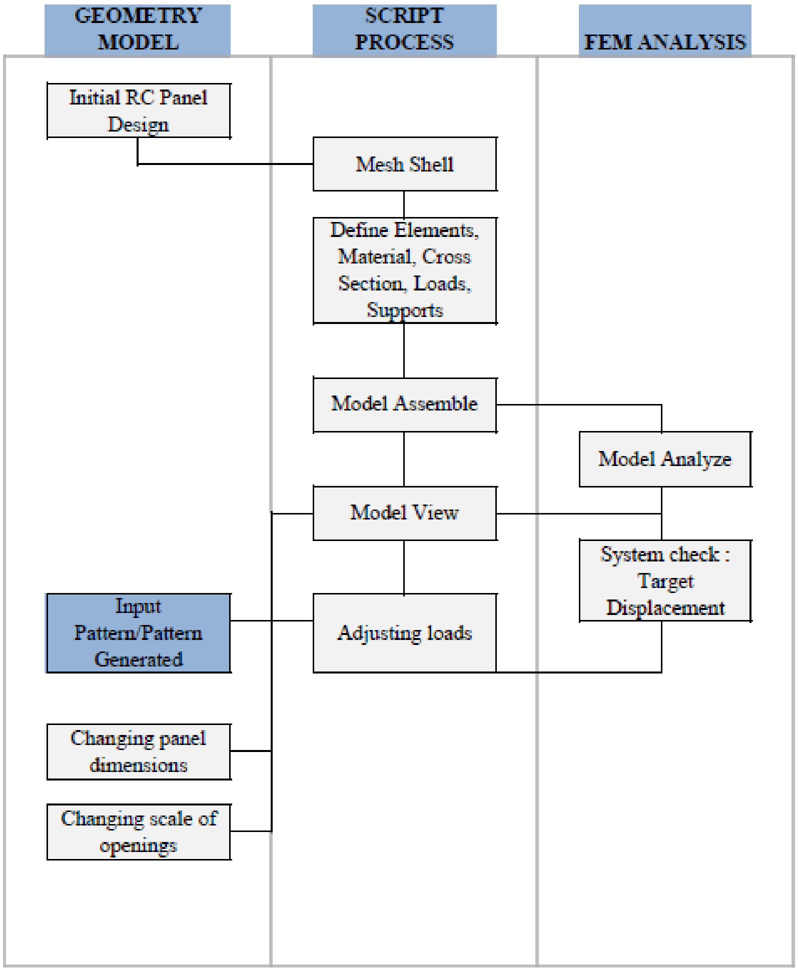


Figure 4.6.1. Flowchart of the process of generating the perforated pattern of Structural Wall Element (source: the author)

4.7 Case of a single 10-story perforated shell structure

In order to investigate more on the size of the openings to perforated structural wall, it is important to consider a study conducted in this regard. In this study by (Rusi & Kumaraku, 2020) it is presenting the case of a single structural element.

Referred to the study, the Structural Wall, part of the dual system, was generated as a pattern for a 10-story structure. The frames were neglected. The single Structural Wall was considered and modelled as a shell element. The shell is considered a reinforced concrete with a thickness of 30 cm.

"The programed used for modelling and analysing the structure is Lunch Box and Karamba 3D, both plugins of Grasshopper. It seems of interest analysing this element, since due to different perforation ratio it can be qualify as a stereotomic model or sometimes as a tectonic model but structurally acting very similarly. In order to get through structural analysis it is used a simple design method: the lateral load design with the final target that of maximum displacement of the perforated pattern generated." (Rusi & Kumaraku, 2020)

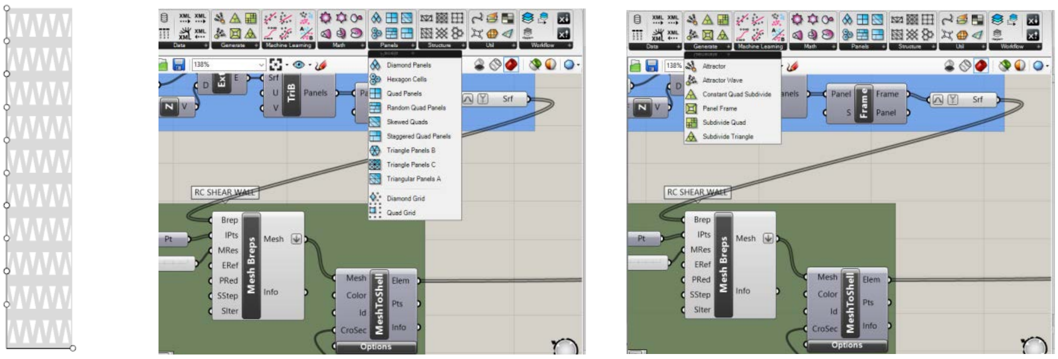


Figure 4.7.1. Rendered perforated Shell element (left), Panel using Lunch Box plugin (centre) and Panel Frame using Lunch Box plugin (right). (source: the author)

4.7.1 Behaviour factor of structure

Referring the Eurocode, to get the behaviour of this structure against external forces, this structure undergoes a dynamic analysis through a design spectrum that consider the structural behaviour factor of the building (q) as following:

$$q = Kw \times qo$$

$$qo = 3.0 \times \alpha u / \alpha i$$

- which qo is the basic value of the behaviour factor, which depends on the chosen structural type. A value of 3.0 has been selected. This value corresponds to a dual system. Regarding the design ductility of the structure, it has been selected the medium ductility class DCM, determined according to the above formula.
- αu / αi for dual systems that are equivalent to walls, this ratio takes the value 1.2.
- Kw, is a factor representing the influence of the predominant form structure failure. Referring the provisions of the design code for the dual system, this factor is recommended to be taken of a value 1.

For study purposes of this thesis, since it is not going to evaluate the ductility of all structural elements composing the perforated panles, it is concluded to accept the value of stuctural behaviour factor to be equal to q=3.

4.7.1 Displacements

Referring Eurocode EN 1998-1:

In a linear analysis are performed the displacements induced by the design seismic action and shall be calculated on the basis of the elastic deformations of the structural system by means of the following simplified expression:

$$d_s = q_d \, d_e$$

where:

ds is the displacement of a point of the structural system induced by the design seismic action;

qd is the displacement behaviour factor, assumed equal to *q* unless otherwise specified;

de is the displacement of the same point of the structural system, as determined by a linear analysis based on the design response spectrum Sd(T).

The value of ***d*s** can not be larger than the value derived from the elastic spectrum Se(T).

When determining the displacements *d*e, the torsional effects of the seismic action shall be considered.

4.7.2 Limitation of displacements

Referring Eurocode: **EN 1998-1**

a) for buildings having non-structural elements of brittle materials attached to the structure:

$d_{rv} \le 0{,}005h$;

b) for buildings having ductile non-structural elements:

$d_{rv} \le 0{,}0075h$;

c) for buildings having non-structural elements fixed in a way so as not to interfere with structural deformations, or without non-structural elements:

$d_{rv} \le 0{,}010\,h$

where:

*d*r is the design interstorey drift
h is the storey height;
ν is the reduction factor which takes into account the lower return period of the seismic action associated with the damage limitation requirement.

Substituting ν = 0.5 for importance classes I and II of, the above formula takes the form:

for cases a) dr ≤ 0.01 h or dr ≤ 1/100 h

for cases b) dr ≤ 0.015 h or dr ≤ 1/66.6 h

for cases c) dr ≤ 0.020 h or dr≤ 1/50 h

where dr is the evaluated as the difference of the average lateral displacements *d*s at the top and bottom of the storey.

Thus, refered to building height H and the corresponding accepted value of structural behavior factor q=3, the above formulas take the final form:

for case a) ds=q de ≤ 0.01 H or de ≤ 1/300 H

for case b) ds=q de ≤ 0.015 H or de ≤ 1/200 H

for case c) ds=q de ≤ 0.020 H or de ≤ 1/150 H

4.7.3 Lateral Load Design Philosophy

The methodology followed for analysing the case study is the Lateral Load Design Philosophy. Over the past few years, emphasis is being given to "performance" rather than "strength" in terms of seismic resistance. This realization has led to the development of alternative design philosophies based on deformation rather than force. These are labelled as Performance Based Design (PBD) philosophies.

These philosophies consider the fact that the distribution of strength throughout the structure is more important than absolute volume of base shear design. Generally, the various procedures following this approach represent minor changes to existing design codes and only apply displacement checks in the end.

Displacement Based Design was first introduced by M.J.N. Priestley in 1993 and has been given much attention since then. It is emphasized that the simplicity and rationality are the key features of this method.

Overall, the method is being accepted while also being advocated as an alternative seismic design procedure for seismic procedure according to EC-8.

4.7.4 Modal response spectrum analysis

It is important to apreciate the effective modal mass m_k, corresponding to a mode k of the building in order to be determinated the base shear force F_{bk}, acting in the direction of application of the seismic action, expressed as $F_{bk} = S_d(T_k)\, m_k$. It can be shown that the sum of the effective modal masses (for all modes and agiven direction) is equal to the mass of the structure.

For this purpose, for a more precise evaluation of the perforated panel and the specifics of the building to which it will fit, in the table below are examined some various spectra of modal analysis that refer to different values of the structural behavior factor (q), ground acceleration Ag and soil conditions(C) for type 1 of elastic spectrum.

T	ag	S	TB	η	Torsional Systems q	Structural Wall Systems q	TC	TD	Elastic spectrum plot values (η=1)	Design spectrum plot values (q=2)	Design spectrum plot values (q=3)	Increasing factor (0.3*9.81)ag	Beta (0.2) β	Calculations according Eurocode 8
0	0.3	1.15	0.2	1	2	3			1.1500	0.7671	0.7671	2.94		Se (T) = ag S [1 + T/TB (η 2.5-1)]
0.1	0.3	1.15	0.2	1	2	3			2.0125	1.1023	0.8627	2.94		Sd (T) = ag S [2/3 + T/TB (2.5/q-2/3)]
0.2	0.3	1.15		1	2	3	0.6		2.8750	1.4375	0.9583	2.94		
0.3	0.3	1.15		1	2	3	0.6		2.8750	1.4375	0.9583	2.94		Se (T) = ag S η 2.5
0.4	0.3	1.15		1	2	3	0.6		2.8750	1.4375	0.9583	2.94		Sd (T) = ag S 2.5/q
0.5	0.3	1.15		1	2	3	0.6		2.8750	1.4375	0.9583	2.94		
0.6	0.3	1.15		1	2	3	0.6		2.8750	1.4375	0.9583	2.94		
0.7	0.3	1.15		1	2	3	0.6		2.4643	1.2321	0.8214	2.94		
0.8	0.3	1.15		1	2	3	0.6		2.1563	1.0781	0.7188	2.94		
0.9	0.3	1.15		1	2	3	0.6		1.9167	0.9583	0.6389	2.94		
1.0	0.3	1.15		1	2	3	0.6		1.7250	0.8625	0.5750	2.94		SDe (T) = Se (T) [T/2π]²
1.1	0.3	1.15		1	2	3	0.6		1.5682	0.7841	0.5227	2.94		
1.2	0.3	1.15		1	2	3	0.6		1.4375	0.7188	0.4792	2.94		
1.3	0.3	1.15		1	2	3	0.6		1.3269	0.6635	0.4423	2.94		Se (T) = ag S η 2.5[TC/T]
1.4	0.3	1.15		1	2	3	0.6		1.2321	0.6161	0.4107	2.94		Sd (T) = ag S 2.5/q[TC/T]
1.5	0.3	1.15		1	2	3	0.6		1.1500	0.5750	0.3833	2.94		≥ β ag
1.6	0.3	1.15		1	2	3	0.6		1.0781	0.5391	0.3594	2.94		
1.7	0.3	1.15		1	2	3	0.6		1.0147	0.5074	0.3382	2.94		
1.8	0.3	1.15		1	2	3	0.6		0.9583	0.4792	0.3194	2.94		
1.9	0.3	1.15		1	2	3	0.6		0.9079	0.4539	0.3026	2.94		
2	0.3	1.15		1	2	3	0.6		0.8625	0.4313	0.2875	2.94		
2.1	0.3	1.15		1	2	3	0.6	2	0.7823	0.3912	0.2608	2.94	0.2	
2.2	0.3	1.15		1	2	3	0.6	2	0.7128	0.3564	0.2376	2.94	0.2	Sd (T) = ag S η 2.5[(TC TD)/T2]
2.3	0.3	1.15		1	2	3	0.6	2	0.6522	0.3261	0.2174	2.94	0.2	T≤ 4 sec
2.4	0.3	1.15		1	2	3	0.6	2	0.5990	0.2995	0.2000	2.94	0.2	Sd (T) = ag S 2.5/q[(TC TD)/T2]
2.5	0.3	1.15		1	2	3	0.6	2	0.5520	0.2760	0.2000	2.94	0.2	≥ β ag
2.6	0.3	1.15		1	2	3	0.6	2	0.5104	0.2552	0.2000	2.94	0.2	
2.7	0.3	1.15		1	2	3	0.6	2	0.4733	0.2366	0.2000	2.94	0.2	
2.8	0.3	1.15		1	2	3	0.6	2	0.4401	0.2200	0.2000	2.94	0.2	
2.9	0.3	1.15		1	2	3	0.6	2	0.4102	0.2051	0.2000	2.94	0.2	
3	0.3	1.15		1	2	3	0.6	2	0.3833	0.2000	0.2000	2.94	0.2	
4	0.3	1.15		1	2	3	0.6	2	0.2156	0.2000	0.2000	2.94	0.2	

Table 4.7.1. Various values of spectra for modal analysis (source: the author)

Referring to the Eurocode 8, the lateral load is been calculated according the seismic forces of the dynamic method. At each story are determined the seismic forces as point loads applied at the level of 10 stories. The main formula used is as follows:

$$Fb = Sd(T1) * m * \lambda \qquad \text{where:}$$

- Sd the value of the ordinate of the spectrum according to the base period value T1 in the design spectrum graph
- m total weight of the building over the foundation or on the upper quota of the ground floor rigid slab
- λ correction coefficient; λ = 0.85 if T1 ≤ 2 Tc. The other cases λ = 1.

Determination of the base period T1 for building up to 40 m height:

T1= Ct * H^¾

Ct = 0.075 for reinforced concrete structure

- H building height in meters from the foundation quota up to the ground floor rigid slab quota

For the panel height equal to 31 meters from the foundation, the value of period is given:

T1= Ct * H^¾ = 0.075 * 31 * H^¾ = 0.075 * 13.14 = 0.985 ~ 1.0 sec

For T1 = 1.0s it is taken the acceleration value Sd taken from the above table of spectra considering the structural behaviour factor q=3.

Sd = 0.575*0.3g = 0.575*2.94 = 1.69

Hence, the evaluation of seismic mass in ton / m^2 referring to a grid of columns with span 6x6 m is given as below.

Dead Loads:

Interstorey slab; 0.16*2.5 = 0.400

Layers; 0.05*2 = 0.100

Beams; 2x(0.5-0.16)*0.30*6*2.5/36 = 0.085

Masonry walls on the beams; 2*6*3*0.2/36 = 0.200

Columns; 1*0.5*0.5*3*2.5/36 = 0.052

Perforated Structural Walls; 0.5*6*3*0.3*2.5/100 = 0.068

Σ =0.905 t/m2

Live Loads 0.300 t/m^2

The mass of interstorey in t/m^2: (0.905*0.9+0.3*0.4)/9.81=0.935/9.81 = 0.095

For the control of the perforated panel with a width of 6 m, it is being considered a surface area loads from the building about 100 m^2.

Evaluation of the seismic force applied to the perforated wall panel; Fbp = Fb x Cred; where Cred is the reduction coefficient reffering to the lateral force taking into account the contribution of Frame elements by 25%.

Determination of the seismic force to the panel for each story:

$$Fip = Fbp * (zi * mi) / \Sigma\ zj * mj$$

Reference structure coordinates (ETABS)		**Perforated Shell Panel (Karamba 3D)**		**Story surface**	**weight(m2)Σ Pk x Xk (1)**	**weight (story)**	**Sd**	**λ**	**Fb (Frame)**	**Reduction Factor**	**Fb (Paneli)**	**Σ zj x mj**	**Referred to model units used in ETABS *Ton-m***
X10	31	X10	31	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	294.5	**18.13**
X9	28	X9	28	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	266.0	**16.38**
X8	25	X8	25	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	237.5	**14.62**
X7	22	X7	22	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	209.0	**12.87**
X6	19	X6	19	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	180.5	**11.11**
X5	16	X5	16	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	152.0	**9.36**
X4	13	X4	13	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	123.5	**7.60**
X3	10	X3	10	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	95.0	**5.85**
X2	7	X2	7	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	66.5	**4.09**
X1	4	X1	4	100	0.095	9.5	1.69	0.85	13.65	0.75	10.24	38.0	**2.34**
			Sum	**1000**		**95**			**136.47**		**102.35**	**1663**	

Table 4.7.2. Lateral Loads calculations for applying in the structure at each story level in Karamba 3D_case of a 100 m² surface (source: the author)

The mass is assumed to be calculated for each story depending on the story weights. For a simple building 10 story tall, the lateral seismic forces apply as increasing from above to top stories. The concept used for performance based design modelling is driven from generating the main forces acting in a multi-storey building. Under the seismic excitation, the main forces acting on a building are inertia forces. This inertia forces are lateral forces acting at each story and applying at the mass of the buildings.

The horizontal inertia forces cause a lateral displacement of the frame building. Evaluating this parameter under the requirements of the code design will ensure the structural stability of the given multi-storey building.

Based on the panel chosen, it has been followed a methodology towards obtaining the shell element in both cases, as a volume and as a frame modelling. In this regard, the process is presented in the flowchart below.

By changing the scale of perforation, where from 0.1 to 0.5 is considered modelling with perforated shells and from 0.6 to 0.9 it is considered modelling with frame elements like in the case of bracing systems.

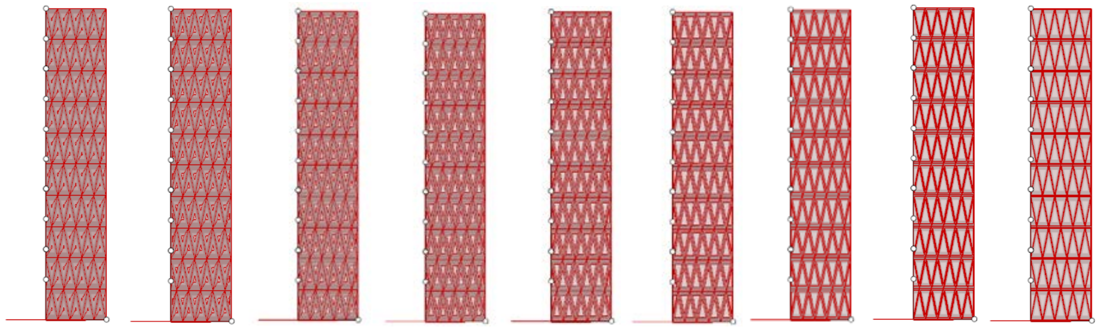
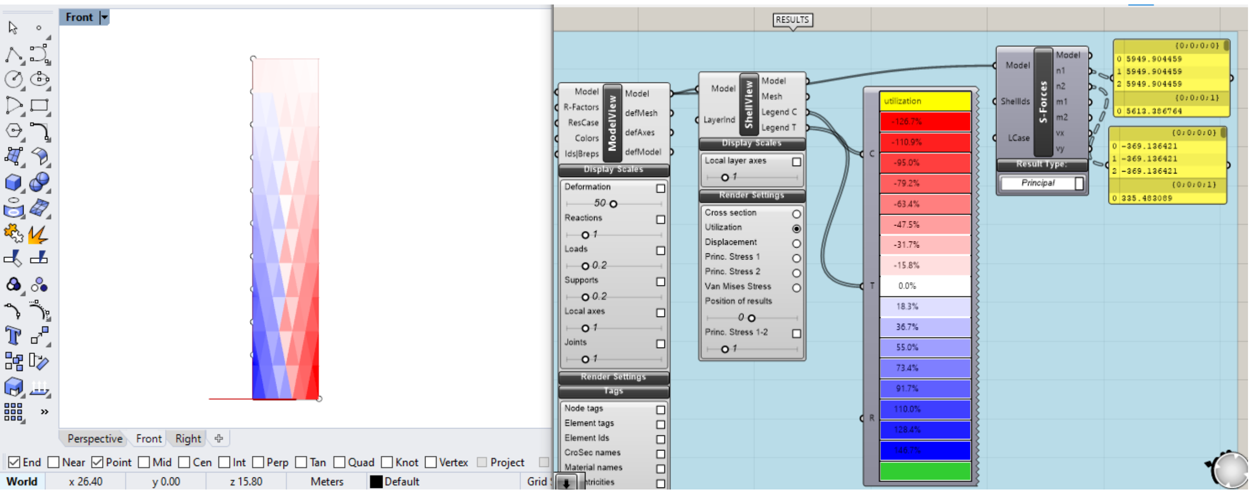


Figure 4.7.2. Perforated Triangle Panel with different scale of openings from 0.1 (left) to 0.9 (right) (source: the author)

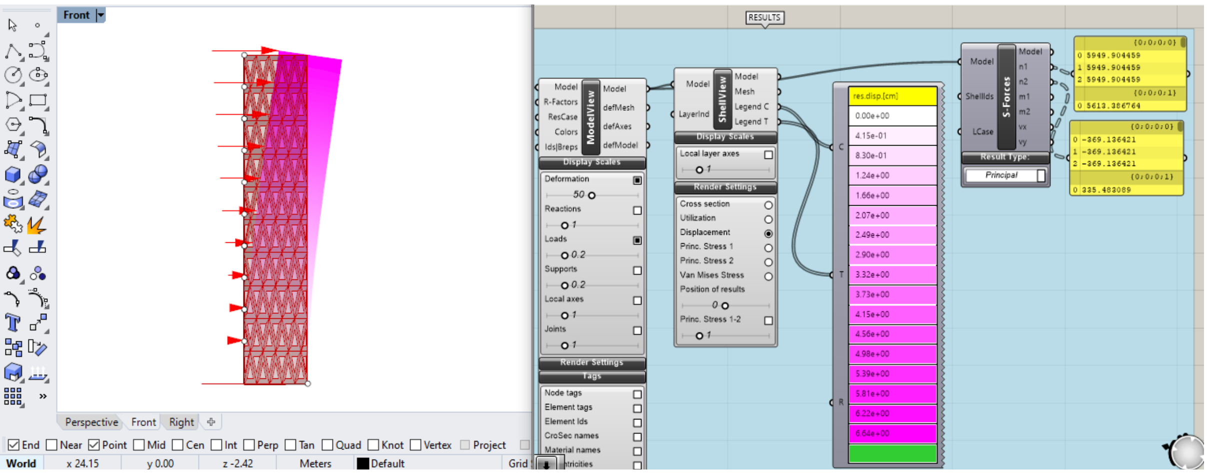
As it can be seen, the first and last panel do reflect several changing in their member sizes, vertical, horizontal and braces. In the first panels, it can be easily recognize a solid wall and at the last panels, you can tell the contrary. The last panels are more similar to steel bracing system, exoskeleton or external diagrid. In addition to this, they all have in common the structural element of reinforced concrete shell with different arrangement of openings. The structure analysis was run using 3 scale of openings, the lower, the average and the high values were selected, 0.1, 0.5 and 0.9.

The software of Karamba 3D do access to several structural results of structure behaviour in terms of internal forces acting on shell element. Below are presented some of these results for the panel with the scale of openings 0.5.

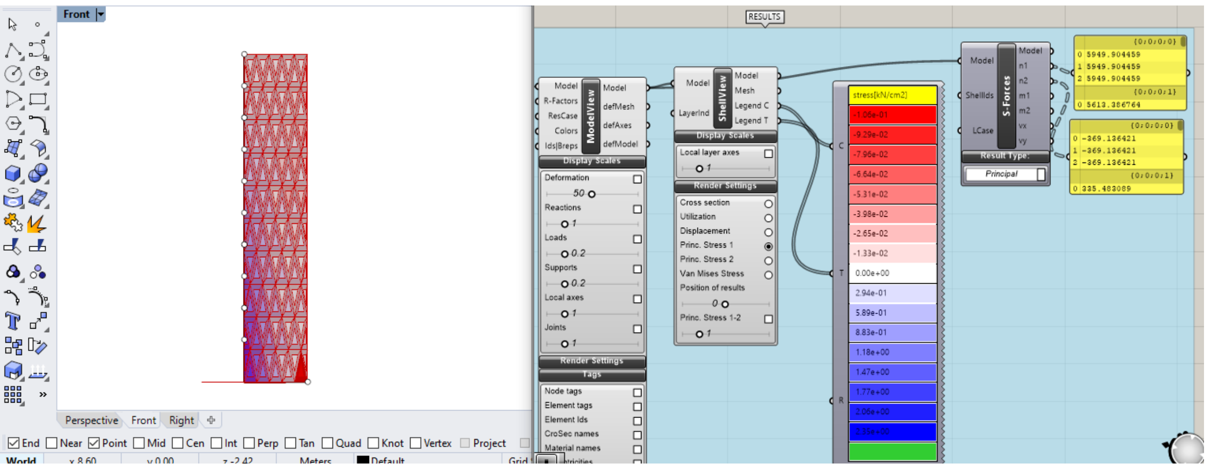
a) Utilization renders the material utilization. The utilization is calculated as the ratio between the material strength and the maximum Van Mises stress. A negative sign results if the negative value of the second principal stress is larger than the first principal stress.



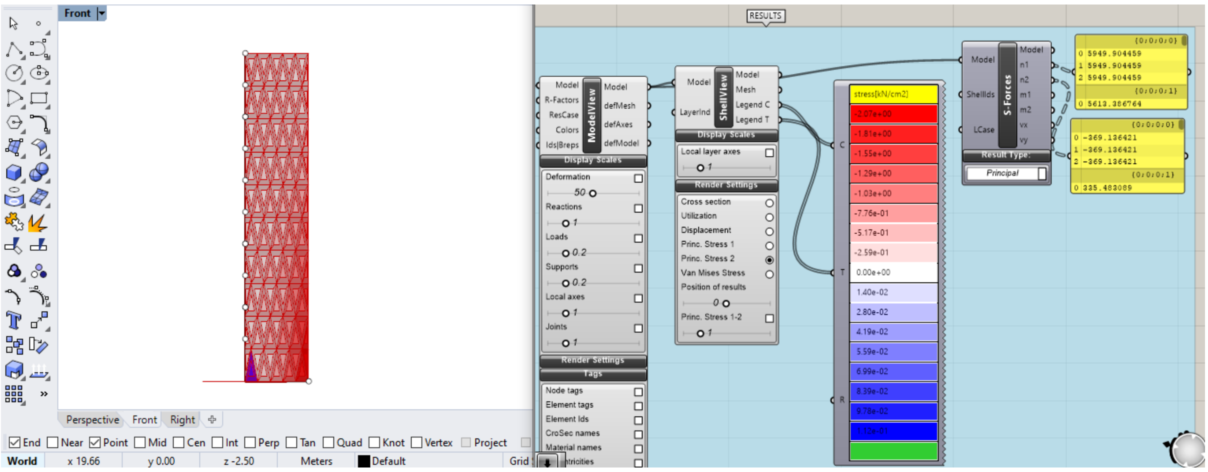
b) Displacements, colours the shell according to the resultant displacement.



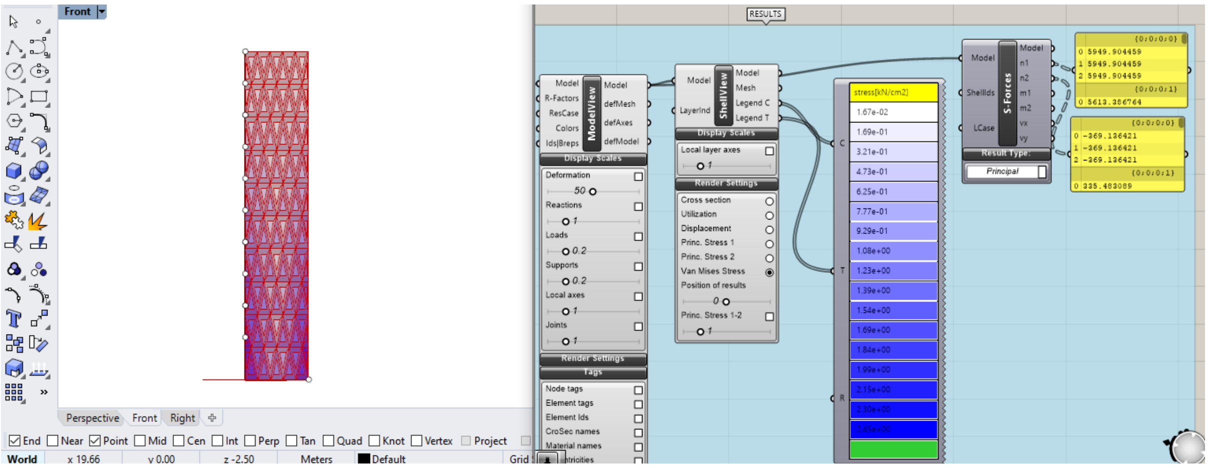
c) Principal Stresses 1, visualizes the resultant value of the first principal stress in the current fibre of the current layer.



d) Principal Stresses 2, displays the resultant value of the second principal stress in the current fibre.



e) Van Misses Stresses, renders the Van Mises Stress in the current layer and position.



Beside the internal forces acting on shell element, the most important factor is checking the lateral displacement of the structure in each cases. In this section, there were provided the values of displacements in each cases analysed. The varies of the displacements and their values do provide some interesting results in terms of differing modelling of a shell element.

The results are being summarized in the following tables.

Panel 3B Triangle Displacements (cm)		*v (division)*								
		10			20			40		
		0.1	0.5	0.9	0.1	0.5	0.9	0.1	0.5	0.9
u (division)	10	5.38	6.01	6.64	6.45	6.79	7.13	7.52	7.57	7.62
	20	7.60	7.85	8.10	10.40	12.16	13.92	16.15	16.34	16.52
	40	8.58	8.73	8.88	16.07	16.67	17.26	32.31	37.275	42.24

Limitation of displacement										
Case a	1/300H	10.33	10.33	10.33	10.33	10.33	10.33	10.33	10.33	10.33
Case b	1/200H	15.50	15.50	15.50	15.50	15.50	15.50	15.50	15.50	15.50
Case c	1/150H	20.67	20.67	20.67	20.67	20.67	20.67	20.67	20.67	20.67

Case a Displacements (cm)		*v (division)*								
		10			20			40		
		0.1	0.5	0.9	0.1	0.5	0.9	0.1	0.5	0.9
u (division)	10	5.38	6.01	6.64	6.45	6.79	7.13	7.52	7.57	7.62
	20	7.60	7.85	8.10	**10.40**	**12.16**	**13.92**	**16.15**	**16.34**	**16.52**
	40	8.58	8.73	8.88	**16.07**	**16.67**	**17.26**	**32.31**	**37.275**	**42.24**

Case b Displacements (cm)		*v (division)*								
		10			20			40		
		0.1	0.5	0.9	0.1	0.5	0.9	0.1	0.5	0.9
u (division)	10	5.38	6.01	6.64	6.45	6.79	7.13	7.52	7.57	7.62
	20	7.60	7.85	8.10	10.40	12.16	13.92	**16.15**	**16.34**	**16.52**
	40	8.58	8.73	8.88	**16.07**	**16.67**	**17.26**	**32.31**	**37.275**	**42.24**

Case c Displacements (cm)		*v (division)*								
		10			20			40		
		0.1	0.5	0.9	0.1	0.5	0.9	0.1	0.5	0.9
u (division)	10	5.38	6.01	6.64	6.45	6.79	7.13	7.52	7.57	7.62
	20	7.60	7.85	8.10	10.40	12.16	13.92	16.15	16.34	16.52
	40	8.58	8.73	8.88	16.07	16.67	17.26	**32.31**	**37.275**	**42.24**

Table 4.7.3. Displacements of the shell structure with different arrangements of openings (source: the author)

As it can be seen from the above table, there were drawn some important and interesting conclusions.

- ✓ The black values of panel displacements in white cell are within the required values of lateral displacements refered to Eurocode and the red values of displacements in white cell do not satisfy this condition. They are beyond the limitation of displacements that Eurocode specifies.
- ✓ In each division of u and v taken, it can be seen that with the increasing of the scale of perforation the displacements increase. It totally follows the theory on structure behaviour that the elements slenderness do absorb fewer forces and therefore will give

larger displacements. On the other hands, the greater the elements will absorb more forces and show lower values of displacements.

- ✓ The scale of perforation does effect very little the results of lateral deformations of structure. Three different scale of perforation were used, 0.1, 0.5 and 0.9. The maximum values does not exceed 24 %.
- ✓ With the increasing of the values of the u and v from the default division (10 by 10), it can be seen that the values of the displacements rise, so it can be concluded that the larger divisions (large opening size) do affect the interstory drifts of the structure. Each of the panel behave like one story, and it is perforated in its story height. The internal forces are distributed in the concept of tension and compression members.

4.7.5 Panel repetition

Huard et al. studied panel repetition with planar elements. Following a concept developed by Alain Lobel, they stress that the planarity constraint are hard to handle for arbitrary meshes, but are instantly satisfied for triangular meshes. They study the design space offered by meshes constituted of equilateral triangles only. An example of such is displayed in the figure below:

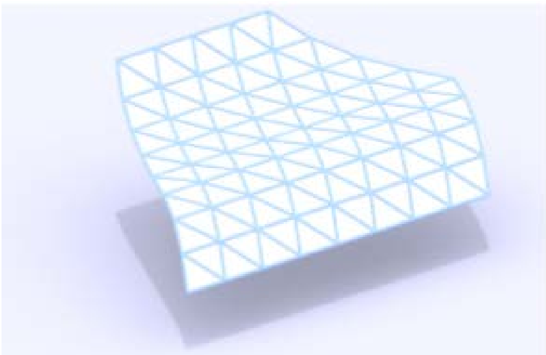


Figure 4.7.3. A Lobel mesh, constituted only of equilateral triangles

It is easy to see that the Gaussian curvature of Lobel frames is zero, in other terms, that only developable surfaces can be meshed with one unique triangular panel. Considering the fact that the Gaussian curvature at a vertex of a mesh is defined by equation:

$$\kappa = 2\pi - \mathbf{S}\,(\omega i)$$

In the case of Lobel frames, where the panels are equilateral triangles, $\omega = \pi/3$, the node of valence N has a Gaussian curvature of $(6-N)\,\pi/3$. Nodes of valence 6 have thus zero Gaussian curvature. Nodes of valence 7 correspond to negative Gaussian curvature and nodes of valence 5 correspond to positive Gaussian curvature. This restricts considerably the design space with extreme panel repetition. It is also noticed that node repetition is not achieved with Lobel meshes.

The example of Lobel frames shows that building with one unique panel restricts drastically the design space. From a practical point of view, constructing with a restricted family of panels could be just as economically efficient. There is a strong interest on clustering techniques, which have been combined with optimisation several times in order to minimise the number of families of panels necessary to approximate a given shape.

A combination of clustering technique with optimisation has been proposed for triangular meshes by Singh et al. and for quad meshes by Fu et al.. Both methods implement the k−mean algorithm and approximate a surface by a mesh where facets belong to k different families. Compatibility between adjacent faces is ensured by the computation of an edge-adjacency graph after clustering.

A comprehensive method based on clustering for panel's approximation was developed in Case Studies from Eigensatz. The user can assign costs to each technological solution (flat, cylindrical, developable, toroidal panels) and reduce the number of different panels or moulds used. The algorithm does an optimal fitting of the surface for each geometry of panel and can discard solutions where the approximated panels do not meet within a given tolerance.

Notice finally that the methods existing in the literature focus only on face repetition, without taking into account their thickness. While probably negligible for thin cladding elements, the consideration of offsets should play a role for a wide family of applications in architectural design.

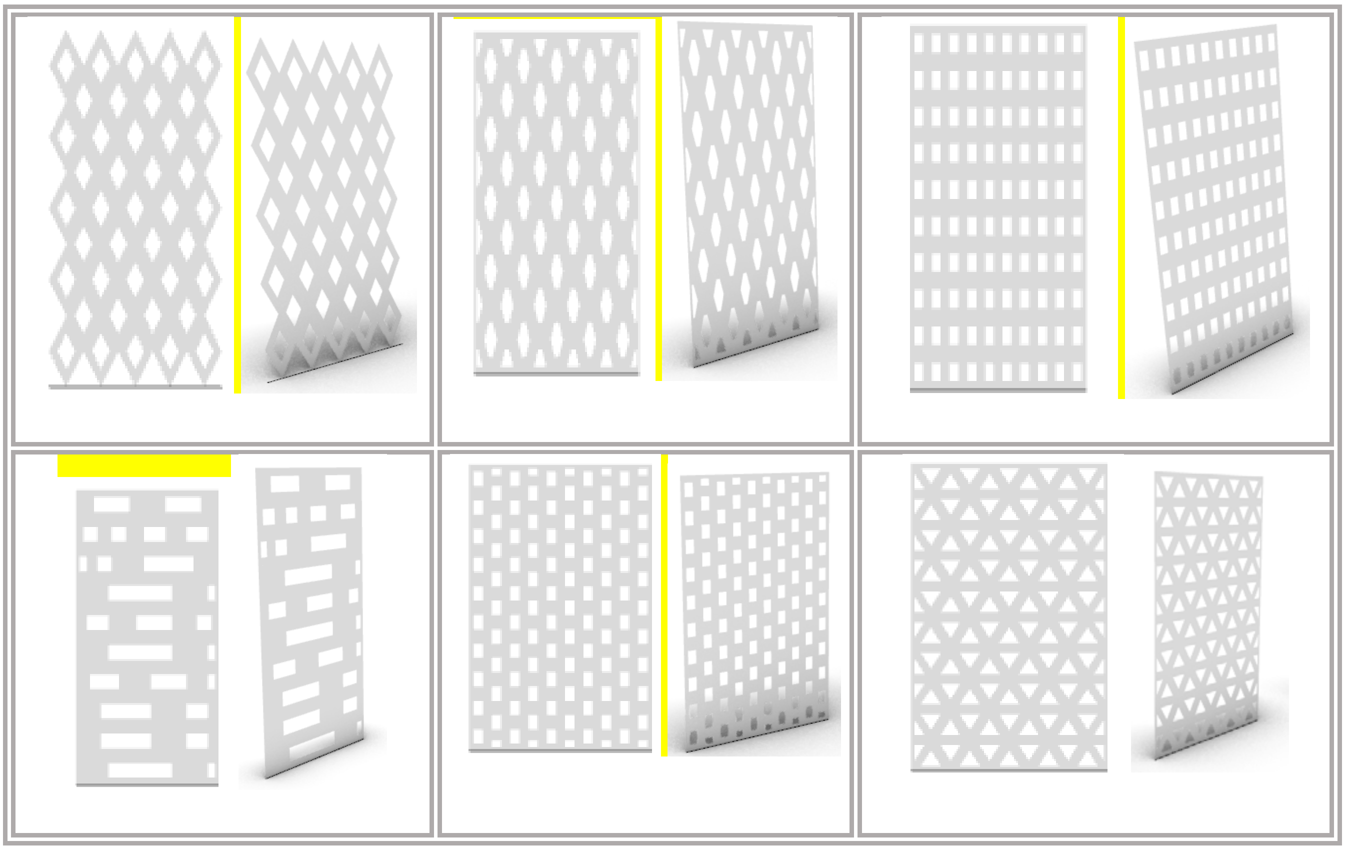
4.7.6 Shell elements in Karamba

To generate the model of a shell structure in Karamba, the surface is subdivided into a finite element mesh. The resolution of the mesh affects the accuracy of the results, but also the computation time of the FEA. The goal is to obtain a solution within a prescribed accuracy at a minimal computational cost. Karamba (Clemens Preisinger, Karamba developer) explained in a Grasshopper3D forum that the shell elements are triangular elements with 6 degree of freedom per node based on Kirchhoff theory. No in-plane rotational stiffness is added.

The Kirchhoff theory for thin plates neglects transverse shear deformation, that is $\gamma_{yz} = \gamma_{zx} = 0$. If the plate gets too thick this assumption is not valid anymore. Thus, for the thin plate theory to be valid, the following guideline of the thickness/length-ratio should be followed: t/L ≤ 1/10. The shells investigated in this thesis will have values of t/L smaller than this ratio.

The main parametric tool to be used in the the study is Grasshopper which is a visual programming editor and a plug-in for Rhino3D (Robert McNeel & Associates, 2020), Grasshopper is integrated with the modelling environment used in e.g. architecture and engineering. The Grasshopper offers a define precise parametric control. It explores also several generative design work flows over models, while developing a platform for higher-level programming logic by using a graphical interface. (ModeLab Accessed 2020-14-04).

For structural evaluation of structures modelled within the parametric design tools Karamba (Matthew Tam, 2020) will be used. Karamba is a plug-in for Grasshopper that makes it easy to combine geometric models, finite element calculations and optimization algorithms. For evaluation of the structural outputs given from Karamba, ETABS 2018 will be used which also uses the finite element method (FEM). This will be achieved by remodelling the perforated panel in ETABS.



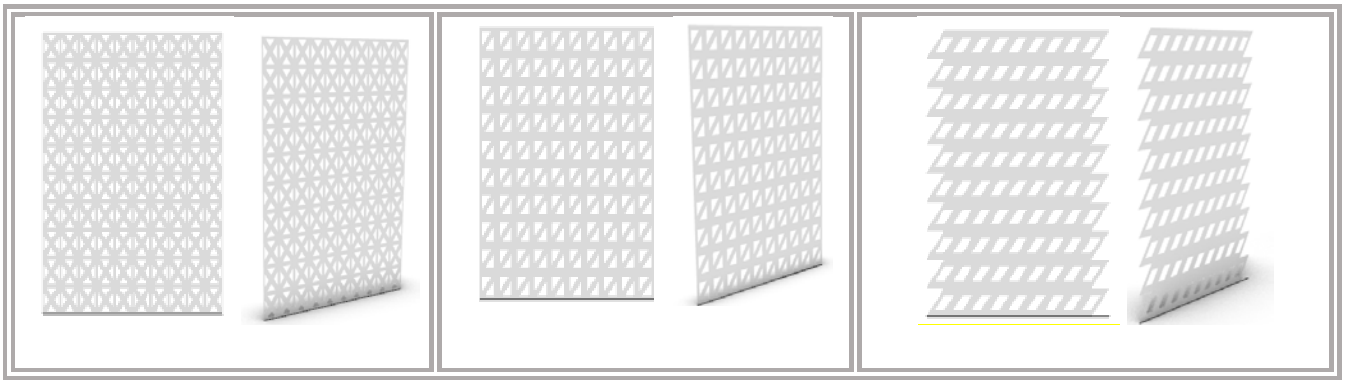


Figure 4.7.4. Perforated Panels generating in Grasshopper using LunchBox plugin (source: the author)

The geometry model code for each of them is given below.

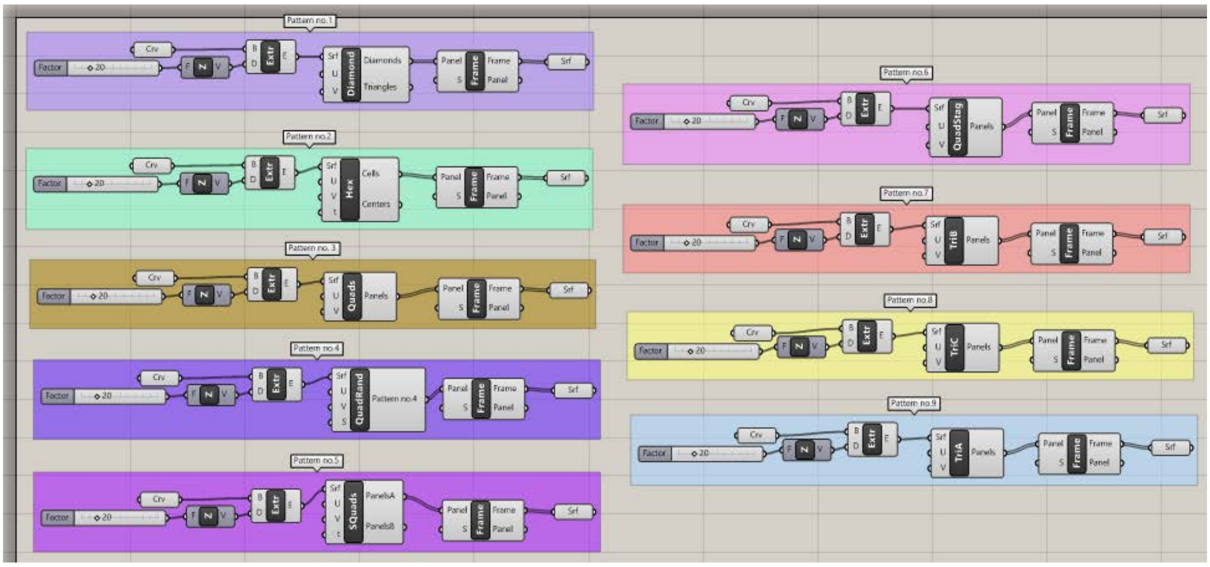


Figure 4.7.5. Geometry Model Code of Perforated Panels generating in Grasshopper using LunchBox plugin (source: the author)

4.8 Triangle 3B Panel

4.8.1 The Panel Geometry

As it can be seen above, the plugin of LunchBox provide nine-panel configuration, each of them based in a simple shape for instance, from the diamond shape to hexagon, quadrative, skewed, staggered and triangular. In the case of using a solid material or a filled surface area, the plugin automatically divide the surface in the above geometries defining the inner axes for each of them.

The perforation of the panels is provided by using the Panel Frame component. By using this component, it is created an offset in the internal area of the panel. In this regard, it is obtained for each of them a given arrangement of openings. All panel areas are perforated then by a scale factor of 0.5, which means that 50% of the surface has material and 50% of the area contains voids. The programme offers the possibility that once you have created the geometry, it can be modified further in terms of the perforation scale, the openings may vary from very small openings 0.1 to large openings 0.9.

As can be seen from the figure of the above panels, a series of panel configurations are taken into consideration, which reflect a certain architectural performance. At this point in the analysis, it is more important to argue about the selection of the panel configuration.

This study does not reclaim to use one of these nine panels; on the contrary, the program itself offers the possibility of treating several different geometries by designers. They can configure different areas by designing with their own taste. The final panel configuration may result from a simple regular shape of openings to a very complicated and irregular shape of openings. In each case, it is important to provide a perforated panel that provide not only the architectural feature but also it is also a structural element itself, the so-called perforated structural wall.

Following the above logic and in order to analyse a structural wall with openings, a pattern was selected from the nine models above. The final geometry obtained for this pattern is briefly described below.

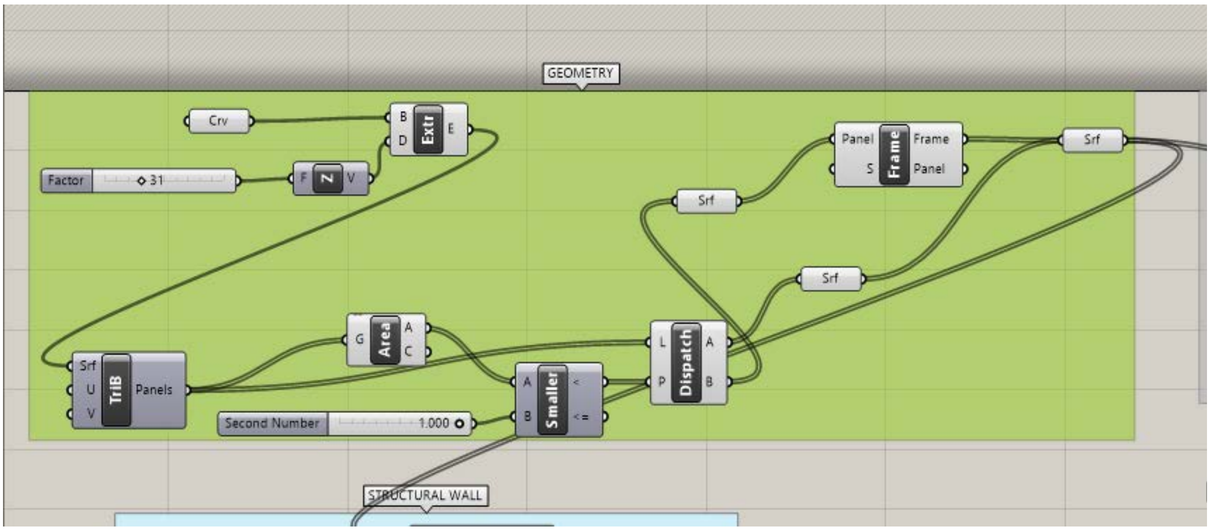


Figure 4.8.1. Geometry Model Code of Triangle 3B Perforated Panel generating in Grasshopper using LunchBox plugin (source: the author)

It first started with a single line of 6 meters length, which represent the panel length. Knowing the fact that this panel will play the role of a structural wall, a length of 6 meters is sufficient for a wall positioned between the axes of two consecutive columns. These axes of columns in a multi-storey building generally vary from five to 7 meters, for a reason an average of 6 meters is taken. However, the program allows the modification of each parameter even after the final solution has been obtained, so that like any other parameter, the length of the element can be modified later and in real time can been observed the total behaviour of the element.

So after designing a single line of 6 meters to Rhino, in the Grasshopper it is putted the first component, that of *Curve*. Then a curve it is extruded along the Z vector by a factor of 31. The number 31 represent the ten stories of the panel. The first story with a height of 4 meters and the rest of them with a height of 3 meters which make in total 1 x 4 m + 9 x 3 m = 31 meters.

The process then follows with the component of panel chosen from the plugin of LunchBox. So as it was stated before, it is selected only one panel configuration to run analysis, and that is the *Triangle 3B* panel, which creates triangular panels on the surface. After applying this component it is observed that, the edge of the panel were very thin. In the previous chapter it was explained extensively the need to have boundary elements for structural walls. So keeping in the same logic, a modification is done to the perforated panel configuration in order to have thicker elements in the corners.

To achieve the above requirement, the component of *Triangle 3B* panel configuration it is linked with the component of *Area*. In this regard, are being provided all the surface areas for the panel and the following component *Smaller than* divide all measured surfaces in two groups. The first group are the boundary surfaces and the second group represent the other surfaces. The figures below illustrates the two cases.

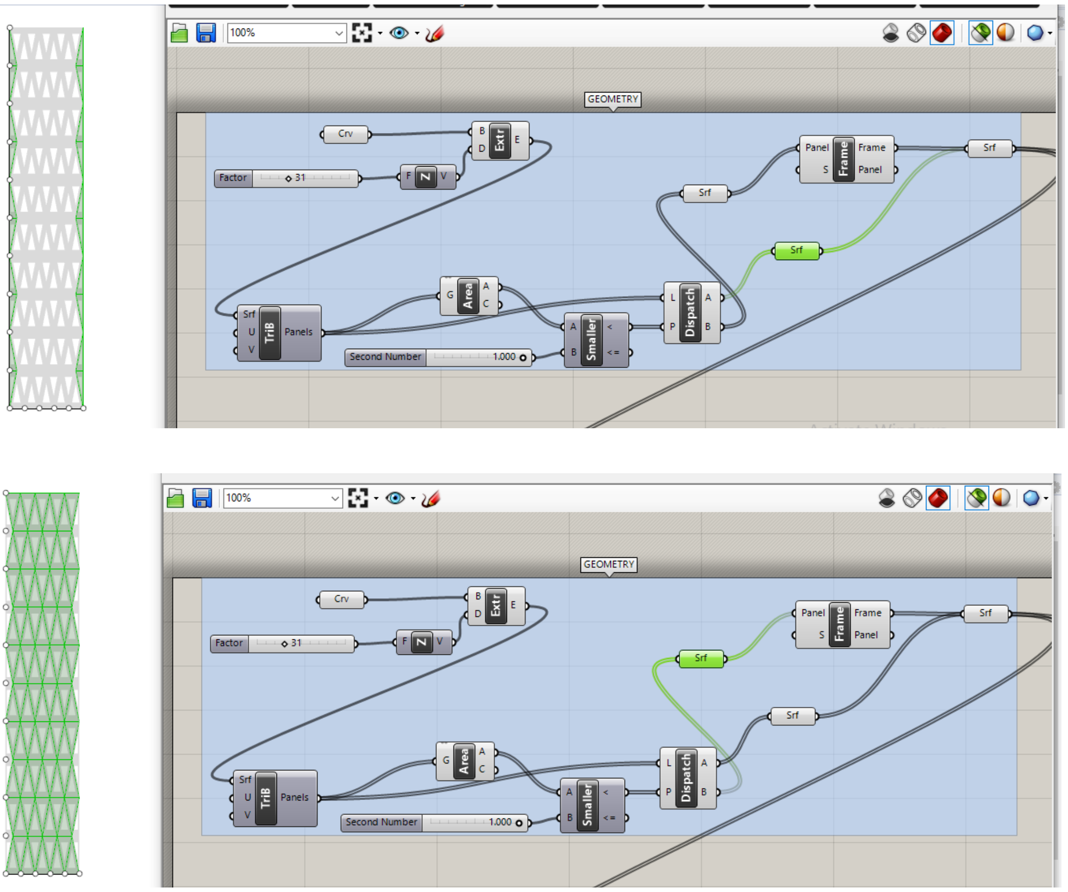


Figure 4.8.2. The outside and inside surfaces of the panel (source: the author)

The inside surfaces are further linked with the component of *Panel Frame*, so are being opened with a defined scale ratio of 0.5 and the outside surfaces are kept filled. In the end, both surfaces are linked with a single *Surface* component resulting in the desired pattern geometry of the panel as shown below.

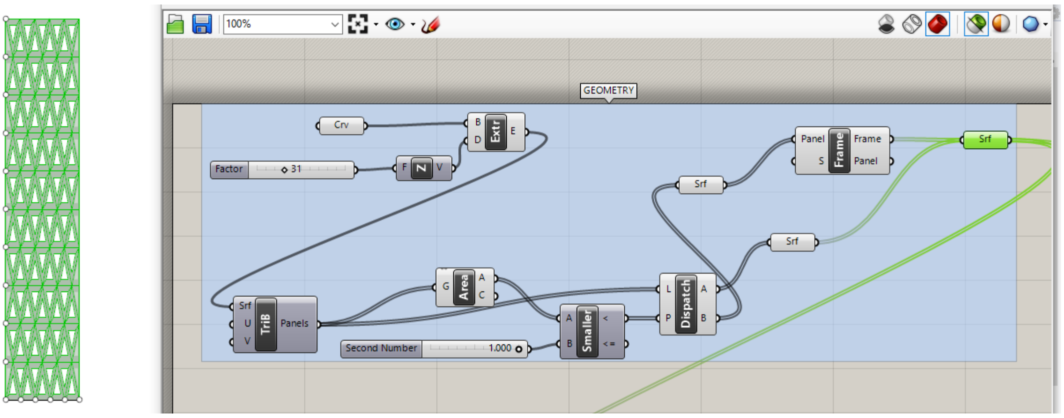


Figure 4.8.3. Total Geometry Model Code modified for obtaining the Perforated Triangle 3B Panel (source: the author)

Moreover in this study it is suggested to use in the design of multi-storey buildings, an innovative pattern for structural wall, which is the structural wall with openings, the so called the Perforated Structural Wall.

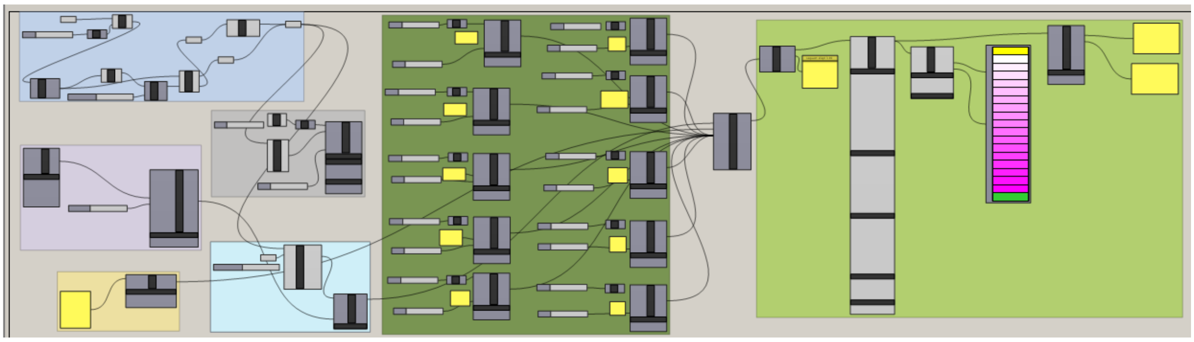


Figure 4.8.4. Total Model Code of Perforated Panels generating in Grasshopper using Karamba 3D plugin (source: the author)

The method used to analyse structures is the Linear Elastic Analysis based on the Finite Element Method (MEF) used.

The model that is being analysed represent a regular structure in elevation with the initial dimensions of 6 metres and 31 metres tall. The first story is assumed to be 4 metres high and the nine stories above to 3 metres high. For the structure analysis is selected the lateral force method and the displacements are being considered regarding the reference eurocode EN 1998-1.

The output number generated is the required the optimal displacement, which is one of the main driven force to the process towards generating the perforated Structural Wall panel.

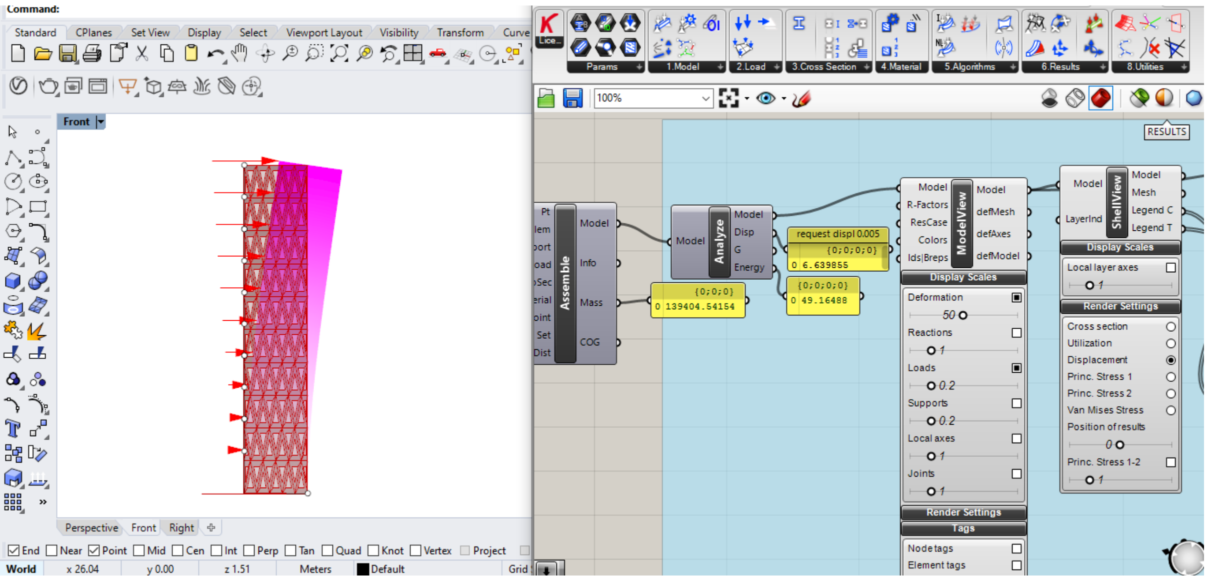


Figure 4.8.5. Maximum Displacement in cm for each load case of the model (source: the author)

4.9 Iterative Structural Analysis

The iterative structural analysis towards obtaining the resulting perforated pattern for Structural Wall is represented by several steps using different software's. A clearer idea of this process is given in the diagram below.

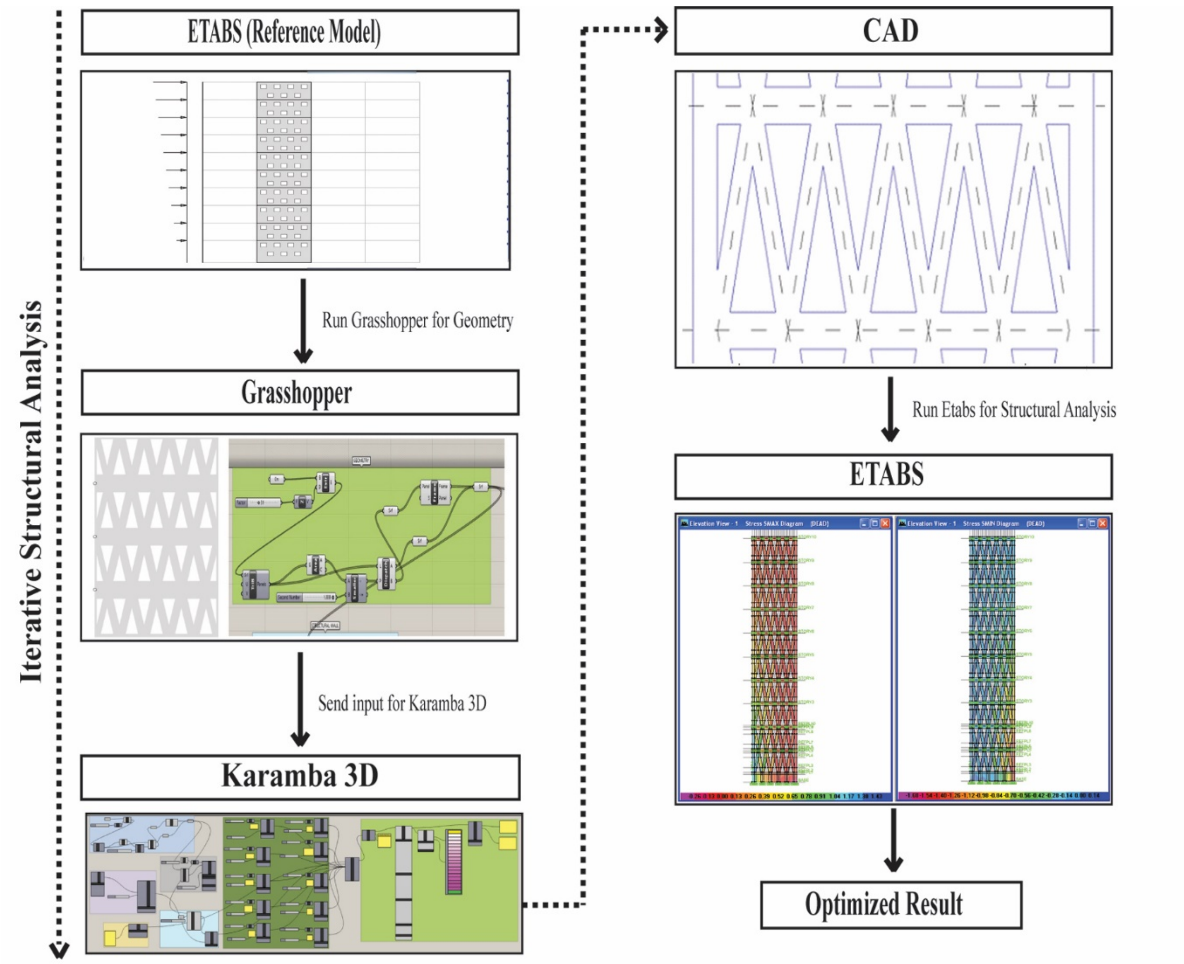


Figure 4.9.1. The Iterative Structural Analysis for generating the Optimal Perforated Pattern (source: the author)

To simplify the procedures for composition of a perforated structural wall panel, it is being accepted the build of a structural model in the vertical plane based on a Dual System formatted by the interaction of frame elements with structural walls which support each other in withstanding horizontal lateral forces from seismic action.

Considering that fact that the structural model will be an integral part of the perimeter facade of the building, it has been accepted that this model will cover a building area of about 100 m^2 with a grid of the frame system about 6m.

Consequently, the structural model will be formed by 4 spans about 6m each, in the longitudinal direction, which will transmit to the system a seismic mass with a depth of about 4 m inside the building.

The structural model is adapted for a 10-storey building, as a representative structure of a multi-storey building. The height on the ground floor is 4m and the other floors are of same height of 3m.

For the structure analysis is selected the lateral force method and the displacements are being considered regarding the reference eurocode EN 1998-1.

In the initial phase it has been determined the seismic force in the perforated panel according to the methodology described in paragraph 4.7 in which approximately 75% of the total dynamic lateral force of the dual system is accepted.

And then, after creating the overall geometry of the element from grasshopper software, the process will continue with the procedure analysis in Karamba from the structural FEM analysis that is presented in the following ten steps:

1- Defining the structural elements. In this case, the element used is the reinforced concrete shell.
2- Meshing the shell using the mesh resolution of scale 1.
3- Setting the supports.
4- Putting the loads. The vertical load is defined by assuming a total load acting on a wall, it is applied to each story height, and the lateral load is putted according to the seismic loads acting also at each story.
5- Selecting the cross section of a rectangular form with plan dimensions of 6x0.3 metres
6- Selecting the material used for the element, reinforced concrete C25/30
7- Assembling the model
8- Analysing the model
9- Viewing the model results.
10- Checking the results, the top displacement of the element according to the eurocode requirements.

Thereafter, for concretization, of the structural analysis, as was mentioned above from the LunchBox plugin, a Triangle 3B panel, 6m wide and 30cm thick, was selected.

According to this analysis, this type of perforated panel with division u and v 10x10 and with perforation coefficient 0.5 is being accepted, which shows the elastic displacement from the design spectrum in the value of 6.01 cm within the allowed value of the elastic displacement 10.33cm for the category of objects Case a, for buildings having non-structural elements of brittle materials attached to the structure.

4.10 Detailing and analysing process of the Triangle 3B panel configuration

After checking the stability of the chosen pattern, it is obtained a final panel configuration for Perforated Structural Wall, the Triangle 3B perforated panel. This panel is further detailed in CAD. There are specified all members dimensions and the axes distances between the openings, see in the Appendix 9.1. Then, the panel is designed in the structural analysis software of ETABS and a complete structural analysis is conducted and a real element behaviour is concieved.

4.10.1 Panel detailing in CAD

As explained in the above paragraph, the detailing process of the panel chosen in CAD software aims in determining several details on the position of the concrete material members as well as the position of openings. In the illustrations given in the Appendix 9.1, can be easily identified five main steps of this process.

Firstly, it is chosen to detail the pattern between two consecutive floors. So a simple configuration of filled elements and the voids is given, that constitutes the first step. Then in the second step, are positioned the main axes of the panel.These axes are being located in the middle of the “side colomns” dimensions. The third and fourth steps, present a very detail dimension of the panel elements, the filled members and the voids. The resulting panel is represented is the fifth step, where it is also given the perforation ratio and the neccesary dimensions required to build the model in the ETABS software.

4.10.2 Panel analysed in ETABS

In the Appendix 9.2 until 9.14 are presented the main outputs of the analysis of the model in ETABS software. Also this process is divided in several phases to better elaborate the concluding remarks for the Perforated Structural Wall Panel. Very briefly, the panel analysed in ETABS covers the following phases:

Based on element detailing in CAD, a similar model is build as reffered in the Appendix 9:

a) a similar wall configuration as the model in Grasshopper, shell elements used

For a better approach to models in reality, the first story of the wall panel is considered underground and therefore the entire story is constrained with a solid concrete wall without openings. This modification is kept the same for the other walls modelling.

The second model build is:

b) a solid wall without openings, shell elements used

The main reason in building this model consists in a rapid survey on the differences between a solid wall and a perforated wall, both using shell elements. Referred to the top maximum displacements of each model, there seems to be no big differences (see appendix 9.2).

A similar model was built with the first one.

c) a frame braced wall, frame elements used

Using a frame braced wall, the wall reinforcing is simpler than the first model. Since the differences between the first and the third model are not significate, is being suggested to consider the third wall modeling since the longitudinal reinforced bars are obtained automatically (in cm^2) for each panel members. It is worth mentioning that the main elements distinguished in this panel are the frame elements of columns and beams and the braced elements, which are considered all the diagonal members.

d) a frame braced wall, frame elements used with wall self-weight considered to zero

This fourth modelling is the same of the third one, but the self wight of the concrete members is being neglected. So in this model, all the results parameters after the structural analysis of the panel, are considered only due to lateral forces applyied in each story level according to the above consideration given in table 7. Some interesting results are obtained also in this case which are presented in the Appendis 9 of the thesis.

4.10.3 Introducing the final panel “Frame Braced Wall“

Based on the third wall modeling described in the above paragraphs, it is concluded to a fifth wall panel modelling. The main concept of a structural wall as described in the theoretical part, deals with the presence entire the wall of the compression and tenssion areas. The third panel modelled does not fullfill this requirements since in the bracing elements are present the moments and the shear forces as well as in the frame elements of colomns and beams.

Following the logic of obtainig a rational element, it is considered to maintain the frame elements of the panel and to provide to braces elements only the compression / tension forces. This is achieved by modifying the restraints of the joints between braces and columns / beams. So there are moments and shear forces into bracing elements and in this way it is provided the final panel called the “Frame Braced Wall” which satisfies all the above mentioned requirements.

4.11 Discussion of results

The structural analysis is limited to checking top displacement and sectional forces and moments in the critical area for the shell against requirements according to Eurocode 2. Creep effects and instability will not be considered. No dynamic analysis will be performed.

The deflection control was done according to EN 2004, where the maximum displacement, which correspond to the top of the element, should not exceed H/200. Therefore, that will be the target displacement. Each of the patterns should fulfil the criteria of above mention and the procedure will be repeated in three distinguished ways:

i) First by changing the panel dimensions (u and v divisions)
ii) Second by scaling the openings factor from 0 to 1, mentioning that the scale of the first step is presuming as default by 0.5.
iii) Third by changing the openings orientation

This procedure will help in identifying if there are problems with the panel in terms of its structural stability.

After checking the stability of the chosen pattern, it is obtained a final panel configuration for Perforated Structural Wall, the Triangle 3B perforated panel. This panel is further detailed in CAD and designed in the structural analysis software of ETABS. A complete structural analysis is conducted and a real element behaviour is concieved, resulting in a final Perforated Structural Wall element, specified as the "Frame Braced Wall".

4.12 Cases of application for the perforated panels to different buildings configurations

Previously is being described in detail the main objective of this topic on the effects of using reinforced concrete panels with special architectural performance in terms of significant structural improvements in multi-storey buildings with considerable extension in plan. As regard, for concretization there are presented various cases of using these panels located in the peripheral parts of buildings with a width of 3,4, 5 and 6 metres but also wider in special cases.

Referring to the authors Paulay and Priestley, it is of great interest to elaborate the two selected cases of buildings identified by these authors with problems in their structural plan and their conceptual recommendations on their structural behavior (Fig 4.12.1) building a and b.

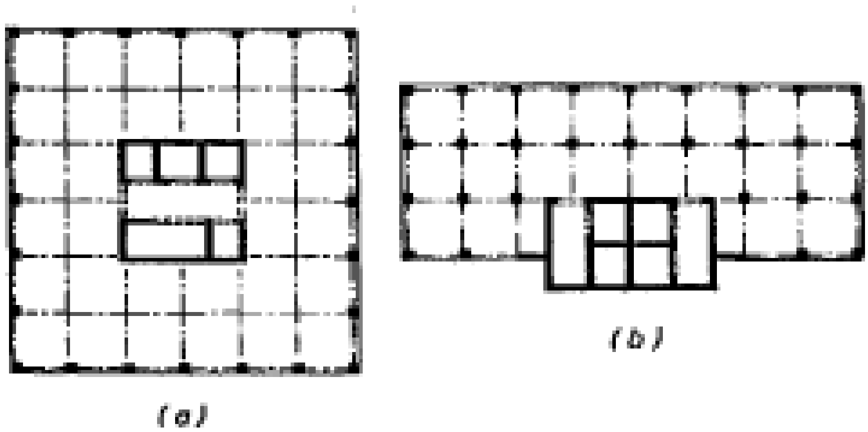


Figure 4.12.1. Lateral force resistance provided by reinforced concrete cores (source: Paulay and Priestley, 1992)

As mention above, the different distinguished cases applying perforated walls in different configurations of buildings are given as follows:

i) Tower type building (section in plan 24x24 meters)
ii) Building with longitudinal extension in plan with dimensions 36x16 meters
iii) Building with extension in three directions in the shape of a star with 120 degrees angel me zgjatim te brinjeve me permasa 15x15m nga baza tre kendore e e objektit
iv) Building with irregular shape in the plan ne forme L me zgjatim te brinjeve me permasa 24x12m

i) Tower type building

In the first case, according to the authors (Fig. 4.12.1a) have been evidenced the conception of the building with a quadratic structural scheme with considerable dimensions in the plan, with a concrete core wall with increased dimensions, also treating the internal traffic distribution corridors with structural wall elements, to ensure stability from the twisting of the object as well as with a grid of beams and columns with considerable cross sections and close distances to maintain the allowed displacements of the building.

According to this conception, and the schematic representation of this object, such an object is configured similarly with plan dimension of 24x24 m with a reinforced concrete core wall located in the center of the building with dimensions 8x8 m and with a system column and of solid beams located at a distance of 4 metres.

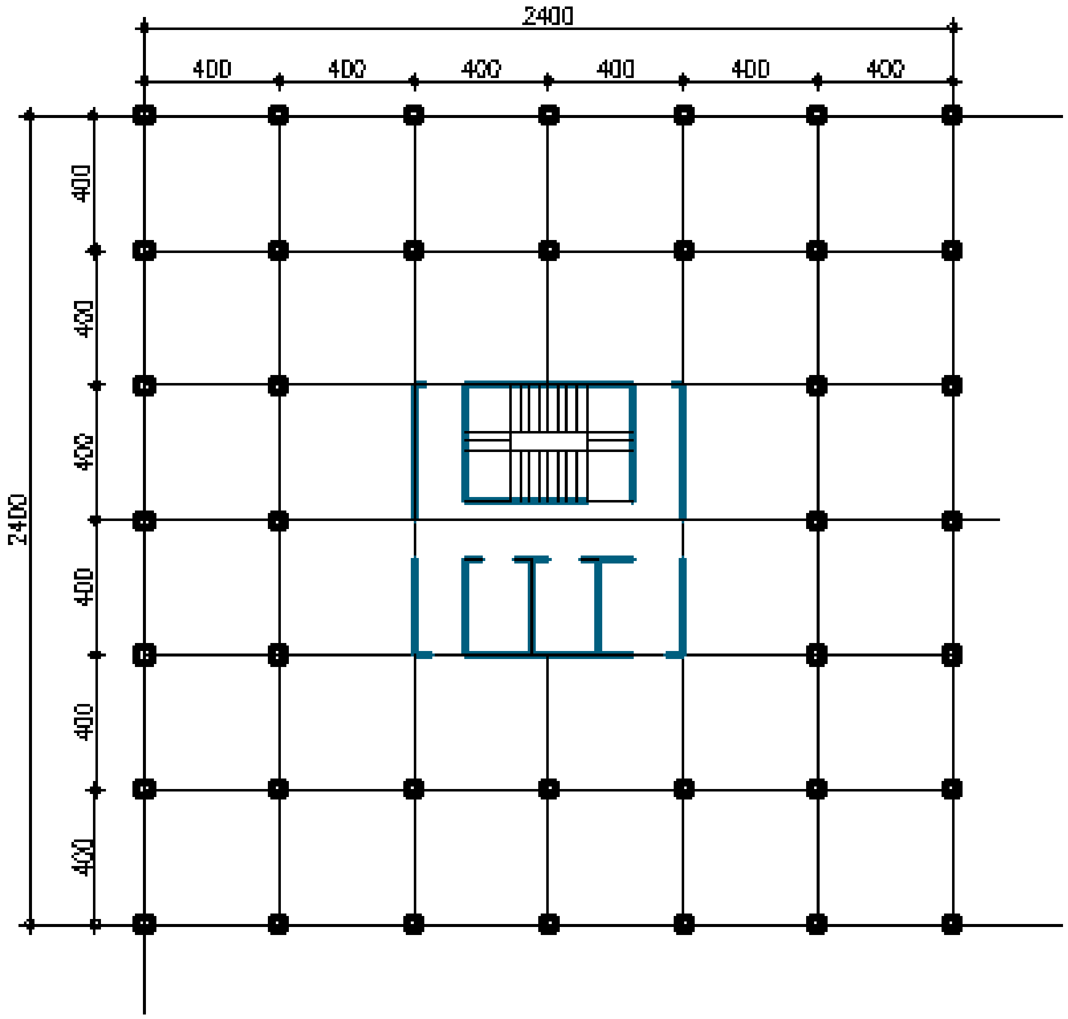


Figure 4.12.2. Building frame with section 24x24 m with columns axes every 4 m with concrete core wall in the centre with dimensions 8x8 m (source: the author)

To compare the improvement of the structural behavior for this case, the building is structurally reconceptualized (Fig. 4.12.3), with the placement of perforated panels with a width of 3 m placed at the edges of the building, and treated with a grid of beams and columns with 6 m span and with a reduced of service core dimensions in the building center.

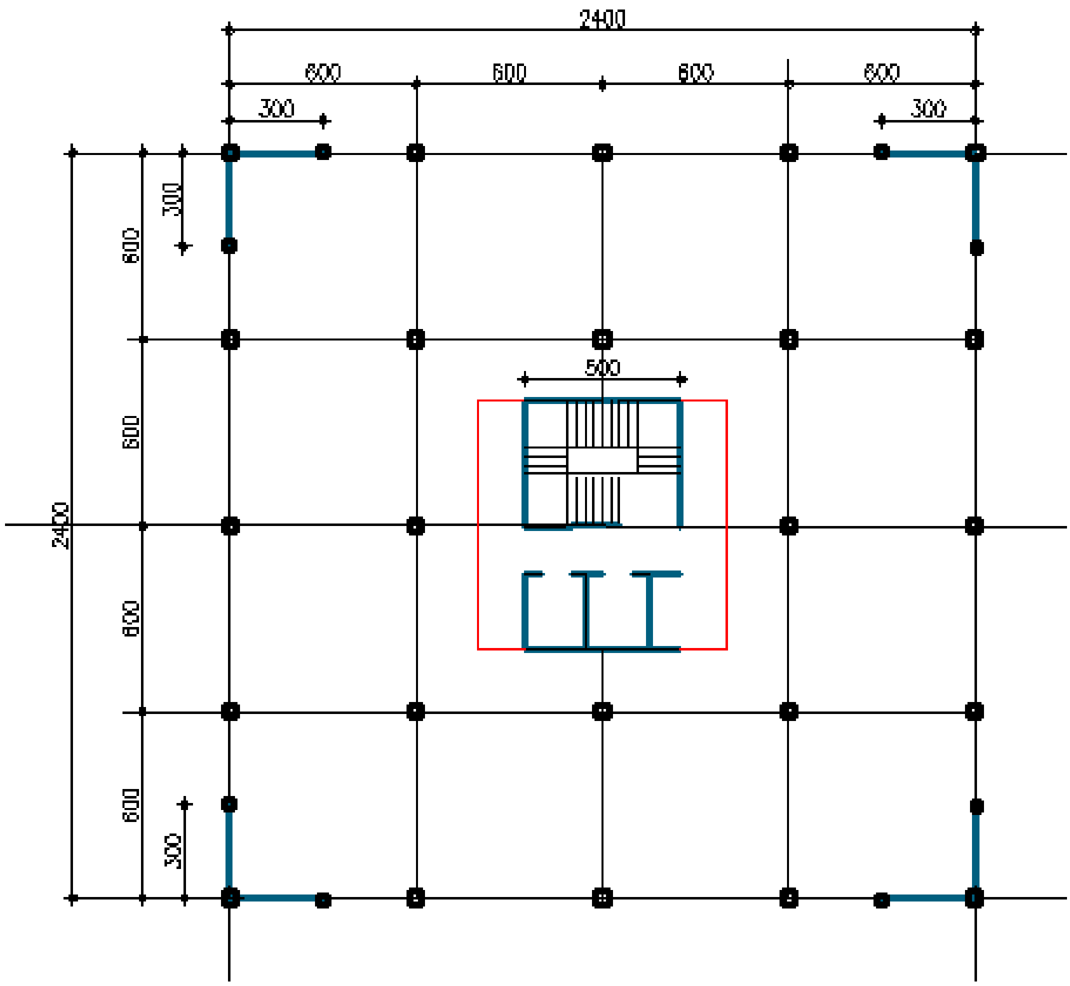


Figure 4.12.3. Building frame with section 24x24 m with columns axes every 6 m with concrete core wall in the centre with dimensions 5x8 m and with perforated panels with dimension 3 m (source: the author)

ii) Building with longitudinal extension in plan

In the second case, from the above mentioned authors (Fig. 4.12.1b),) have been evidenced the conception of the building wiith disproporcional dimensions in plan, due to the conditions of the construction site, which has imposed the placement of a concrete service core in the end part of the longitudinal facade of this building.

According to this conception, and the schematic representation of this object, such an object is configured simirlarly with plan dimensions 36x16 m by placing a reinforced concrete core

7x6m near the side facade of the building, and with a very dense grid of columns at 4m span to ensure stability against the torsion.

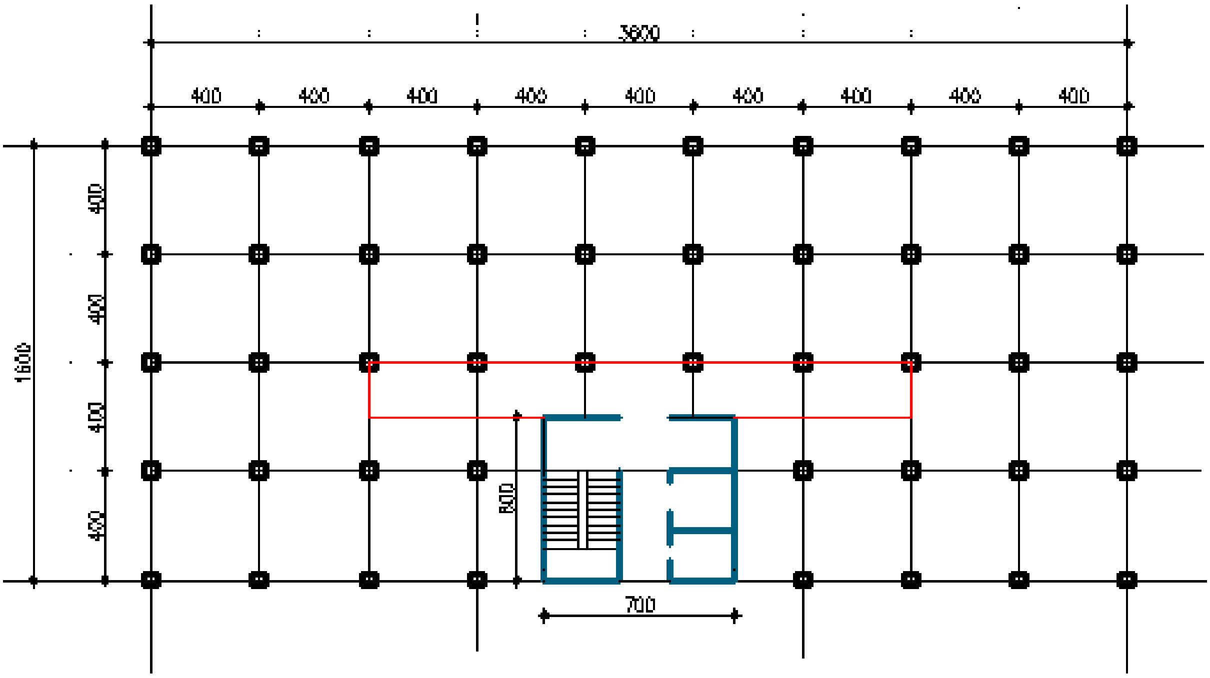


Figure 4.12.4. Rectangular structure with dimension16x36 m and with columns axis, every 4 m with concrete core wall to one side with dimensions 6x7 m (source: the author)

For comparison of this model, the building has been reconceptualized (Fig. 4.12.6) from the structural side, with the placement of perforated panels as structural walls with a width of 6 m each, placed in the other three side facades of the building, as well as composed with beams and columns at the distance of 6 m span and with a reduced of service core dimensions located in the peripheral part of building facade.

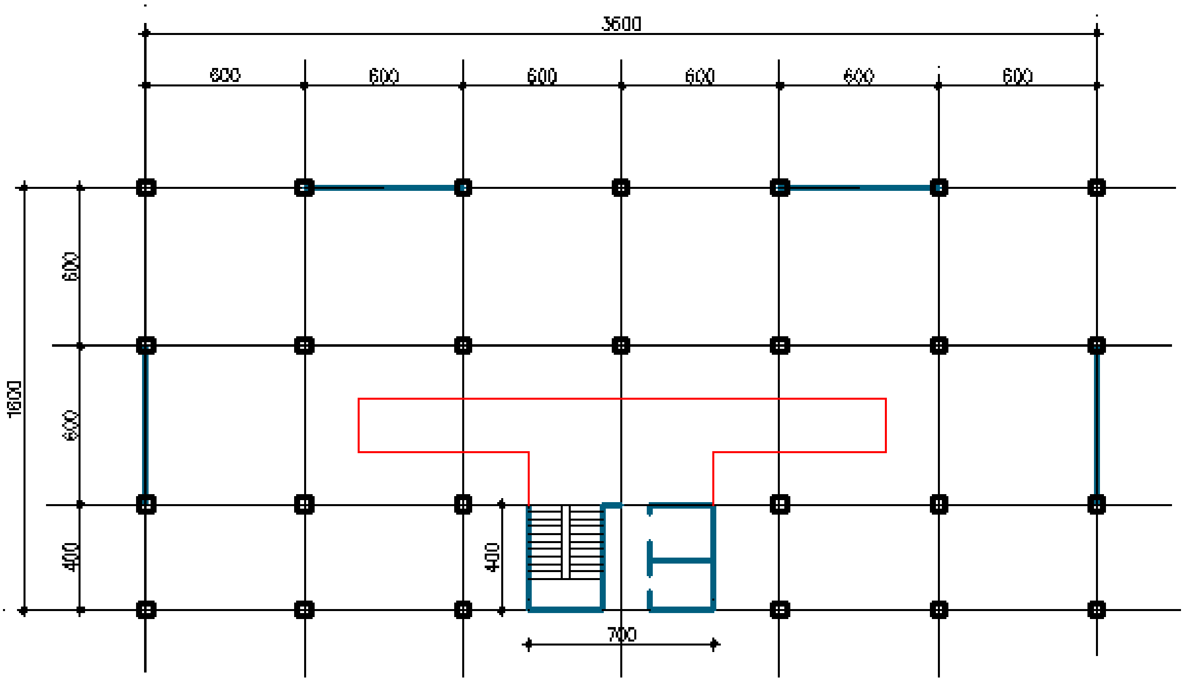


Figure 4.12.5. Rectangular structure with dimension16x36 m and with columns axis, every 6 m with concrete core wall to one side with dimensions 4x7 m and with four peripheral perforated panels with dimension 6 m (source: the author)

In addition to that, in similarity with these two cases, two other cases have been developed treated, the third and fourth case, with even more pronounced shapes and dimensions of their not symmetry building plans.

iii) Building with extension in three directions in the shape of a star

The third case, represents the case of a symmetrically triangular shaped building, with the elongation sections by angle of 120 degrees, with considerable extension in the plan, with an axial length of 19.33 m from the center in each direction, with the placement of the reinforced concrete core wall in the center of the building.

In this case, as a solution with even significant structural effects (Fig. 4.12.7), perforated panels as structural wall with a width of 5m have been placed in the three final parts of the facades of this building.

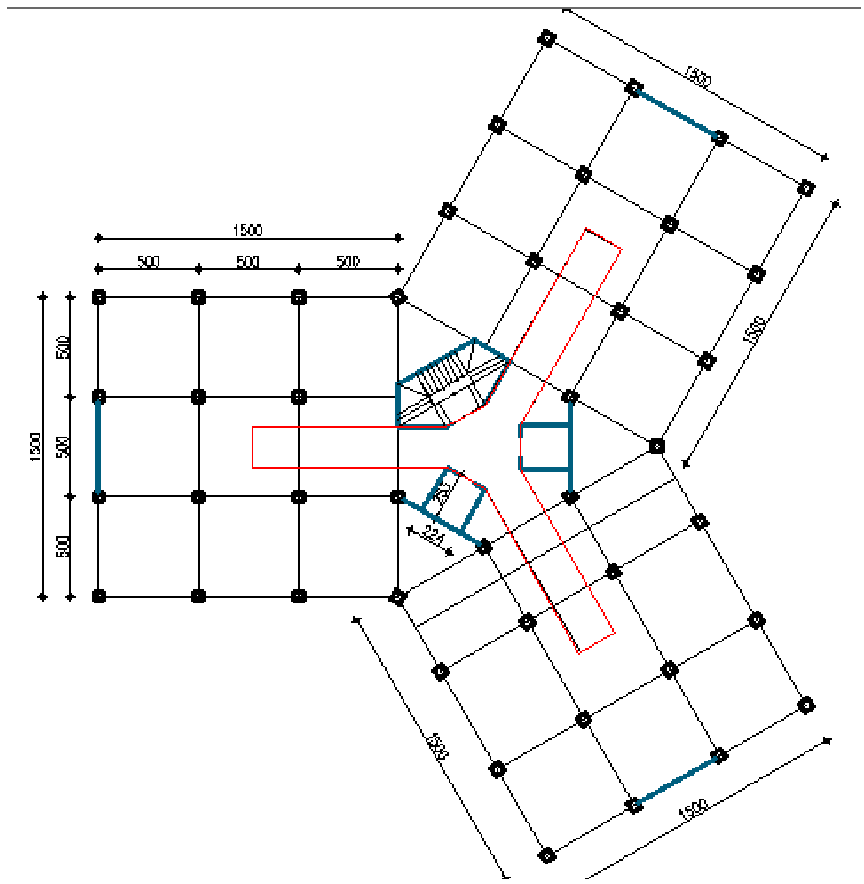


Figure 4.12.6. Three corner structure oriented with 120 degrees with section 3x15x15 m and with columns axis every 5 m with hexagonal concrete core wall in the centre of the building and perforated walls with dimension 5 m located to the side facades (source: the author)

iv) *Building with irregular shape in the plan*

The fourth case, represents the case of a building with L-shaped plan extension with equal ribs, i ekspozuar prane kryqezimit te dy aterieve kryesore te levizjes se popullates.

According to this conception, and the schematic representation of this object, such an object (Fig 4.12.8) is configured simirlarly with plan dimensions of 36x16 m by placing a reinforced concrete core 7x6m near the side facade of the building, and with a very dense grid of columns spans of 4m to ensure stability against the torsion

In this case, as a special solution in terms of architectural performance of the building, but also as a necessary solution to ensure the torsional stability of this building due to the presence of asymetry of this building and service core position, it is achieved by placing a perforated hexagonal wall panel in the center of its facade with a width of 10 m, adding other two more perforated panels with a width of 6m placed in the longitudinal facades of this building.

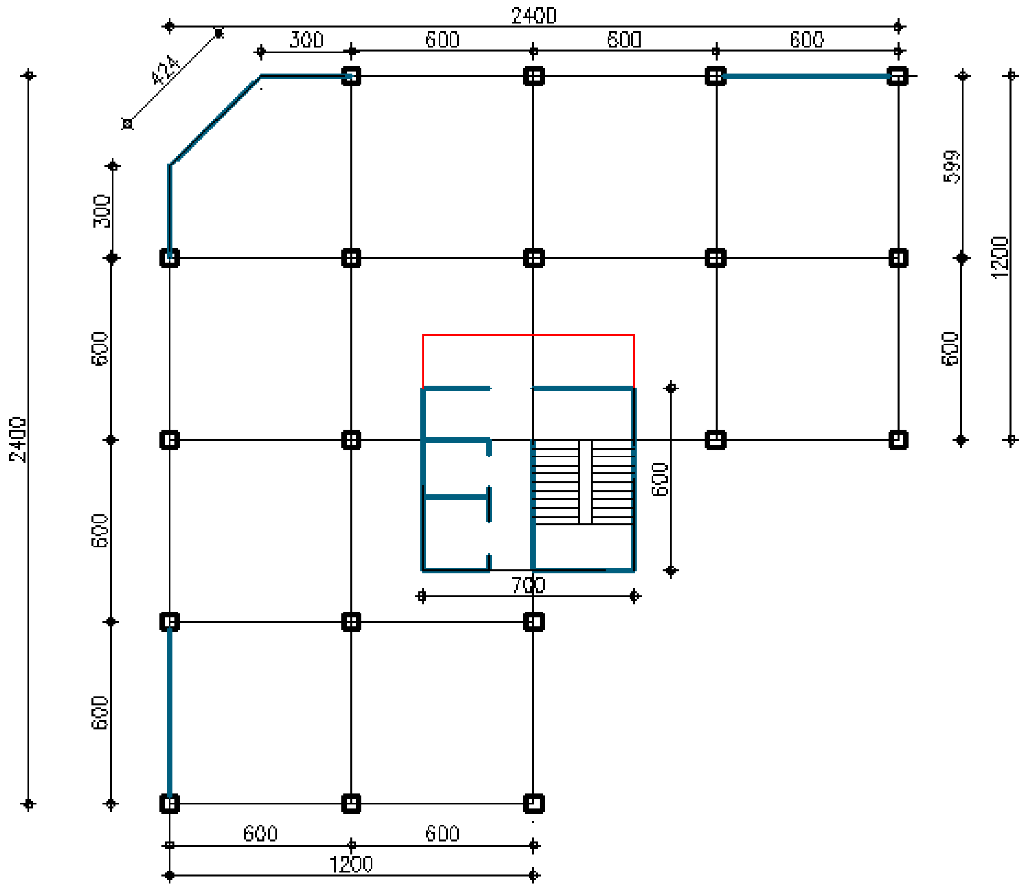


Figure 4.12.7. L-shaped structure with dimensions 24x24 m with columns axis every 6 m with a centre concrete core wall with dimensions 6x7 m with hexagonal perforated panel 10 m in the central front and perforated panel 6 m to the longitudinal side (source: the author)

4.13 Analysis of cases

Referring to the main object of this thesis, to observe the improvement of the structural behavior of referring buildings, THE TWO FIRST CASES of these buildings are structurally modeled in the forms presented by these authors compared to their reconceptualization with the placement of perforated panels in the peripheral parts of these objects, according to the condition in deformation by seismic forces, for approximately considering the same displacements in the upper floors of the respective models compared for these buildings.

After that TWO OTHER CASES of this study are being investigated, moreover the advantages of perforated panels to be used in multi-storey buildings as in the case of shear walls which are very important structural elements, required to the structural plan configuration of this building typology.

In order to obtain a more realistic approach, these buildings are structurally modeled in accordance with the requirements of Erocode 8 for seismic action, for Type 1 of the design spectrum, for the site that have a surface-wave magnitude, Ms larger than 5.5, for type C soil conditions with relevant characteristics, as well as ground acceleration value of ag = 0.3g.

For a wider and clearer perception on the structural behavior of these buildings, referring to Eurocode 8 for study effect, the behavior factors for the above building cases are considered, the value q = 2 for the building that show the first self vibration period in torsion and the value q = 3 for dual system in their normal conditions that appear as primary self vibration period in lateral displacements and then followed by the appearance of torsional effect in lower periods.

For the modal analysis of structural models, there are being considered only the three first consecutive self vibration periods for each of the building being analyzed.

THE FIRST CASE, distinguished as Building Type 1, according to these authors, is composed as Structural Model 1, which represents the case of a 10-storey tower type building with quadratic plan of structural scheme, with dimensions 24x24m, with a central service core with considerable extension in plan with dimensions 8x8m, with reinforced concrete walls of a thickness of 25 cm, to ensure stability from torsion, as well as with a grid with columns every 4 m with section 50x50cm and internal beams 30x40cm and with enlarged perimeter beams with section 30x50cm to increase the lateral rigidity of this building.

Referring to the object of this topic, for evaluation analysis, this object has been re-conceptualized according to Structural Model 2, which consists of reducing the dimensions of the central service core to dimensions 5x8m, placing grid of columns 50x50 cm, at an axial distance of 6m, and maintaining same beams with dimensions 30x50cm, as well as adding perforated structural walls with a width of 3 m and a thickness of 30 cm, placed on perimetric parts of the building, on both sides of its corner columns.

Results and evaluations:

In both of these structural models, the same period of the first self vibration period is maintained equal to the value T = 1.0 sec.

Model 1 shows the first mode of seismic oscillations in torsion of the building with period T = 1.001 sec, the second mode with displacement of the building with period T = 0.908 sec in the Y direction, and the third mode with displacement of the building with period T = 0.847 sec in the X direction.

As it can be seen in this model, the torsion effect is clearly primary due to the low ductility of the structural elements of this model, which to increase the rigidity in torsion, the service core, the columns and beams have significant cross section dimensions in relation to the typical building span. Therefore, referring to Eurocode 8, the behavior factor in this model is approximate taken to the value of q = 2.

As a result, the values of displacements for this model according to the design spectrum Sd (T) are as following; de = 0.088m in the X direction and de = 0.080m in the Y direction. While the total displacement value; ds = 0.089x2 = 0.178m in direction X, and ds = 0.080x2 = 0.16m in direction Y, which are smaller than the maximum value of building displacement, from elastic spectrum Se (T) ds = 0.18m, and within the allowed limitation of displacement on the top of object dst=1/100H=31/100=0.31m.

Model 2 shows the first mode of seismic oscillations in the displacement of the building with periods T = 1.03 sec, in the Y direction. The second mode also appears in lateral movement, with the displacement of the object with periods T = 1.0 sec in the X direction, and in the third mode appears the effect of torsion in the horizontal plane with period T = 0.91 sec.

With the placement of perforated walls with a width of 3m in the perimeter of the building according to this model, it has been achieved that the cross sections of the beams to take appropriate dimensions in relation to the building columns spans, as well as the reduced dimensions of service core. In this way it was achieved the required rigidity of this twisted building, which automatically increase the ductility for the entire building. For the study effect it is been accepted the behavior factor for this model the value of q = 3.

As a result, the values of displacements for this model according to the design spectrum Sd (T) are as following; de = 0.062m in the X direction, and de = 0.066m in the Y direction. While the total displacement value; ds = 0.062x3 = 0.186m in the X direction, and ds = 0.065x3 = 0.195m in direction Y which are smaller than the maximum value of building displacement, from elastic spectrum Se (T) ds = 0.196m, and within allowed limitation of displacement on the top of object dst=1/100H=31/100=0.31m.

THE SECOND CASE, distinguished as Building Type 2, referring to the same authors, is composed to Structural Model 2, which represents the case of a 10-storey building with a rectangular structural scheme in plan with dimensions 16x36m, with a service core located on the side of the building, with considerable extension in plan with dimensions 6x7m, with reinforced concrete walls with a thickness of 25 cm, to ensure the stability of this service core from seismic oscillations, as well as with a grid of columns every 4 m with section 50x50cm and internal beams 30x40cm and 30x50cm placed near the side faces of the building as well as with enlarged perimeter beams with section 30x60cm to increase the lateral rigidity of this building.

Referring to the plan configuration of this building, for evaluation analysis, this building has been re-conceptualized according to Structural Model 2, which consists of an reduced dimensions of the central service core to dimensions 6x4m, also with placing a grid of columns 50x50 cm, at an axial distance of 6m, and maintaining same cross section beams dimensions 30x50 cm, as well as adding perforated structural walls with a width of 6 m with a thickness of 30 cm, placed on the other three sides of this building, respectively two panels on the front side and one panel on each other sides.

Results and evaluations:

In both of these structural models, for the very building configuration with very extension in the plan, for comparison among them, for this building is considered the same self vibration period in the first mode of seismic oscillations in the value around T = 1.2 sec.

Model 1 clearly shows the effects of torsion in the first and second self vibration modes with the respective periods T = 1.191 sec and T = 0.973sec, with rotations in opposite directions, and only in the third mode the lateral displacement of the building with period T = 0.937 sec in the y direction appears.

As can it can be seen in this model, the effect of torsion is even more sensitive in the first two periods of seismic oscillations due to the lower ductility of the structural elements of this model, which require an increase in the cross section dimensions of the beams compared to the first building. This step is important to ensure the balance for the unbalanced rigidity against torsion of service core. Even in this case for unification purposes, it is considered the same behavior factor in the value of q = 2.

As a result, the values of displacements for this model according to the design spectrum Sd (T) are as following; de = 0.093 in the X direction, and de = 0.121 m in the Y direction. While the total displacement value; ds = 0.093x2 = 0.186m in the X direction, and ds = 0.120x2 = 0.240m in direction Y which are smaller than the maximum value of building displacement, from elastic spectrum Se (T) ds = 0.242m, and within allowed limitation of displacement on the top of object dst=1/100H=31/100=0.31m.

Model 2 shows the first mode of seismic oscillations in the lateral displacement in the Y direction of the building with period T = 1.191 sec. The second mode also appears with the lateral displacement in the X direction of the building with period T = 1.15 sec, and in the third mode appears the effect of torsion in the horizontal plane with period T = 0.98sec.

With the placement of perforated walls with a width of 6m in the perimeter on the three side faces of this building, according to this model, it has been achieved that the cross sections of the beams to take appropriate dimensions in relation to the building columns spans, as well as the reduced dimensions of service core. In this way it is achieved the the required rigidity of this twisted building, which automatically increase the ductility for the entire building. For the study effect it is been accepted the behavior factor for this model the value of q = 3.

As a result, the values of displacements for this model according to the design spectrum Sd (T) are as following; de = 0.073 m in the X direction, and de = 0.067 m in the Y direction. While the total displacement value; ds = 0.073x3 = 0.21 m in the X direction, and ds = 0.067x3 = 0.20 m in direction Y which are smaller than the maximum value of building displacement, from elastic spectrum Se (T) ds = 0.22m, and within allowed limitation of displacement on the top of object dst=1/100H=31/100=0.31m.

Conclusions:

So as it can be noticed from the above comparison analysis and structural models composed for these two buildings, it can be stated that, referring to the main object of this research, the suggestion for placing perforated structural walls on the peripheral facades of buildings show significant advantages as following:

-The use of perforated structural walls, in addition to visual effects, creates opportunities for allowing larger application into a design process.

-The use of perforated structural walls, give significant effects on the balancing of buildings against torsion phenomena, contributing at same time to other structural elements, in terms of cross section dimensions reduced of service core, beams, etc. by enabling also the receiving a higher degree of ductility for the entire building.

-The use of perforated structural walls, significantly improve the structural behavior of buildings, with the primary effect of the torsion phenomena. The structural behavior factor (q) is 1.5 times higher in the second models which means that the ductility of the structural elements is 1.5 times higher in the second models.

-The use of perforated structural walls brings qualitative changes in the appearance of seismic oscillation periods, displacing the effect of twisting of these buildings in the third mode of seismic oscillations, thus showing torsion in lower periods of seismic action rather than in the first or second self vibration periods modes where the value are much more higher than in third mode.

-The use of perforated structural walls makes the buildings to behave much more rigid, which is clearly seen in the lowest values of the calculated displacements (de) to the extent of 1.5 times smaller in the second models, which means the seismic energy absorption power, from moment of having the first cracks in the structural elements until the formation of plastic hinges is 1.5 times higher in the second models.

4.14 Cost Efficiency

The cost efficiency in the design of multi-storey buildings with a structural system containing the structural wall with openings is evidenced by running the analysis of the two models as follows.

For taken the effect of volumetric evaluation of the constituent elements of the structural models, the buildings are being composed with different level of the basic self vibration period, which are taken in different distinguished values for both these cases, related to the shape of the object in the plan, regarding the value of torsional imbalance, based on structural solution criteria to balance these objects in the most optimal periods referring to the level of displacement of objects.

Referring to the volumetric analysis of structural elements for the comparison of the two models of each two cases, it results that the use of perforated panels placed on the facades of buildings can reduce the structural volumes by up to 20%, which is more sensitive in more rigid buildings, with the base period of the first vibration mode of lower seismic oscillations.

From the comparison of these two models for THE FIRST CASE, according to the volumetric evaluation of the structural components results in a difference of volume reduced by 22% of structural Model 2 in comparison with structural Model 1.

Structural Model	Specification of structural elements according to structural models	section m^2	quantity pcs	length/width ml	thickness m	height ml	volume m^3
Structural volume analysis of building type 1							
10-storey Tower building with plan dimensions 24 x 24 meters							
	Volumetric indicators of structural elements for 1 storey of the building						
1	**10-storey tower building with center service core and grid of coloumns of 4m**						
	with composition of structural elements as follows:						
	Service core						
	Wall t=25 cm at axis 3, 5		2	6.8	0.25	3	10.2
	Wall t=25 cm at axis 3b		1	6.2	0.25	3	4.65
	Wall t=25 cm at axis 3e		1	2.8	0.25	3	2.1
	Wall t=25 cm at axis 3e, 4b		2	2.8	0.25	3	4.2
	Wall t=25 cm at axis 4c		1	3.4	0.25	3	2.55
	Wall t=25cm at axis C, E		2	6	0.25	3	9
	Wall t=25 cm at axis C1		1	3	0.25	3	2.25
	Wall t=25 cm at axis D1		1	4	0.25	3	3
	Sum						***37.95***
	Coloumns						
	Coloumn 50x50 cm	0.25	40			3	***30***
	Beams						
	Side beams 30x50 cm	0.15	4	24			14.4
	Beams 30x40 cm at axis 2,6, B, F	0.12	4	24			11.52
	Beams 30x40 cm at axis 3,4,5, C, D, E	0.12	12	8			11.52
	Beams 30x30 cm at service core with length 1.0 ml	0.09	6	1			0.54
	Beams 30x30 cm at service core with length 1.5 ml	0.09	4	1.5			0.54
	Beams 30x30 cm at service core with length 1.8 ml	0.09	4	1.8			0.648
	Sum						***39.17***
	Sum 1						**107.12**
2	**10-storey tower building with center service core and grid of coloumns of 6m**						
	with composition of structural elements as follows:						
	Service core						
	Wall t=25 cm at axis 2c, 3c		2	6.8	0.25	3	10.2
	Wall t=25 cm at axis 3		1	2.8	0.25	3	2.1
	Wall t=25 cm at axis B1, C4		2	5	0.25	3	7.5
	Wall t=25 cm at axis B2		1	3	0.25	3	2.25
	Wall t=25 cm at axis C1		1	4	0.25	3	3
	Sum						***25.05***
	Triangle 3B Perforated Structural Walls with length 3m						
	Brace frame element of perforated structural wall 30x50 cm	2.95	8		0.3		7.08
	Boundary element of perforated structural wall 30x50 cm	0.15	8			2.55	3.06
	Sum						***10.14***
	Coloumns						
	Coloumn 50x50 cm	0.25	24			3	***18***
	Beams						
	Side beams 30x45 cm	0.135	4	24			12.96
	Beams 30x50 cm at axis 2, 4, B, D	0.135	4	24			12.96
	Beams 30x50 cm at axis 3, C	0.135	4	5			2.7
	Beams 30x30 cm at axis 3	0.09	2	2			0.36
	Beams 30x30 cm at axis B	0.09	2	3.5			0.63
	Beams 30x30 cm at service core with length 1.0 ml	0.09	5	1			0.45
	Beams 30x30 cm at service core with length 1.8 ml	0.09	2	1.8			0.32
	Sum						***30.38***
	Sum 2						**83.57**
	Difference volume of structural elements of model 2 to 1						**-22%**

Table 4.14.1. Volumetric evaluation of the structural components_Building Type 1 (source: the author)

Also, from the comparison of these two models for THE SECOND CASE, according to the volumetric evaluation of the structural components results in a difference of volume reduced by 19% of structural Model 2 in comparison with structural Model 1.

Structural Volume analysis of building type 2 10-storey Rectangular shape building with plan dimensions 16 x36 m							
Structural Model	Specification of structural elements according to structural models	section m^2	quantity *pcs*	length/width *ml*	thickness *m*	height *ml*	volume m^3
	Volumetric indicators of structural elements for 1 storey of the building						
1	**10-storey tower building with side service core and grid of coloumns of 4m**						
	with composition of structural elements as follows:						
	Service core						
	Wall t=25 cm at axis 4a, 6a		2	6	0.25	3	9
	Wall t=25 cm at axis 5a		1	4	0.25	3	3
	Wall t=25 cm at axis 5b		1	2	0.25	3	1.5
	Wall t=25 cm at axis A, B1		2	5.2	0.25	3	7.8
	Wall t=25 cm at axis A3, B		2	2.4	0.25	3	3.6
	Sum						***24.9***
	Coloumns						
	Coloumn 50x50 cm	0.25	46			3	***34.5***
	Beams						
	Beams 30x60 cm at axis 1, 10	0.18	2	16			5.76
	Beams 30x60 cm at axis A	0.18	2	12			4.32
	Beams 30x60 cm at axis E	0.18	1	36			6.48
	Beams 30x50 cm at axis 2, 9	0.15	2	16			4.8
	Beams 30x50 cm at axis D	0.15	1	36			5.4
	Beams 30x40 cm at axis 3, 4, 7, 8	0.12	4	16			7.68
	Beams 30x40 cm at axis 5, 6	0.12	2	8			1.92
	Beams 30x40 cm at axis B	0.12	2	12			2.88
	Beams 30x30 cm at service core with length 1.0 ml	0.09	2	1			0.18
	Beams 30x30 at service core with length 1.8 ml	0.09	3	1.8			0.486
	Beams 30x30 at service core with length 2.0 ml	0.09	2	2			0.36
	Beams 30x30 at service core with length 2.8 ml	0.09	2	2.8			0.504
	Sum						***40.77***
	Sum 1						**100.17**
2	**10-storey tower building with side service core and grid of coloumns of 6m**						
	with composition of structural elements as follows:						
	Service core						
	Wall t=25 cm at axis 3a, 3d, 4c		3	4	0.25	3	9
	Wall t=25 cm at axis 4a		1	2	0.25	3	1.5
	Wall t=25 cm at axis A		1	5.2	0.25	3	3.9
	Wall t=25 cm at axis B		1	3.1	0.25	3	2.33
	Sum						***16.73***
	Triangle 3B Perforated Structural Walls with length 6m						
	Brace frame element of perforated structural wall	7.05	4		0.3		***8.46***
	Coloumns						
	Coloumn 50x50	0.25	26			3	***19.5***
	Beams						
	Beams 30x50 cm at axis 1, 2, 3, 5, 6, 7	0.15	6	16			14.4
	Beams 30x50 cm at axis 4	0.15	1	12			1.8
	Beams 30x50 cm at axis A, B	0.15	4	12			7.2
	Beams 30x50 cm at axis C, D	0.15	2	36			10.8
	Beams 30x30 cm at axis A, B	0.09	4	2.5			0.9
	Beams 30x30 cm at service core with length 1.0 ml	0.09	3	1			0.27
	Beams 30x30 cm at service core with length 1.8 ml	0.09	1	1.8			0.162
	Beams 30x30 cm at service core with length 2.8 ml	0.09	2	2.8			0.50
	Sum						***36.04***
	Sum 2						**80.72**
	Difference volume of structural elements of model 2 to 1						**-19%**

Table 4.14.2. Volumetric evaluation of the structural components_Building Type 2 (source: the author)

In the appendix with supplementary tables are given the values of these volumes for the models analyzed in these cases with the inclusion of the volumes of slabs for these cases.

Likewise, in similarity with these two cases, two other cases have been identified, the third and fourth case, with even more pronounced building plan configurations symmetry as follows;

THE THIRD CASE, represents the case of a symmetrically shaped object triangular, with an angle of 120 degrees, with considerable extension in the plan, with an axial length of 19.33m from the center in each direction, consisting of three joined blocks with dimensions 15x15m, with axial distances every 5m in both directions, with placement of the n / b of the stairs and elevators in the center of the building. In this case, as a solution with even significant structural effects, perforated panels with a width of 5m have been placed in the three final parts of the facades of this building.

FOURTH CASE, represents the case of an object with L-shaped plan layout with equal ribs of considerable size with dimensions 12x24m, with placement of the b / a nucleus of the stairs and elevators at the end of joining these two blocks, and with axial distances of columns every 6m. In this case, as a special solution in terms of architectural performance of the building, but also as a necessary solution to ensure the torsional stability of this building due to the pronounced asymmetry of this building, a panel reinforced in center of its facade with a width of 10m in the shape of an exaggeration formed by two parts of a perforated panel with a width of 3m lying on the sides of the building and a third part of the panel with a width of 4 m placed in front of the building, and two other panels with a width of 6m at the end of the longitudinal facades of this building.

Comments

For these cases, based on the results and analysis of the first two cases, to balance the effect of the torsion, for the very shape with pronounced symmetry plan configuration, it will be required that structural solutions be modeled with the placement of perforated structural walls in the perimeter facades of these buildings.

The suggestion made by this research topic, for the use of perforated panels it is considered as an optimal solution, which meets the requirements to achieve a required architectural performance that would be used in these cases instead of putting shear wall walls imposed by structural model solutions.

The use of perforated panels in the modeling of these buildings, for the unbalanced forms in plan that they have to the effect of torsion, would bring even more significant improvements in the structural behavior of these buildings, making this case even more imperative in composition of harmonized facades with perforated panels in studied forms suitable for use in the architectural treatment of the facades of this type of buildings.

Nevertheless, despite the cases analysed above in general, the composition of buildings with perforated facades as an architectural element of contemporary architecture, currently has taken a considerable application in the world. Following this trend, the use of perforated panels with architectural performance, as a special element of this architecture, can find a place to adapt as a rational solution in the architectural treatment of the facades of multi-storey buildings.

4.15 Summary

In this chapter was represented the overall methodology of the thesis towards generating several perforated patterns for Structural Walls with openings. As was stated in the previous chapters, the Perforated Structural Walls are suggested to be located in the perimeter of the multi-storey buildings since they play a significate role in the global structural behavior of the whole building. While also obtaining an architectural performance, these perforated structural elements prove to obtain a rational design in terms of a cost efficient design.

A brief summary of the subtopics described in this chapter, are given as below:

The chapter begins with a general describtion of the perforation technique. The technique covers two main elementary process; the adding and the cutting process of the material towards obtain a desiderable perforated pattern at the end.

Then, some practical approximations for modeling structural walls are given in regard of the perforation technique described before. A special attention is paid to several architectural patterns generated using software modelling for Structural Walls. The process covers several steps. It begins with a pattern chosed for Wall modelling, the Triangle 3B configuration. A representative model of Wall in ETABS was used for running a similar structural analysis. The panel was further configurated in Grasshopper and analysed in Karamba3D.

A first check it is done according the element structural stability. The method used for the control is according to the Lateral Load Design Philosophy. So the perforated panel is checked for its top maximum displacement. Those displacements should be satisfied the required displacement given in the design code. So the geometry of the panel is further adjusted to meet the given requirements.

After this process, it is obtained a final panel configuration for Perforated Structural Wall, which is further being detailed in CAD. There are specified all members dimensions and the axes distances between the openings. Then, the panel is designed in the structural analysis software of ETABS. A complete structural analysis is conducted and a real element behavior is conceived.

The chapter ends with some concluding remarks given in the sub topic of Discussion of results.

CHAPTER 5

Discussions | Conclusions | Recommendations

C H A P T E R 5

5 Discussions, Conclusions and Recommendations

5.1 Discussions

In multi-storey building the positions of the structural walls within a building are usually dictated by functional requirements. Often these requirements may not suit structural planning. The purpose of a building and the consequent allocation of floor space may dictate arrangements of walls that can often be readily utilized for lateral force resistance. Building sites, architectural interests, or clients desires may lead, on the other hand, to positions of walls that are undesirable from a structural point of view.

In this context it should be appreciated that to accommodate any kind of wall arrangement, is very difficult to ensure satisfactory overall building response to large earthquakes when wall locations deviate considerably from those dictated by seismic considerations.

In this regard, as an optimal solution, in order to fulfill the above reqirement, in the object of this research has been clearly stated and suggested, the using of perforated structural wall panel as an aesthetic element with a significant architectural performance to be an integral part of facade of multi-storey buildings.

In the following paragraphs, in summary are being emphasizing the main content issues of this research in an iterative way refered to the descriptions that have been analyzed in the previous chapters from chapter one to chapter four.

5.1 Discussion on the aim of the Research_Chapter 1

The research investigates innovative structural system techniques in multi-storey buildings. While enhancing the broad application of exposed perforated structural system in several tall buildings worldwide, the example of a design process of an architectural volume using the technique of perforation is of a great interest because an interaction field can be found which can offer the possibility to explore in the future the preliminary design process for this kind of building typologies by both the architects and engineers.

The technique of perforation is used by several architects, following several consecutive steps towards obtaining the final perforated pattern. The initial idea lies in using a similar pattern through the same technique but in the case of a single element, which is represented as a perforated panel, defined as a structural element of reinforced concrete material.

Inspirational examples of tall buildings contain the perforated element of the structural wall as the total membrane covering the whole building. Some of its main aspects are related to structural performance, to pattern geometry, to design efficiency and cost of the building as well as aspects of its constructive implementation on site.

The main issues faced by designers during the design process of multi-storey buildings are related to the fact on: how to achieve structural rigidity, architectural integration and cost efficiency.

In previous building design practices there are some cases when to ensure the stability of the building, solid elements are required to be placed on the perimeter of the buildings.

On the other hand, these structural elements can affect the architectural aspects of the building including the facade, the interior space and the whole volume / shape of the object.

Addressing the above issues forms the basis for creating a new reinforced concrete panel which can be seen as an architectural element in itself. The element, in addition to the aspect of structural stability, offers the opportunity to be used in the creation of various architectural designs and to be identified simultaneously as a structural and architectural element of the multi-storey building.

Two design perspectives are being emphasized in the first chapet: the architectural and structural design of multi-storey buildings. It was represented the Structural Wall elements design following a clear methodology on generating an innovative perforated pattern. The resulting Structural Wall with different arrangement of openings, called Perforated Structural Wall Panels, characterized by a pattern of openings in different sizes and forms cut into a solid web concrete wall, provide a strong presence as visual screen and at the same time resisting lateral forces in a multi-storey building.

Underlining since in the beginning the typology of the structure analyzed, it is very important for the whole objective and the aim and conclusions proposed in this thesis. The main advantages were then described, representing in this way the rationale of the research using the perforated structural walls in the multi-storey building design.

In addition to this, several gaps were identified in this research considering the fact that was only consider Structural Wall cross section in the construction building plan. However, the dimension variation along the height of the element should be considered carefully. In this regards, it is important that in the future research, improvements should be made towards considering the overall structural wall arrangement of openings.

This process will help to widen the application of this structural element in the building design. Considering some basic aspects in the detailing of the structural wall, there is a possibility in the future, to produce stable panels of structural wall with openings, studied and verified in advance, to be launched in production line and to be applied in the multi-storey buildings design. Moreover, there is a need to offer some trainings or courses for engineers in order to access in the computational software's proposed in above paragraphs, to take all the advantages that these computational systems offer.

5.2 Discussion on Theoretical Framework_Chapter 2

The literature used in this study includes several titles of books by foreign authors in general such as the volumes of authors Charleson, Macdonald, Feng and Allen where in each of them are distinguished some key concepts developed and with simple diagrams is described in general terms, the main line that follows the research thesis. So in the preliminary design, the structure of a high-rise building and the structural element of the concrete wall, can generate its architectural form using computer modeling tools towards the final acquisition of the structural configuration that affects the architectural volume of the building.

The most accurate terminology in the constructive aspect of perforated panels is the structural wall with openings. The main engineering concepts of structural wall are summarized in the book Seismic Design of Reinforced concrete and mansonry buildings by the authors Paulay & Priestly. Some of these concepts are related to strategies in positioning these walls in buildings, their analysis for strength and ductility as well as the cases of the structural wall with and without openings.

The research framework of the thesis defines the background, the hypothesis raised, the research gap and research questions, the methodology followed as well as the acquisition of the final results and conclusions.

In this chapter is being discussed the assessment of perforated structural walls located in the perimeter of a multi-storey building, towards increasing the general knowledge related to these typology of architecture.

Moreover, it addresses the optimization of structural element to fulfil the low cost criteria. By at the same time offering the possibility to enrich the architectural aspect of multi-storey buildings via perforated structural wall panels.

The main purpose is that this vertical structural element to be recognized as architectural and structural values of multi-storey buildings façade and by means of a co-design process elaborate an appropriate design in terms of architectural and structural aspects.

The methods used are through case study, which give a better understanding of perforated shell performance on multi-storey buildings and get inspiration for perforated panels as structural wall elements.

There have been identified eight cases of multi-storey buildings worldwide and for each of them have been presented the main design idea, architectural plans and details regarding the perforated facade. All of these buildings at their façade have exterior concrete skeleton that frees the core from the burden of lateral forces, and at the same time is the primary vertical and lateral structure for the building itself.

To justify the selected structural system that of structural wall panels with openings putted in the perimeter of multi-storey buildings, it is important to analyze in general terms the structural systems in multi-storey buildings but also in high-rise buildings. Based on the studies of eight different authors, a classification of structural systems has been made, dividing these systems into main categories and subcategories, materials used (concrete and steel), advantages and disadvantages of each of them as well as an example building for each category (Table 2.1).

The technique of perforation in materials or structural elements is evidenced in 8 case studies where for each of them are specified data related to the architects or architectural firms that have designed it, the initial design idea, the total height of the building, the number of upper and underground floors and type of facade and texture used.

The chronological transformation of the perforated facades of the buildings dates back to: Traditional perforation patterns as a functional response to climatic conditions, such as "Mashrabiyya", "Takhtabush", etc. in the 12th century. During the 20th century, detached from the past, using perforation in a functional way ("Notre dame du haut", "Unité d'habitation", by Le Corbusier)- The approach between imitating, copying or reshaping traditional architectural perforated models in their form intertwined with technological advancements (e.g. "Arab World Institute" by Jean Nouvel). From the beginning of the 21st century, the new perforation trend emerged in connection with digital technologies representing a contemporary global architectural trend.

5.3 Discussion on Multi-Storey Buildings Configuration_Chapter 3

The infrastructure that has made it possible for structures to develop at height is based on the original idea by Fazlur Khan the American-Bangladeshan structural engineer known as the father of tubular systems. He proposes that traces of structural elements be moved around the perimeter of the building, holding only the solid core in the center.

This solution will increase the moment of total inertia of the whole building, will result in reducing the cross section dimensions of the elements, affecting the total cost of the building and obtaining larger interior spaces. His concept is explained with a simple graphic illustration as in Figure 3.2.1. In this idea follows the proposal of positioning the structural elements of the structural walls that develops the thesis but brought back as perforated panels and not solid (without openings) as they are in their most widespread forms.

The third chapter deals with the structural walls in multi-storey buildings. The term "structural wall", is elaborated in detail in this chapter by focusing more at the engineering aspect. Emphasizing the fact that, in the literature review, as well as the previous chapters, the structural facades are emphasized more as in the eight case studies. Those eight buildings are composed by the structural schemes of shell element that covers their entire facade. Meanwhile, as it was pointed out in the introduction of the thesis, this thesis deals with the typology of a multi-storey building and not of a high-rise or tall building (skyscrapers).

Consequently, the case studies, some of them represent high-rise buildings, are in the framework of examples and not analytical, though simply inspiring for evidence on the facades of the objects of structural elements. On the other hand, a representative element of multi-storey buildings is the structural wall element. The main aim as stated in the first chapter is generating innovative patterns for Structural Wall element with openings.

The advantages of positioning the structural elements in the facades have been described in the previous chapters, as well as in this chapter this argument is emphasized, qualifying it to contribute in a general improvement of the structural behaviour of the multi-storey building.

After elaborating the above arguments, this chapter clearly highlights the role of the structural wall element as well as the strategies in its positioning in multi-storey buildings. In addition to this, some problems are identified that reflected the buildings of this typology under the effect of past seismic events in different regions. Their analysis is of interest to the issue, as it contributes to the development of a general perception related to the role of different structural systems in a building.

To justify the selected structural system that of structural wall panels with perimeter openings in multi-storey buildings, which will be addressed in the next chapter, it is important to analyse in general the structural systems in multi-storey buildings but also in high-rise buildings. Based on the studies of five authors, a classification of structural systems has been made, dividing these systems into main categories and subcategories, materials used (concrete and steel), advantages and disadvantages of each of them as well as an example building for each category. It is obvious that several of the case studies are evidenced in this table.

In the table described above, where the main structural schemes are categorized, both frame and shell systems are clearly identified. Since the focus of the study is on systems with shell elements and not frames, for the last one mention, are identified some simple diagrams of several tall buildings worldwide. With arrows and blue circles, there were marked some very interesting aspects in their structural system, which makes some of them show similarities and some of these buildings show differences.

What is noticed in all cases is the importance of the one-dimensional structural element as well as the identification of the primary elements, which carry the main loads and the secondary elements. In simplified diagrams, these elements are evidenced by colour. With darker grey, are represented the primary element and with lighter grey, are identified the secondary.

The reinforcement of the structural element of the wall is not part of the focus of this topic; however, some general orientations regarding the importance of a proper reinforcing technique are given, citing a very interesting study that summarizes these concepts.

Regarding the engineering concept of the structural element of the wall, a sub-topic is also presented that addresses two very important aspects, that of strength and stiffness. Often, even in discussions between engineers these concepts come intertwined with each other, using one word instead of the other as a kind of synonym.

This aspect requires proper attention, because as similar as these two words may seem, they are so specifically different. To be more rigorous in their use, it seems of great interest to elaborate these concepts in the sub topic entitled "*Relationship between strength and stiffness of concrete Structural Walls*".

5.4 Discussion on Structural Model of Perforated Structural Wall Panel_Chapter 4

Considering the overall methodology of the thesis towards generating several perforated patterns for Structural Walls with openings and as was stated in the previous chapters, the Perforated Structural Walls are being suggested to be located in the perimeter of the multi-storey buildings. Puuting these elements in the peripheral parts of the building play a fundamental role in the global structural behavior of the whole building. While also obtaining an architectural performance, these perforated structural elements prove to obtain a rational design in terms of a cost efficient design.

An issue of great interest is the topic related to the perforation technique. The chapter begins with a general describtion of the perforation technique. The technique covers two main elementary process; the adding and the cutting process of the material towards obtain a desiderable perforated pattern at the end.

Then, some practical approximations for modeling structural walls are given in regard of the perforation technique described before. A special attention is paid to several architectural patterns generated using software modelling for Structural Walls. The process covers several steps. It begins with a pattern chosed for Wall modelling, the Triangle 3B configuration. A representative model of Wall in ETABS was used for running a similar structural analysis. The panel was further configurated in Grasshopper and analysed in Karamba3D.

A first check it is done according the element structural stability. The method used for the control is according to the Lateral Load Design Philosophy. So the perforated panel is checked for its top maximum displacement. Those displacements should be satisfied the required displacement given in the design code. So the geometry of the panel is further adjusted to meet the given requirements.

After this process, it is obtained a final panel configuration for Perforated Structural Wall, which is further being detailed in CAD. There are specified all members dimensions and the axes distances between the openings. Then, the panel is designed in the structural analysis software of ETABS. A complete structural analysis is conducted and a real element behavior is conceived.

The geometry of panel selection varies between possible combinations of simple / basic plane figures and the regularity of their openings, from openings of the same size to openings of different dimensions and from regular openings to irregular openings.

The thesis methodology relies on a visual method for generating perforated models of a wall panel. The instrument used is that of architectural and engineering software which describes a visual and interactive method on performance, thus enabling the preferences of the designer and at the same time ensuring the control of the structural stability of the built model. Presented in a diagram, the process will be divided into 3 main parts, defining first the geometry model, then the content process and finally the Finite Element Analysis through ETABS engineering software, thus influencing the optimization and design efficiency of element in particular but also the whole building in general.

The element selected in the analysis is that of a structural element, part of the dual system, structural wall for a 10 storey high structure. The frame elements are neglected. The wall is considered and modeled as a shell element, reinforced concrete with a thickness of 30cm.

The analysis of this element is of interest, changing the perforation rate, from 0.1 to 0.5 is considered modeling with solid elements, as a shell element and from 0.6 to 0.9 is considered modeling with contracting elements, according to the principle tension and compression. The results are summarized in a table.

The procedure followed, formulas, calculation bases and performed controls are in accordance with the selected Lateral Design method for the selected panel. This is one of the most important steps of the static control of the panel, ie its structural stability. By fulfilling this condition, one can further advance by selecting the way the panel is perforated and its final design based on the composition of the designers.

The iterative structural analysis towards obtaining the resulting perforated pattern for Structural Wall is represented by several steps using different software's. It first begins with a pattern chosen for Wall modelling, the Triangle 3B configuration. A representative model of Wall in Etabs was used for running a similar structural analysis. The panel was further configured in Grasshopper and analyzed in Karamba3D.

A first check it is done according the element structural stability. The method used for the control is according to the Lateral Load Design Philosophy. So the perforated panel is checked for its top maximum displacement. Those displacements should be satisfied the required displacement given in the design code. So the geometry of the panel is further adjusted to meet the given requirements.

After this process, it is obtained a final panel configuration for Perforated Structural Wall, which is further being detailed in CAD. There are specified all members dimensions and the axes distances between the openings. Then, the panel is designed in the structural analysis software of ETABS. A complete structural analysis is conducted and a real element behavior is conceived.

Considering the effects of using reinforced concrete panels with special architectural performance in terms of significant structural improvements in multi-storey buildings with considerable extension in plan. As regard, for concretization there are presented various cases of using these panels located in the peripheral parts of buildings with a width of 3, 4, 5 and 6 meters but also wider in special cases. Here are presented the case of tower type building, the rectangular configuration and the irregular plan shapes.

The research propose a novel configuration for exterior walls called "Triangle 3B Panel", and explored its geometry and structural seismic performance, by treating the lateral load-resisting system as "Frame Braced Wall".

5.4.1 Discussion on the strategy of structural wall positioning

Thus, the above concept described from the authores, is well explaned for the adavantages towards the general improvement of structural behaviour of multi-storey buildings containing perimetric structural walls in their facades.

From one hand, in structural plan configuration of multi-storey buildings, the elevator shafts and stair wells lend themselves to the formation of a reinforced concrete core. Traditionally, these have been used to provide the major component of lateral force resistance in multi-storey office buildings.

On the other hand, dhe major structural considerations for individual structural walls would be aspects of symmetry in stiffness, torsional stability, and available overturning capacity of the foundations.

In choosing suitable locations for lateral-force-resisting structural walls, three additional aspects were recommended from the authors Paulay & Priestly:

- For the best torsional resistance, as many of the walls as possible should be located at the periphery of the building. The walls on each side may be individual cantilevers.

- The more gravity load can be routed to the foundations via a structural wall, the less will be the demand for flexural reinforcement in that wall and the more readily can foundations be provided to absorb the overturning moments generated in that wall.

- In multi-storey buildings situated in high-seismic-risk areas, a concentration of the total lateral force resistance in only one or two structural walls is likely to introduce very large forces to the foundation structure, so that special enlarged foundations may be required.

The strategy of planning for individual structural walls is, that inelastic deformations be distributed reasonably uniformly over the whole plan of the building rather than being allowed to concentrate in only a few walls.

For more this seems to had caused the reduce of the cost of the building, since the structural plan of the multi-storey building is composed by fewer structural elements throughout the building plan, and at the same time by lowering also the structural member sizes of other structural elements such as colums and beams.

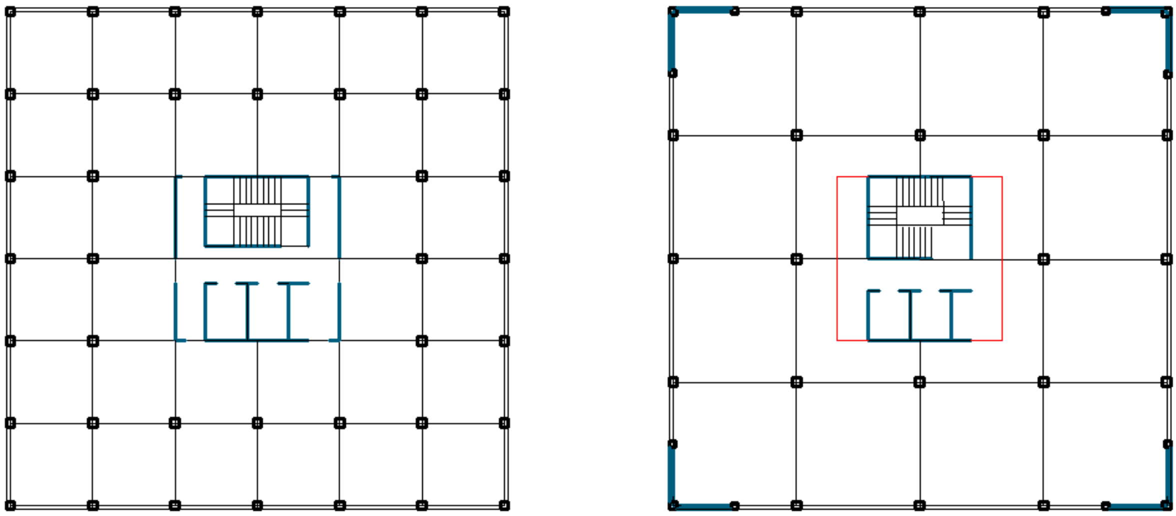


Figure 5.4.1. Quadratic building configuration with plan dimension 24x24m: left – structural plan with a dense grid of columns and with enlarged service core in the center; right – structural plan with eight perimetric perforated structural walls 3m wide with an enclosed service core in center and with a grid of enlarged columns (source: the author)

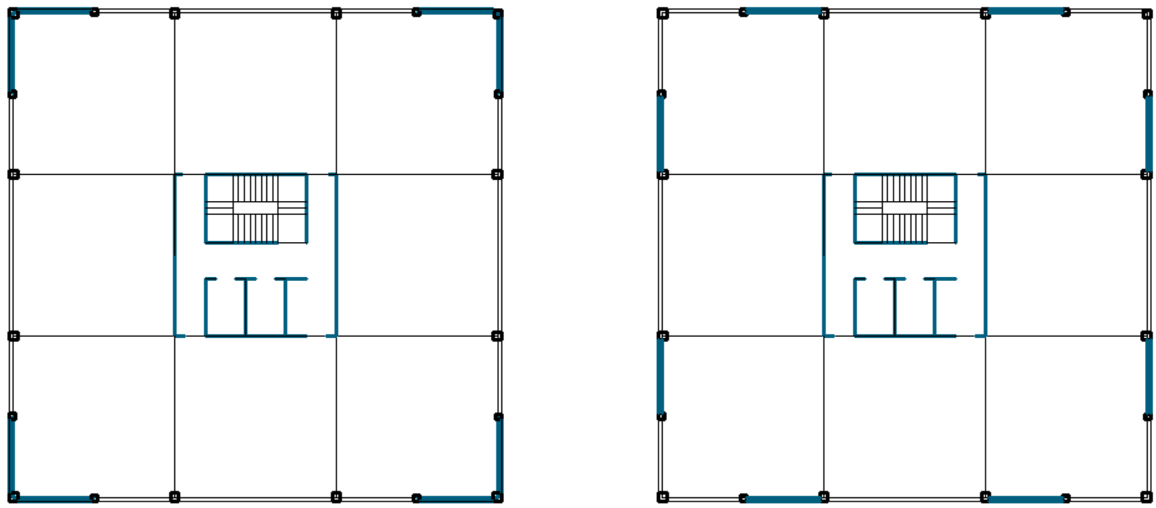


Figure 5.4.2. Alternative of quadratic building configuration with plan dimension 24x24m: left – structural plan with eight perimetric perforated structural walls 4m wide placed in the corner of the buildings maintaining the same service core in the center and with a grid of much more enlarged coloumns; right – structural plan with eight perimetric perforated structural walls 4m wide placed in the different part of the building perimeter (source: the author)

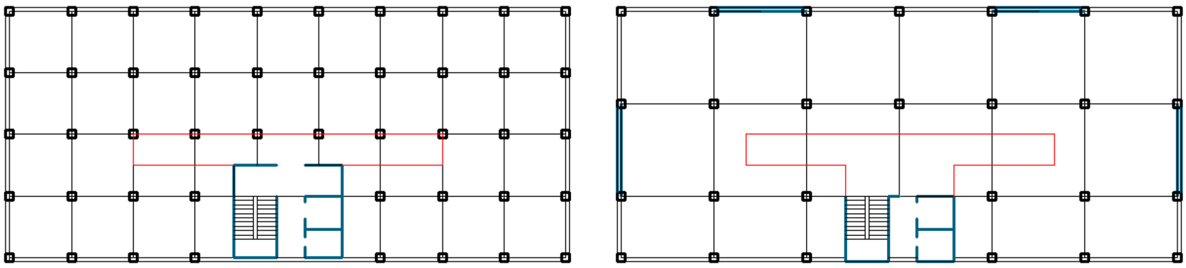


Figure 5.4.3. Rectangular building configuration with plan dimension 16x36m: left – structural plan with a grid of encloused coloumns and with an enlarged service core placed in excentricity of the structural plan configuration; right – structural plan with four perimetric perforated structural walls 6m wide with an encloused service core and with a grid of enlarged coloumns (source: the author)

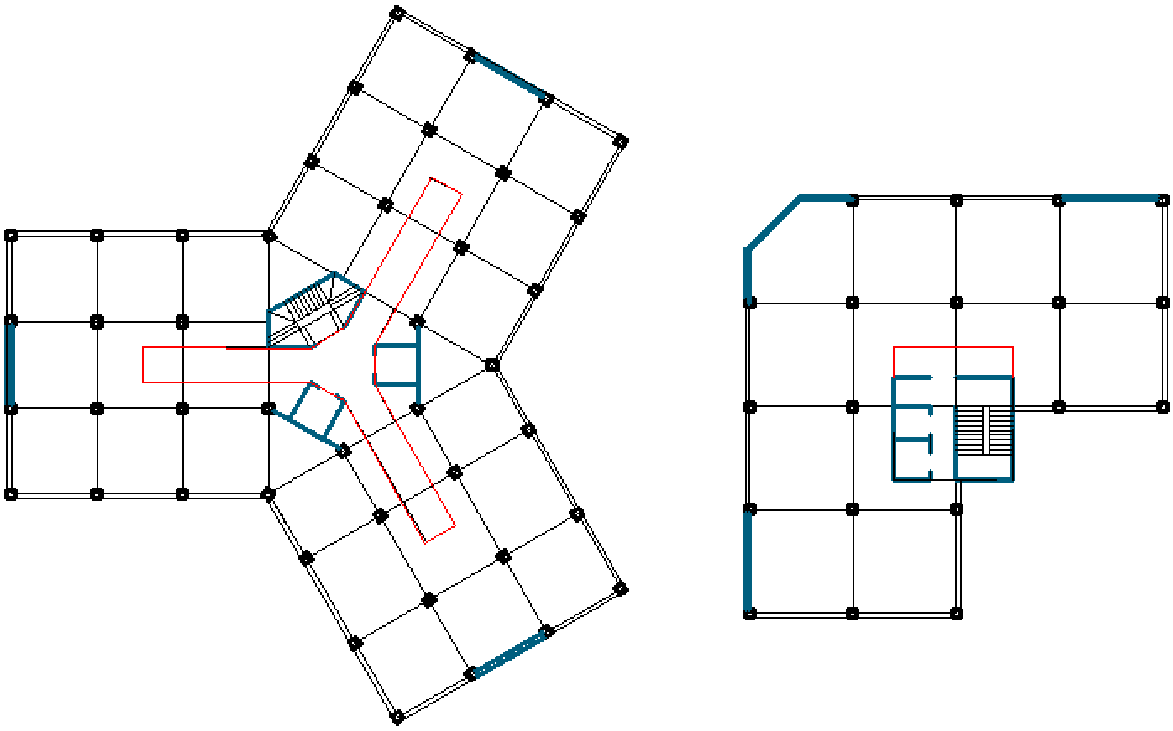


Figure 5.4.4. Irregural plan building configurations with elongation in plan: left – three angle structure with plan dimensions 15x15 m with 3 perforated structural wall panels 5m wide located at the front facades and with an enlarged service core placed in the center of the building; right – one angle structure with plan dimensions 12x24 m with perforated structural wall panels 10(3+ 4+3)m width at the center façade and 2 other perforated structural wall panels 6m wide at the side facades of the building and with an enlarged service core placed in the center of the building (source: the author)

5.4.1 Discussion on the perforation technique of the pattern

As it was stated in the paragraph 3.4.5, several cases of wall openings are being represented satisfying the request to accommodate the openings for doors and windows in the buildings together with the relevant recommendations.

Thus, for example when the openings are very close in the horizontal and vertical direction, it is difficult to make such connections sufficiently ductile and to avoid early damage in earthquakes, and hence it is preferable to avoid this arrangement.

A larger space between the staggered openings would, however, allow an effective diagonal compression and tension field to develop after the formation of diagonal cracks. With a suitably reinforced, using diagonal reinforcement, distress of regions between openings due to shear can be prevented.

In such a way, it has been noticed that in squat walls with openings, where tension and compresion forces are treated as "strut and tie" models, in which the strut elements represent the compression forces of concrete and the tie elements representing the tension forces of steel material.

Based on these techniques, in the plug-ins of grasshopper and karamba, different forms of openings are treated aesthetically by guaranteeing in themselves the stability of the perforated panels.

From these forms of openings, in our case the triangle 3B model is selected, analyzed in detail through an analytical process, first for the stability of the perforated panel and then its adaptation to a similar model in stages where the results are reconciled.

Then, after the complete configuration has been made with the necessary elements in the autocad, the structural model has been adapted to be treated as an integral part of the structural elements in the composition of the structural models of the objects where they are adapted.

Below are being reflected the stages of structural modeling of this selected panel, 6m wide and 30cm thick, designed to be used on the perimeter facade of a 10-storey building.

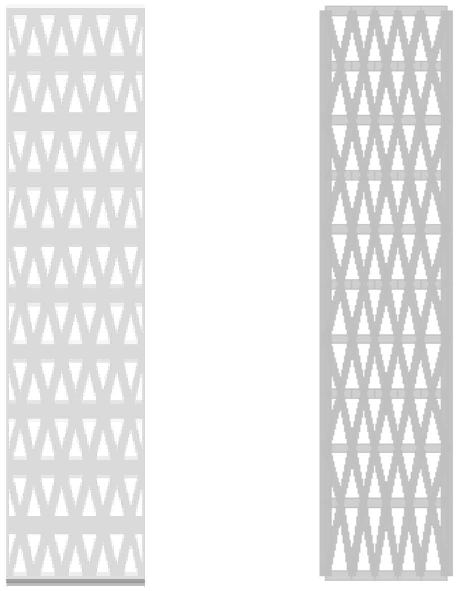


Figure 5.4.5. Panel configuration: left – perforated panel from Karamba 3D plugin; right – structural model of the panel adapted in Etabs software (source: the author)

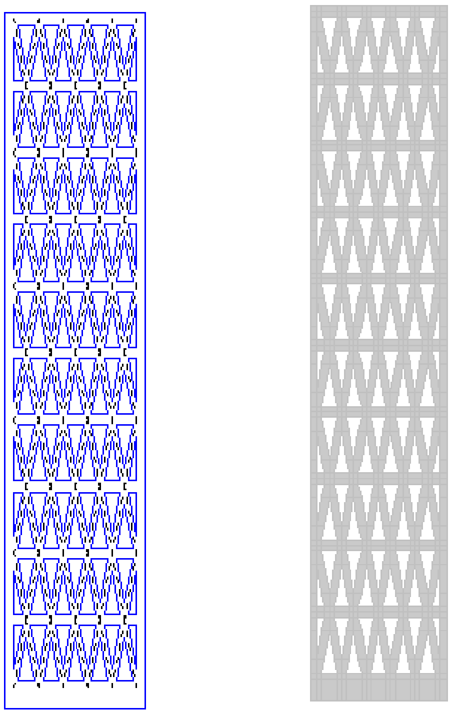


Figure 5.4.6. Panel configuration: left – structural detailing of the panel in Cad software; right – the adapted model as a structural element to building modeling (source: the author)

5.4.2 Structural detailing and verification of perforated panels concrete members

The generation of one or more geometrically perforated panels and then controlled also structurally, is valid until the stage of a modal analysis based on the theory of displacements at the top of the perforated panel fulfilling the condition of limiting this displacement according to the design code of each country.

Of course it is worth noting the fact that the structural analysis of the perforated panel (perforated structural wall) does not end here. The perforated panel putted in the desirable plan location determined by the designer of the building, becomes part of the complete analysis of the building as a whole.

After fulfilling the initial conditions and controls over the periods (oscillation modes), their values, the top displacements of the building, the inter-storey drifts, or internal forces in the most critical areas of the element, etc., a very important process of structural analysis of the structural wall element (perforated panel) is its structural detail and reinforcement.

Thus, in order to generalize the cases of analysis of this process, the shear forces control, performed in the case of Shear Wall (ie a solid wall without opening) is brought to attention, although the study case analyzed Triangle 3B panel does not reveal the shear forces but the possibility is not ruled out that any of the other eight cases of panel configurations may exhibit this force. Also very important is the compression control of concrete for those perforated panel's element or areas that work in compression.

Regarding the study case treated in this thesis, that of a structural wall with openings, it has been emphasized in the previous chapters treated above that the main scheme of work of this structural element is that with elements in compression and tension.

Regarding the panel's elements that work in tension, the stress there is withstood by the reinforcement, while in the panel's areas under compression, it is withstood by the concrete, its ability to compress. In vertical structural elements such as columns and structural walls, the compression control of the element is a very important process. In the case of perforated panels, first the elements (brace frame wall) of the wall that work in compression are being identified and then the control is performed in accordance with the relevant formulas defined by the design code.

5.4.3 Optimal dimension of perforated structural wall

An issue that is of interest in the discussion of this thesis is the determination of the dimensions of the structural wall element with openings in the general configuration of the building plan. In fact, this issue is not only important when structurally dealing with reinforced walls (perforated panels) but also in the case of ordinary solid walls without openings that are commonly used in the design of multi-storey buildings.

In this context, the impact caused by a proper dimensioning of this element is directly related to the cost-effectiveness of the building. Structural requirements for balancing the center of mass with the center of rigidity can also be achieved by using massive elements with significant dimensions but this would not be efficient in terms of financial cost of the building but also affects the organization of the interior of the building or the treatment of its façade.

So the solution tends to go towards finding a rational alternative to the structural configuration in the plan of a multi-storey building. In the treatments of a volumetric object in the previous chapter of the thesis, such an issue has been taken into account.

In the structural schemes with columns spaces (ie placement of the building axes) every six meters, initially it was perceived also the positioning of eight perforated perimeter walls in the corners of the building (from two angular walls in each corner) to ensure the restrain of the whole building.

Visually but also with the help of some quick structural controls, these wall dimensions were somewhat large. Solutions are presented in two main directions:

- these dimensions can be maintained but the rigid core of the building (the concrete core wall) can be significantly reduced (perhaps it is possible to completely remove the reinforced concrete walls there, and replace them with non-retaining walls, for example columns and brick walls),
- to reduce the dimensions of the perimeter walls while also maintaining the rigid core of the building.

Each of the variants should be discussed between the building designers, architects and engineers to make the respective choice. In this thesis, the solution is selected according to the second variant. So the dimensions of the perimeter walls were changed and from six meters were kept four meters, maintaining at the same time the rigid core of the building.

5.4.4 Perforated Structural walls location impacting the foundation of the building

An important issue for discussion is also the issue related to the positioning of the walls in the building plan. The main reason for placing the walls in certain areas in a plan of a building is related to the fulfillment of the condition of as close as possible to maintain the two centers; center of mass and center of rigidity.

Of course, after fulfilling this condition and achieving the required solution, it is important to keep in mind the building foundation control in order to check the main stresses, the aspect of differentiation of deformations and proper reinforce detailing of this element as a whole.

To understand the importance of considering this issue, it is assumed for a moment a contrary argument. If for a moment after detailing the total structural plan of a multi-storey building and assigning a foundation with dimensions as specified in the design code, and the above additional verifications for this foundation are not being performed, then the construction of this element would be done only on the basis of the strain scheme of the foundation plate.

However, the positioning of the structural walls only in some areas of building plan, could result in having areas with significant stresses compared to other areas. Despite the construction of this case (ie with additional reinforcing steel bars in this area to withstand stresses) again this solution is not preferred, areas with higher stresses compared to other areas, affect the occurrence of differentiated deformations, which become even more sensitive in regions with considerable or high seismic activity. It is reccomended to dirstribute the position of the panles in a uniform way related to the acting weights in the building.

5.4.5 Stable perforated panel configuration

This study deals with the panel perforated with Triangle 3B geometry and with structural configuration Brace Frame Wall. Depending on the more detailed structural analyzes, this panel with the geometric configuration generated by itself is stable. So in total from the generation of nine perforated panels, only one of them has undergone a complete structural analysis by changing and adapting and geometrically the constituent elements of the panel.

Thus, the vertical side elements of the panel have been resized by making them a little thicker, given that in structural schemes these side elements are the ones that withstand the greatest stresses of the element by positioning the steel reinforcement in them and creating therefore the so-called boundary elements. Visually, and for the other eight panel configurations, there is a need to increase or decrease the components of the panel, (member sizes) areas without openings, but this process has not been developed in this study and therefore constitutes a limitation of this study.

However, it is worth noting that the resizing of the elements within the panel runs parallel the working scheme of the element itself. Understanding this scheme and the way of development of internal forces within the panel, elaborates the logic of the dimensions of the elements inside the panel, so it must be ensured the required member size and therefore further are being specified the elements openings (panel voids).

5.5 Towards a new technique to obtain an architecture performance using perforated Structural Walls

Considering the evolution of co-design practices the parametric models are very significative in terms of generating quick and several design compositions and at the same time structurally tested. Computational designers likely develop various parametric models during a single design process.

Although the thesis does not intend to present the parametric design tools Grasshopper / Karamba to the design processes, rather, they are a useful tool in their sporadic use at relevant moments of design processes to inform the next iterations of co-evolutionary design cycles. This intended use reinforces the importance of finding good design patterns quickly over finding the optimal one and the importance of performance-informed design in this case the maximum displacement target of the panel.

5.6 Summaries and Conclusions

This research present a rational way to improve the structural behaviour of multi-storey reinforced concrete buildings by suggesting the use of Perforated Structural Walls, with a special aesthetic performance, located near or along the periphery plan of a building, as an architectural and structural element, conceived to be treated in the composition of the facades of those buildings.

The thesis elaborates on some geometric shapes of the perforated panel bringing a constant confrontation between the aesthetics and the structural performance of the multi-storey buildings. During the interpretation of these shapes, a structural optimization of the pattern is naturally achieved, especially considering some minimum and maximum limits of the size of the panel openings.

To express it in another way, and place in one plan the geometry of the panel and in another plan the structural performance, these plans are parallel to each other and do not meet. The created code offers the possibility to geometrize any kind of shape, so the generation of perforated patterns for the structural wall with openings, suitable to improve the structural behavior of multi-storey buildings when positioned on their perimeter.

A very significative example it is presented in this thesis, the Triangle 3B panel configuration which in structural terms it is specified as the “Frame Braced Wall”. It represent a Perforated Structural Wall element located in the periphery of a multi-storey building plan which helps in achieving a better structural behavior while resulting also in a cost effiency co-design process.

To answer the research question made at the beginning of the thesis, the most important advantages of using perforated structural walls are listed as below:

1. Generating innovative patterns of openings can be seen as a benefit in the architecture volume of multi-storey buildings. This is achieved through a co-design process, where architects use contemporary design software’s in order to obtain the desiderable forms of openings and structural engineers adapt them structurally to engineering programs that are suited to these softwares. It should be underlined also the fact that the Triangle 3B pattern used in this study, is selected from several configurations given by the software and this pattern was detailed further to be finally suggested to be used as a Perforated Structural Wall in the multi-storey building design since it provides the architectural performance and also has the required structural rigidity while ensuring a rational design.

2. The perimetric proposed panels in this thesis, are suitable for multi-storey buildings, which have considerable extension in the plan, towards improving their global structural behavior, as in the example analysed in this thesis for a 10-storey building high.

3. These panels with the help of advanced software algorithms and programs such as grasshopper can be configured with different geometries of perforation inspired by designers.

4. The panel contributes rationally to the structural behaviour of buildings in reducing the financial costs of the construction project as a whole.

5. The perforated panel can be considered as an architectural element designed to be treated in harmony with the composition of the rest of the building facades.

6. It is a competitive element in relation to the lateral stiffness of the object compared to the grid of beams and columns of the frame system.

7. It serves as a primary vertical structural element with architectural performance in absorbing horizontal seismic loads of the building.

8. It has a more advanced performance in flexural yielding and ductility compared to the solid concrete wall without openings, after the formation of diagonal cracks, which allow the effective development of areas in compression and tension of braced elements, as well as, thanks to significant openings avoiding the action of shear forces affecting the solid wall.

9. It contributes in the approximation of the centres of mass and rigidity of buildings, because of their positioning in the perimetric areas of the building, ensuring also the confinement of the overall structural plan of the building.

5.7 Recommendations

In contrast to most works in the emerging field of performance informed design tools this model code provides a software implementation and also by putting this implementation, indirectly, which do offer it with prospective users.

The thesis tests the framing of Triangle 3B perforated panel as promoting not only automation but also understanding with a practical software implementation and an empirical user test. In addition to understanding, the user test identifies refinement (i.e., indicating potential directions for improvement) and, more importantly, selection (i.e., allowing choice) as requirements for better integrating the perforated structural element into architectural design processes. The user test also identifies performance informed strategies that provide a starting point for further empirical research into computational design processes.

Although the thesis consists in early design practices can contribute also to pedagogy as such by raising questions on how to integrate architectural design and performance-informed into both architectural and structural curricula.

Architectural students face challenges like the ones faced by practitioners. To apply architectural design and performance-informed modelling, students need to also master parametric design and some performance simulations. Integrating such advanced computational methods into design processes can be challenging especially for learning designers.

Nevertheless, it is important to not understand architectural design and computational methods as separate, or even contradictory. Rather, a proper understanding of the strengths and limitations of such methods comes from applying them to design projects. To improve the integration of compactional methods such as architectural design into professional design processes, it is important to teach such methods early, and in combination with architectural design.

5.8 Final Word

Using a methodology of co-design process, that includes :

- *Conceptual design of perforated pattern*
- *Strategy in the location of structural walls*
- *Evaluation criteria for structural wall with openings;*

it is possible to achieve an architectural performance of perforated structural wall panels as an integral element of facade, to obtain a rational way for a better structural behavior in multi-story buildings.

5.9 Future Research

The results from the model code, increase the confidence that, in the future, visual and interactive features tend to increasingly be common in architectural and structural desing tools and can offer the possibility to help their wider adoption. The feature requests and design strategies resulting from the model code generated, provide promising starting points for further development and testing of such features.

In this regard, the most interesting direction for future research is the further investigation of design practices in performance-informed based analysis. Such an investigation could take the performance-informed strategies as a starting point and empirically examine the concepts of selection, refinement, and understanding with additional model code or case studies of the further developed software. Such an investigation might result in a deeper understanding of computational design processes.

A very interesting aspect to be explored in the future is the topic on environmental sustainability. One of the directions of the research could be possibly be the analysis on the saving of materials. These can be attained both from a peripheric structural core, which is more efficient than a central core to the saving of material allowed by the holes created.

A further topic of discussion could be highlighting the role that perforated structural walls can have in terms of design efficiency. It could possibly explicate an in-depth analysis of how perforated structural walls can contribute to improving many aspects of the project, including sustainability, which is actually considered a key aspect nowadays in whatever analysis involving the built environment. In this regard, a simplified life cycle assessment analysis of the 10-story case study considered could greatly enhance the significance of the thesis.

However, this topic was not emphasized throughout the thesis since generally there is no direct impact on this topic as the perforated panel does not cover the whole building as in the case of high-rise buildings but is located in several parts of the building facade as separate panels in multi-storey buildings. Even in extreme cases with very high or very cold outside temperatures, there is the possibility of modifying the pattern through panel openings or closures directly in the software of Rhino Grasshopper and then adopted in the calculation software of ETABS.

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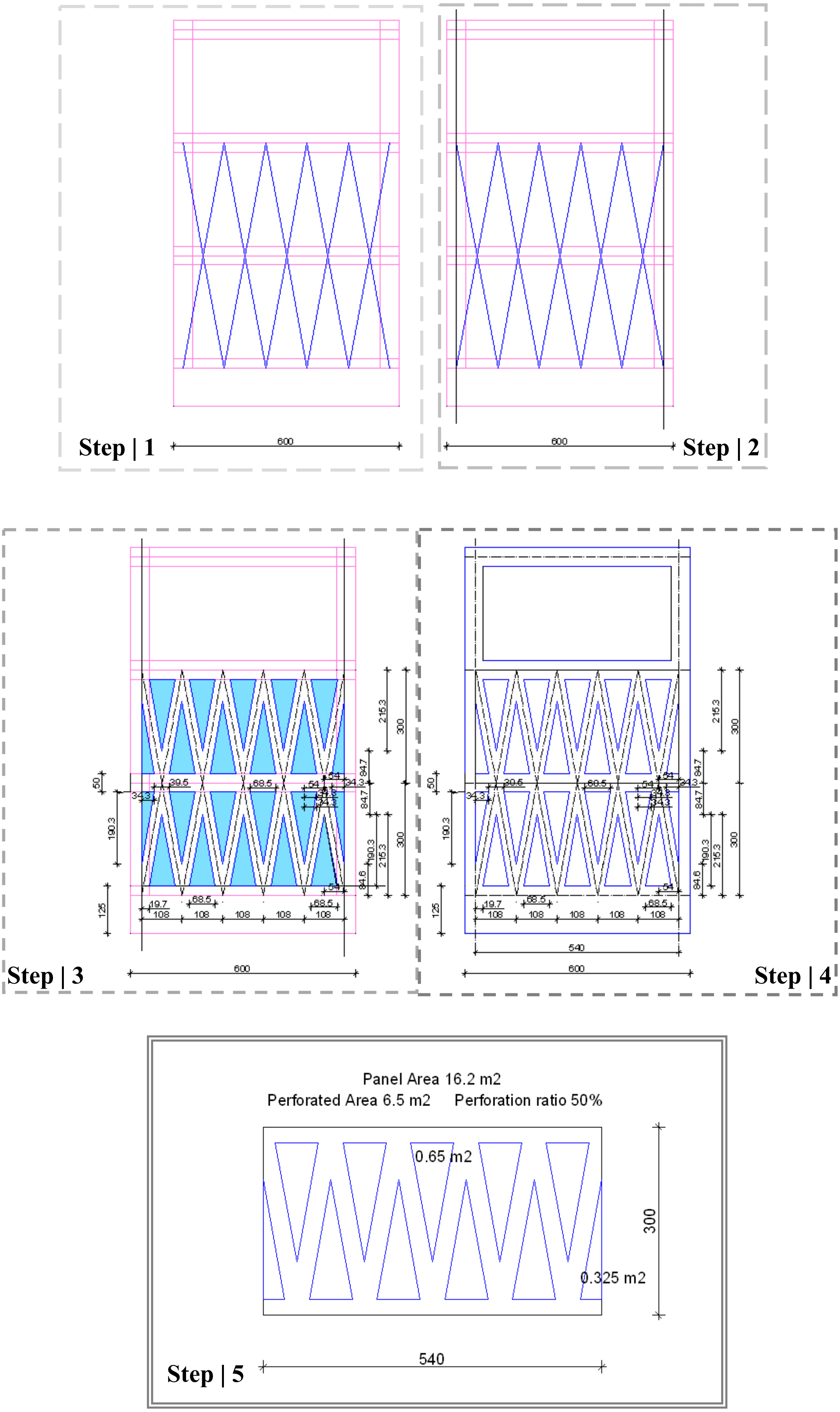
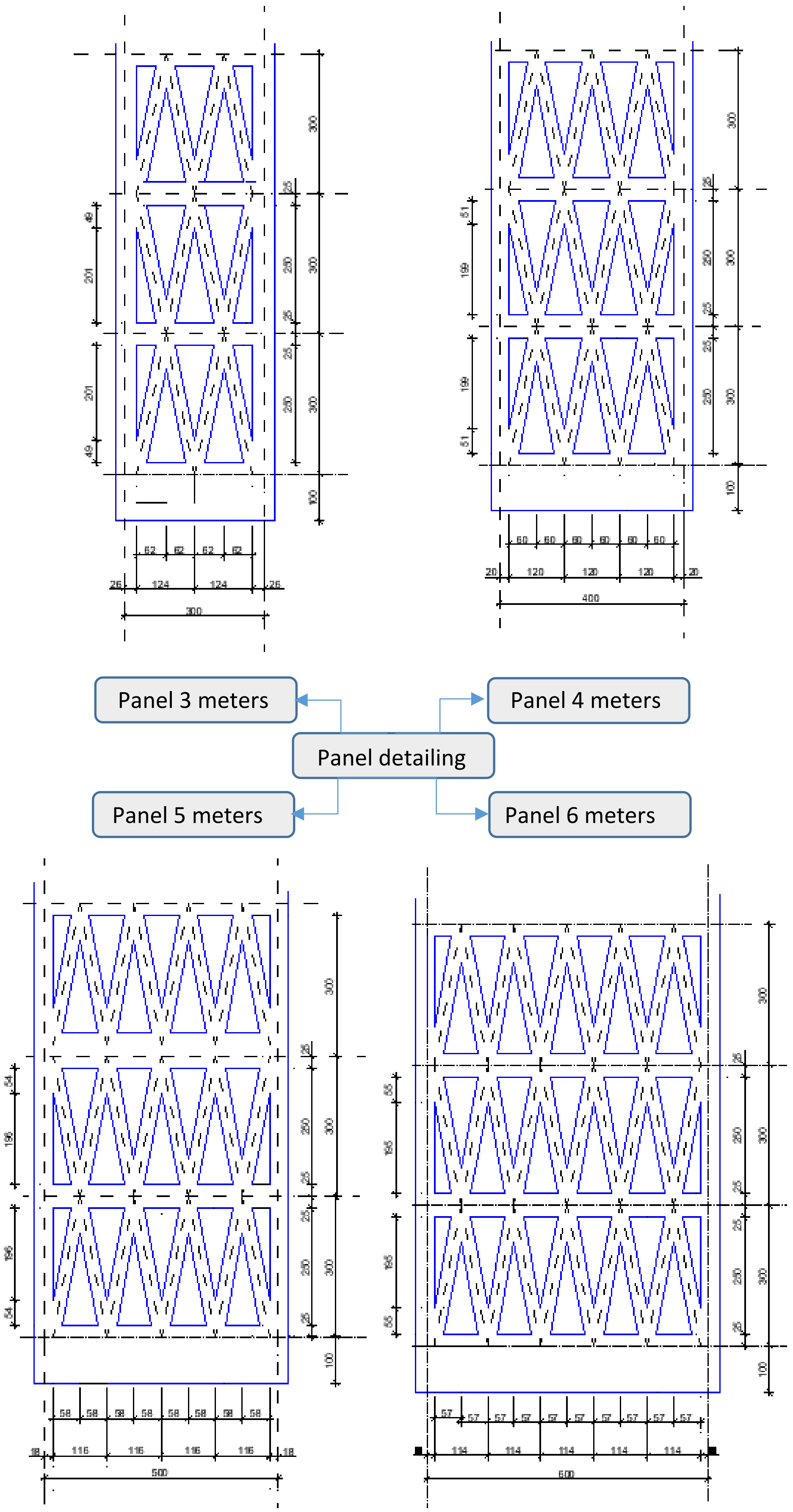
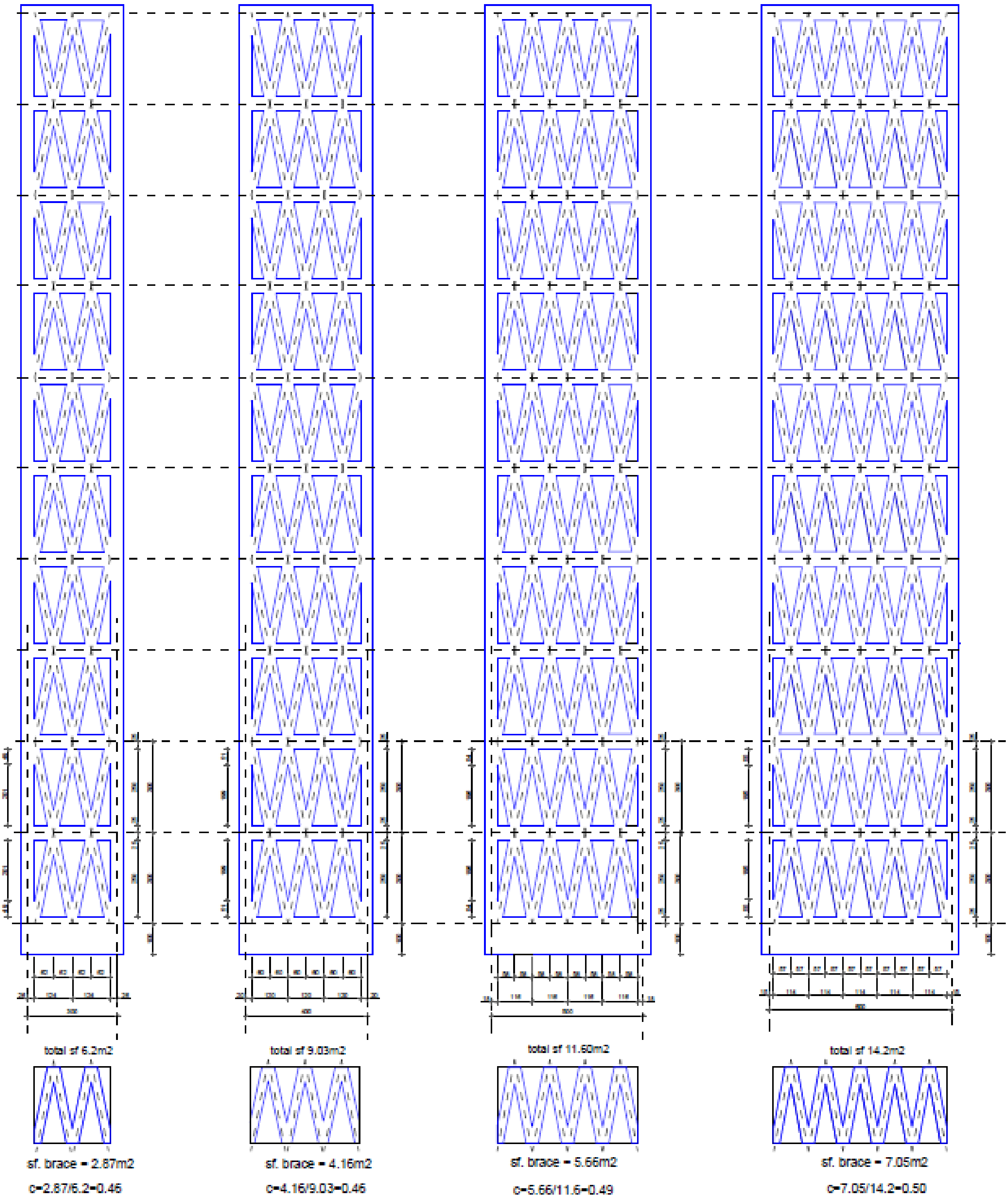
7 Appendix A: The results of the structural analysis for the Perforated Structural Wall – Triangle 3B Panel configuration

7.1 Panel Configuration and CAD detailing process of Triangle 3B Panel for Perforated Structural Wall



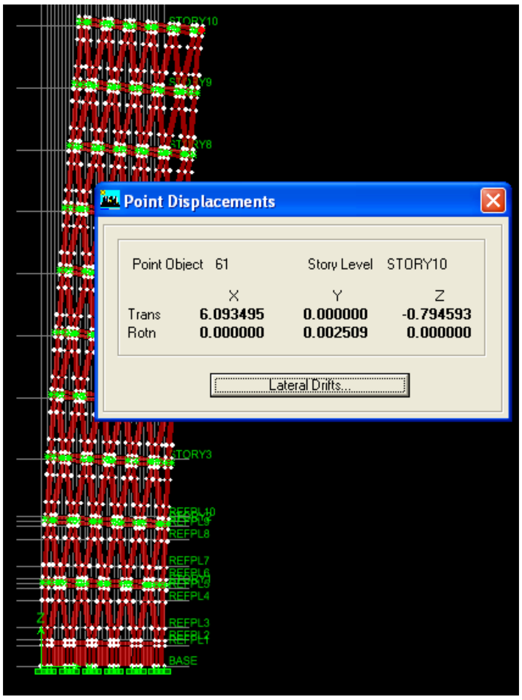

Panel 3 meters
Panel 4 meters
Panel detailing
Panel 5 meters
Panel 6 meters

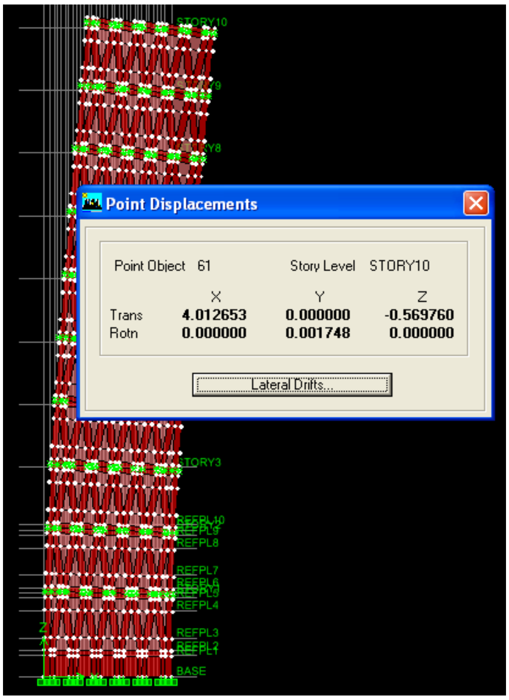

total sf 6.2m2
sf. brace = 2.87m2
c=2.87/6.2=0.46
total sf 9.03m2
sf. brace = 4.16m2
c=4.16/9.03=0.46
total sf 11.60m2
sf. brace = 5.66m2
c=5.66/11.6=0.49
total sf 14.2m2
sf. brace = 7.05m2
c=7.05/14.2=0.50

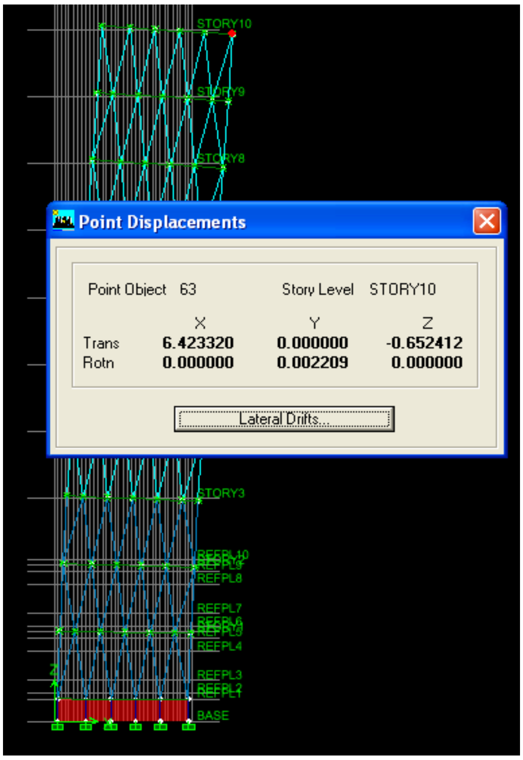
7.2 Top Displacements

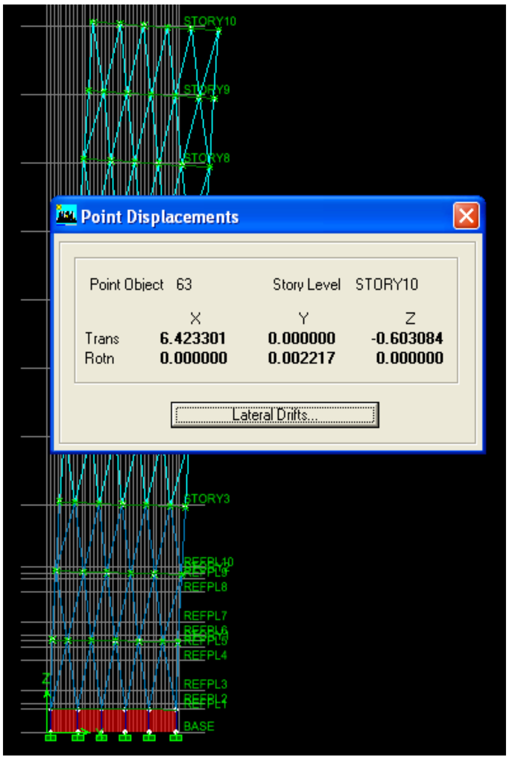
The Top Displacements (in cm) are being considered for the following wall modelling:

a) a similar wall configuration as the model in Grasshopper, shell elements used
b) a solid wall without openings, shell elements used
c) a frame braced wall, frame elements used
d) a frame braced wall, frame elements used with wall self-weight considered to zero

a)


b)


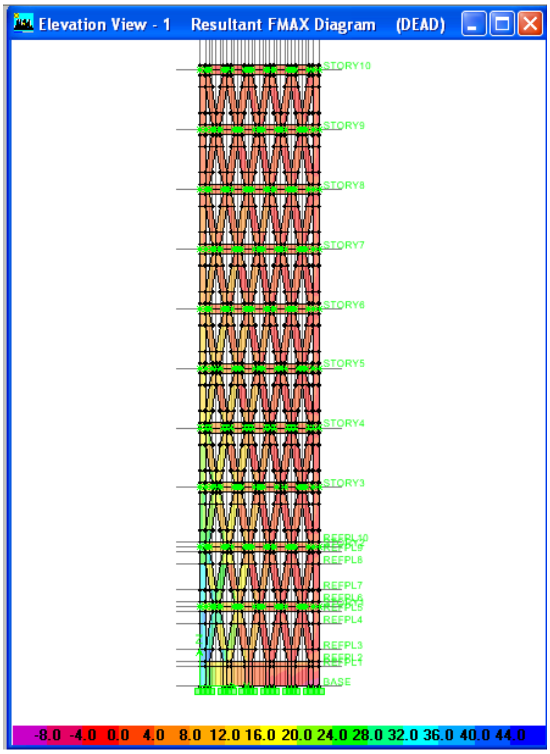
c)


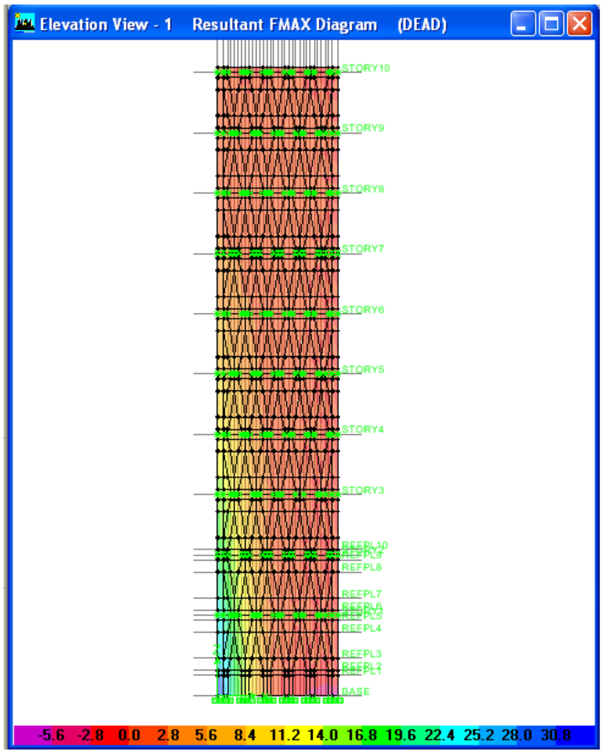
d)


7.3 Resultant FMAX Diagram

The Resultant FMAX Diagram (in kN) for the following wall modelling:

a) a similar wall configuration as the model in Grasshopper, shell elements used
b) a solid wall without openings, shell elements used

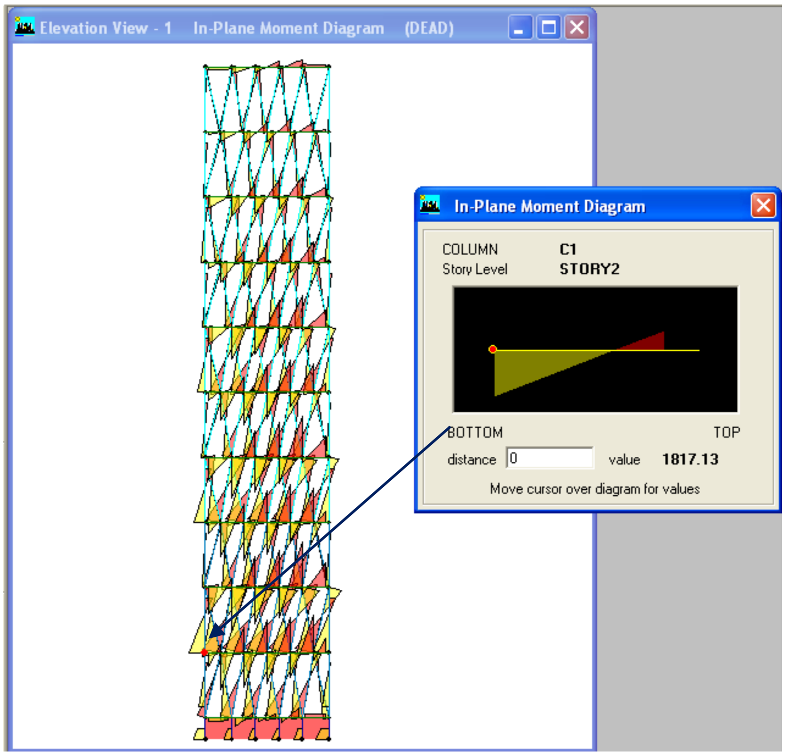




7.4 In-Plane Moment Diagram

The In-Plane Moment Diagram (in kNm) for the following wall modelling:

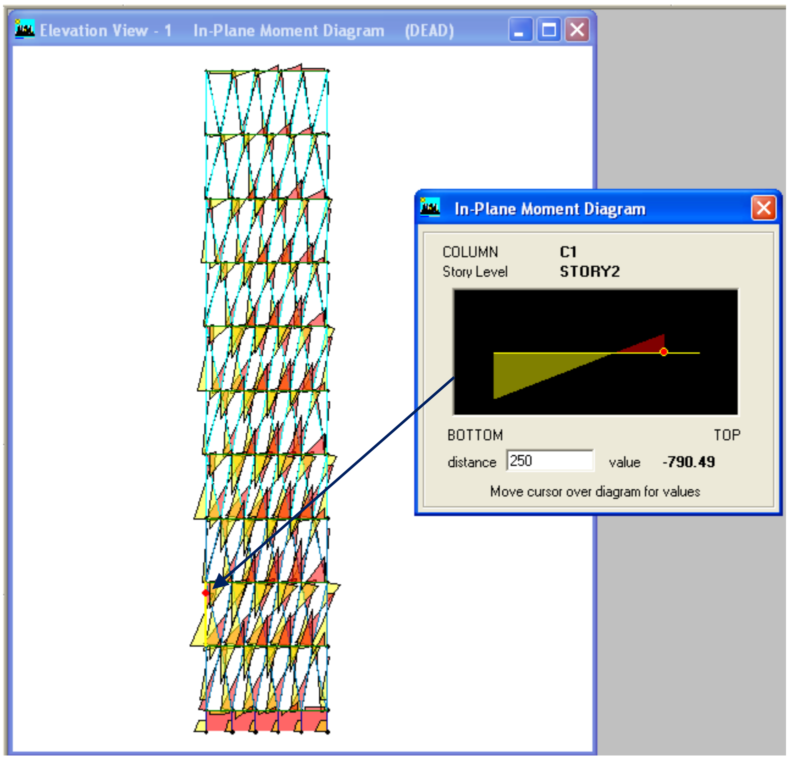
c) a frame braced wall, frame elements used



7.5 In-Plane Moment Diagram

The In-Plane Moment Diagram (in kNm) for the following wall modelling:

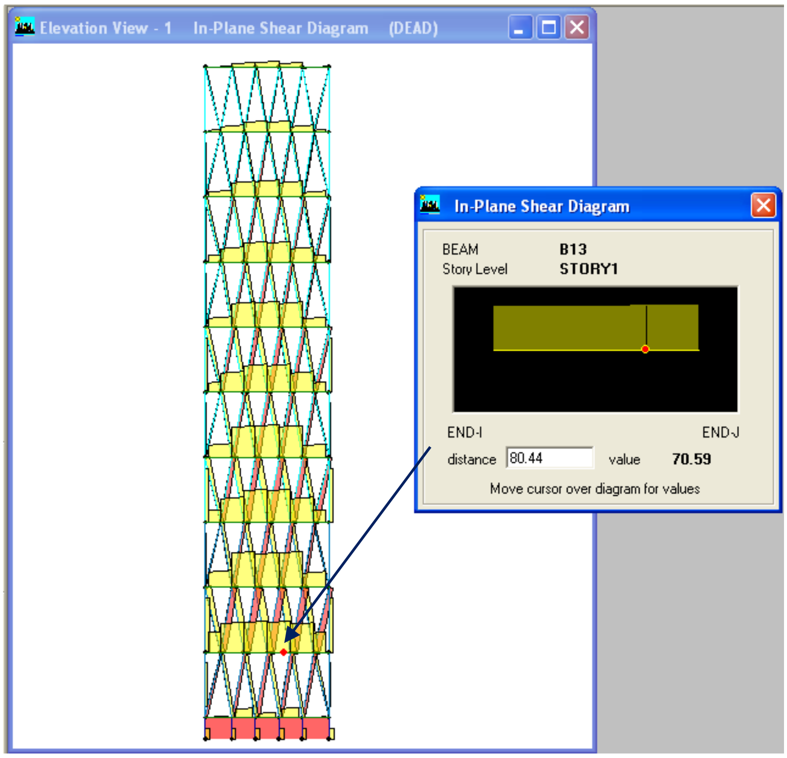
d) a frame braced wall, frame elements used with wall self-weight considered to zero



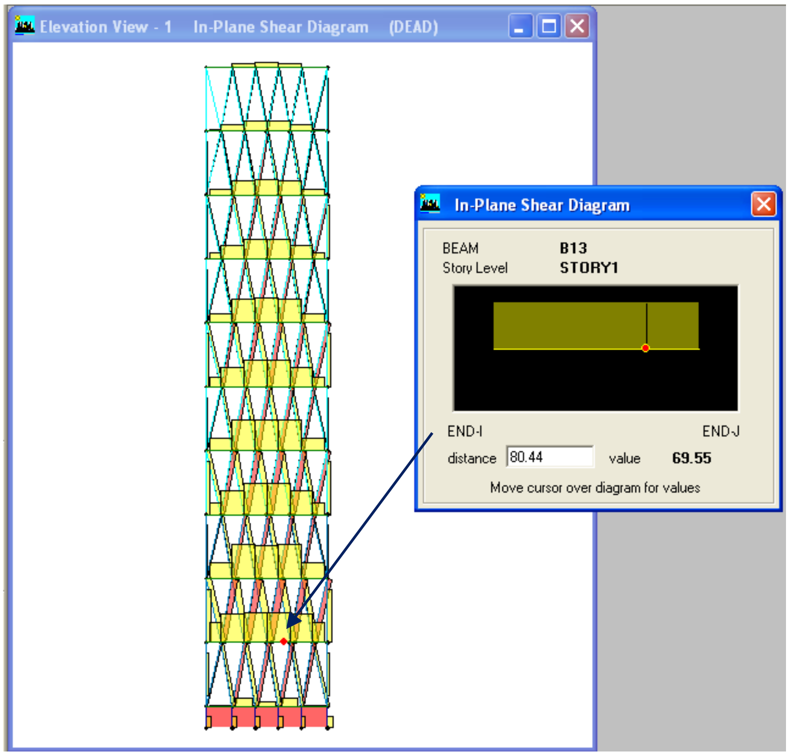
7.6 In-Plane Shear Diagram

The In-Plane Shear Diagram (in kN) for the following wall modelling:

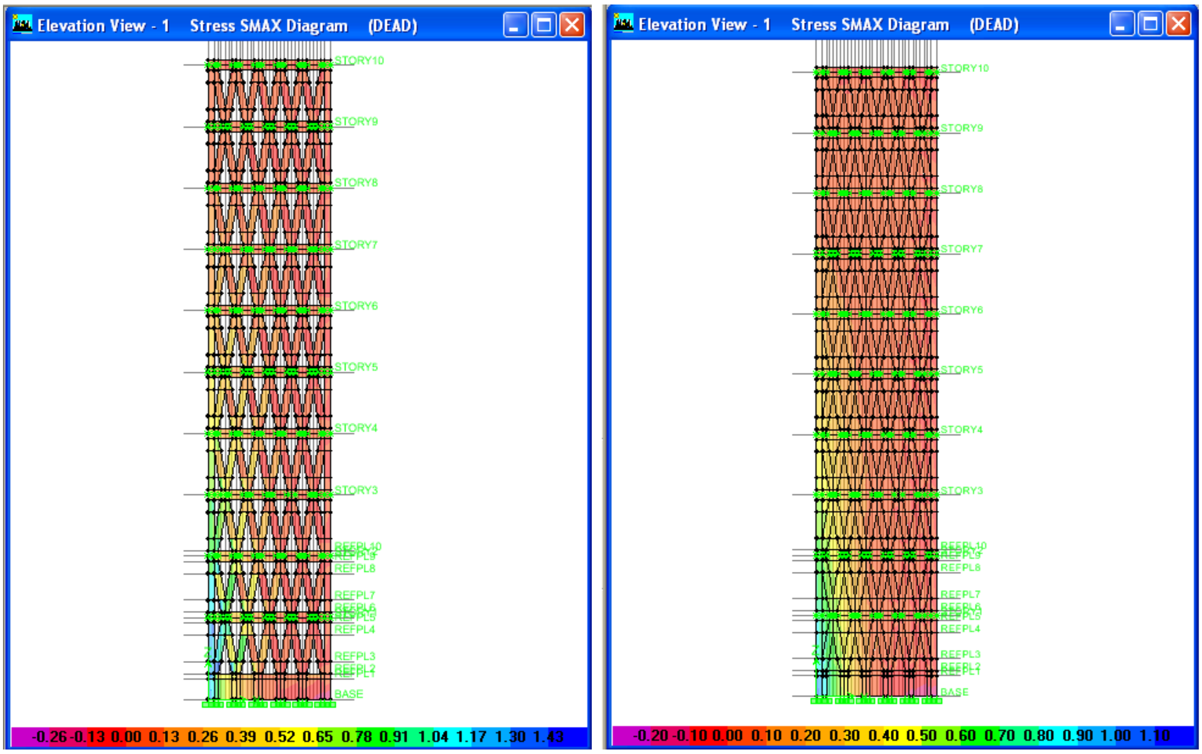
c) a frame braced wall, frame elements used



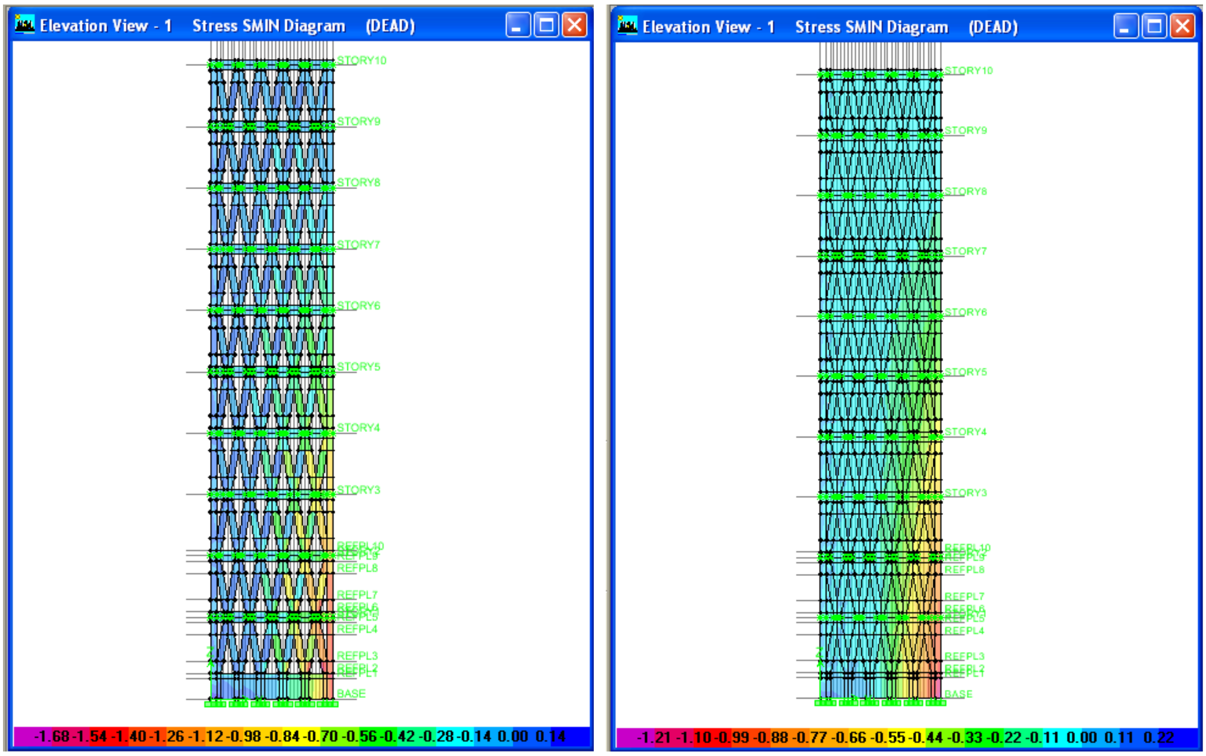
d) a frame braced wall, frame elements used with wall self-weight considered to zero



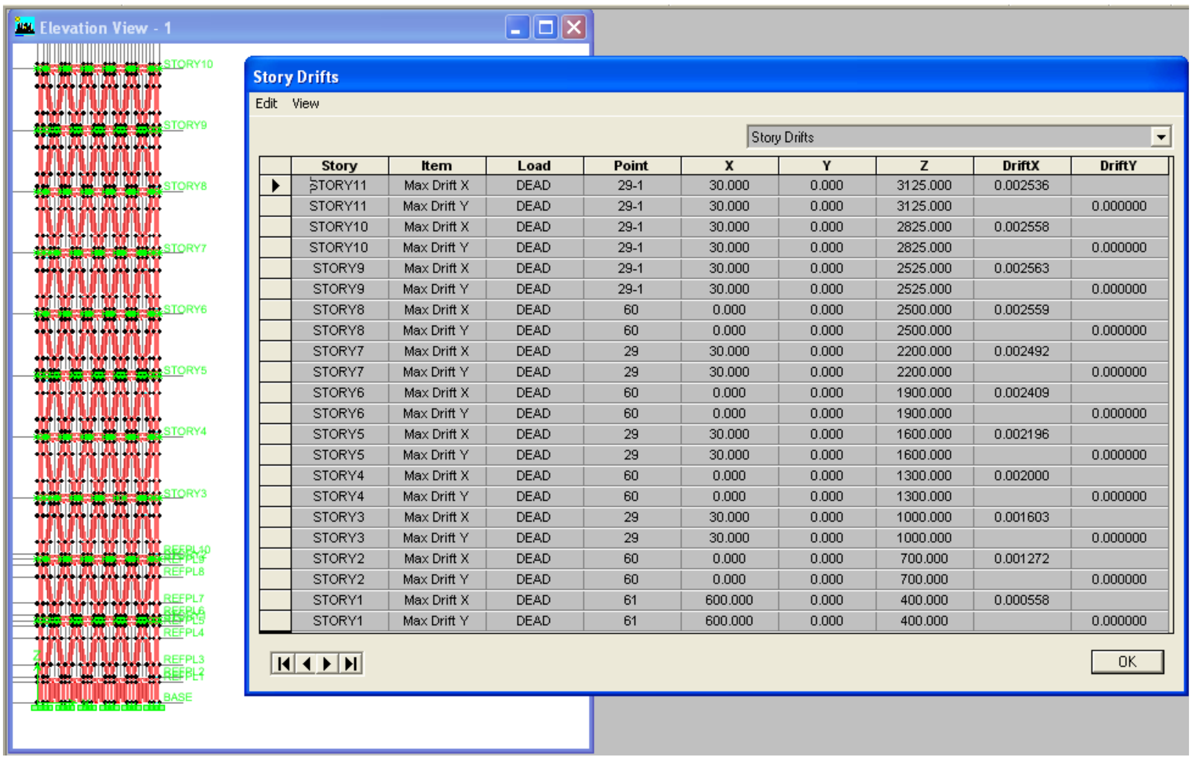
7.7 Stress SMAX Diagram for a) & b) wall modeling with shell elements



7.8 Stress SMIN Diagram for a) & b) wall modeling with shell elements

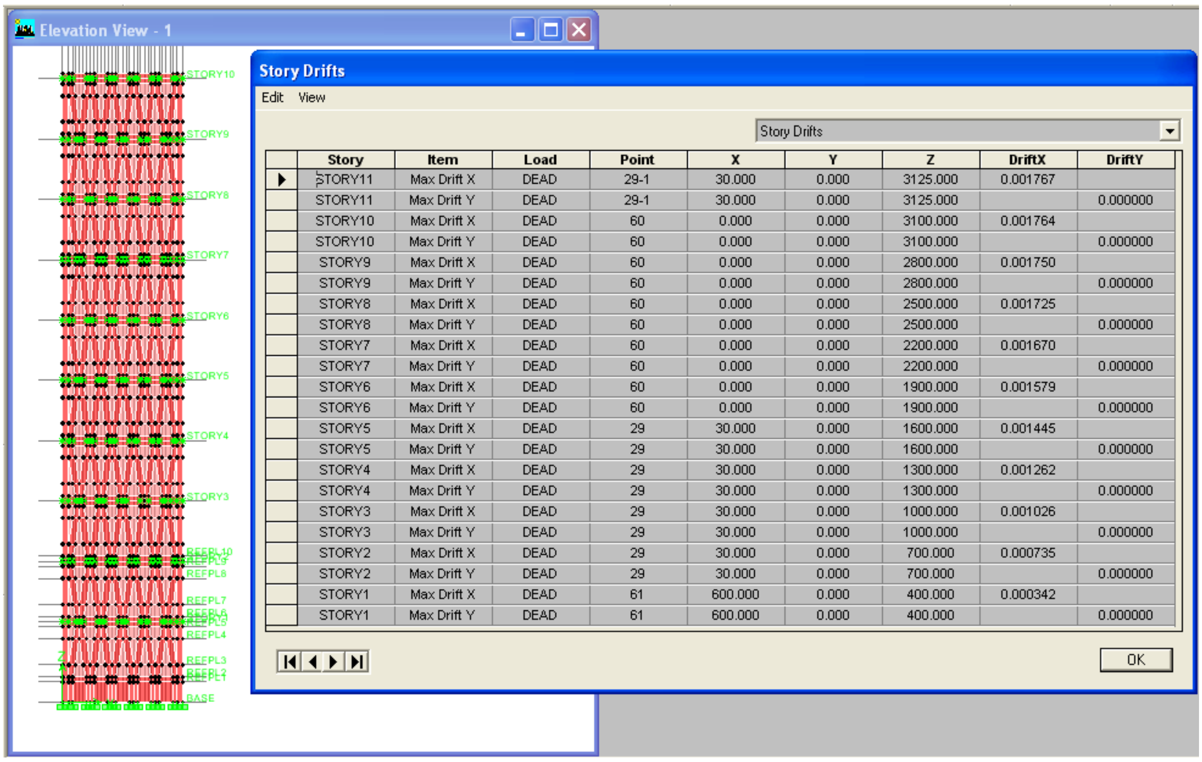


7.9 Story Drifts for a) wall modeling with shell elements



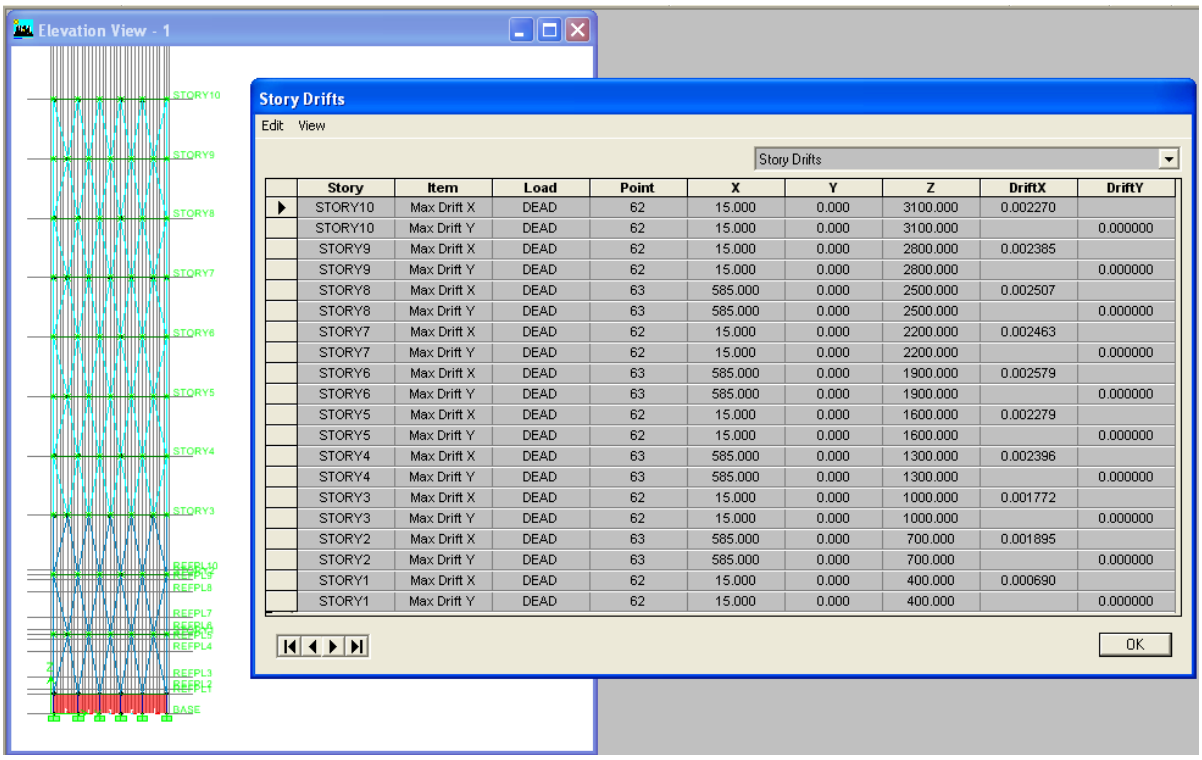
Story	Item	Load	Point	X	Y	Z	DriftX	DriftY
STORY11	Max Drift X	DEAD	29-1	30.000	0.000	3125.000	0.002536	
STORY11	Max Drift Y	DEAD	29-1	30.000	0.000	3125.000		0.000000
STORY10	Max Drift X	DEAD	29-1	30.000	0.000	2825.000	0.002558	
STORY10	Max Drift Y	DEAD	29-1	30.000	0.000	2825.000		0.000000
STORY9	Max Drift X	DEAD	29-1	30.000	0.000	2525.000	0.002563	
STORY9	Max Drift Y	DEAD	29-1	30.000	0.000	2525.000		0.000000
STORY8	Max Drift X	DEAD	60	0.000	0.000	2500.000	0.002559	
STORY8	Max Drift Y	DEAD	60	0.000	0.000	2500.000		0.000000
STORY7	Max Drift X	DEAD	29	30.000	0.000	2200.000	0.002492	
STORY7	Max Drift Y	DEAD	29	30.000	0.000	2200.000		0.000000
STORY6	Max Drift X	DEAD	60	0.000	0.000	1900.000	0.002409	
STORY6	Max Drift Y	DEAD	60	0.000	0.000	1900.000		0.000000
STORY5	Max Drift X	DEAD	29	30.000	0.000	1600.000	0.002196	
STORY5	Max Drift Y	DEAD	29	30.000	0.000	1600.000		0.000000
STORY4	Max Drift X	DEAD	60	0.000	0.000	1300.000	0.002000	
STORY4	Max Drift Y	DEAD	60	0.000	0.000	1300.000		0.000000
STORY3	Max Drift X	DEAD	29	30.000	0.000	1000.000	0.001603	
STORY3	Max Drift Y	DEAD	29	30.000	0.000	1000.000		0.000000
STORY2	Max Drift X	DEAD	60	0.000	0.000	700.000	0.001272	
STORY2	Max Drift Y	DEAD	60	0.000	0.000	700.000		0.000000
STORY1	Max Drift X	DEAD	61	600.000	0.000	400.000	0.000558	
STORY1	Max Drift Y	DEAD	61	600.000	0.000	400.000		0.000000

7.10 Story Drifts for b) wall modeling with shell elements



Story	Item	Load	Point	X	Y	Z	DriftX	DriftY
STORY11	Max Drift X	DEAD	29-1	30.000	0.000	3125.000	0.001767	
STORY11	Max Drift Y	DEAD	29-1	30.000	0.000	3125.000		0.000000
STORY10	Max Drift X	DEAD	60	0.000	0.000	3100.000	0.001764	
STORY10	Max Drift Y	DEAD	60	0.000	0.000	3100.000		0.000000
STORY9	Max Drift X	DEAD	60	0.000	0.000	2800.000	0.001750	
STORY9	Max Drift Y	DEAD	60	0.000	0.000	2800.000		0.000000
STORY8	Max Drift X	DEAD	60	0.000	0.000	2500.000	0.001725	
STORY8	Max Drift Y	DEAD	60	0.000	0.000	2500.000		0.000000
STORY7	Max Drift X	DEAD	60	0.000	0.000	2200.000	0.001670	
STORY7	Max Drift Y	DEAD	60	0.000	0.000	2200.000		0.000000
STORY6	Max Drift X	DEAD	60	0.000	0.000	1900.000	0.001579	
STORY6	Max Drift Y	DEAD	60	0.000	0.000	1900.000		0.000000
STORY5	Max Drift X	DEAD	29	30.000	0.000	1600.000	0.001445	
STORY5	Max Drift Y	DEAD	29	30.000	0.000	1600.000		0.000000
STORY4	Max Drift X	DEAD	29	30.000	0.000	1300.000	0.001262	
STORY4	Max Drift Y	DEAD	29	30.000	0.000	1300.000		0.000000
STORY3	Max Drift X	DEAD	29	30.000	0.000	1000.000	0.001026	
STORY3	Max Drift Y	DEAD	29	30.000	0.000	1000.000		0.000000
STORY2	Max Drift X	DEAD	29	30.000	0.000	700.000	0.000735	
STORY2	Max Drift Y	DEAD	29	30.000	0.000	700.000		0.000000
STORY1	Max Drift X	DEAD	61	600.000	0.000	400.000	0.000342	
STORY1	Max Drift Y	DEAD	61	600.000	0.000	400.000		0.000000

7.11 Story Drifts for c) wall modeling with frame elements



Story	Item	Load	Point	X	Y	Z	DriftX	DriftY
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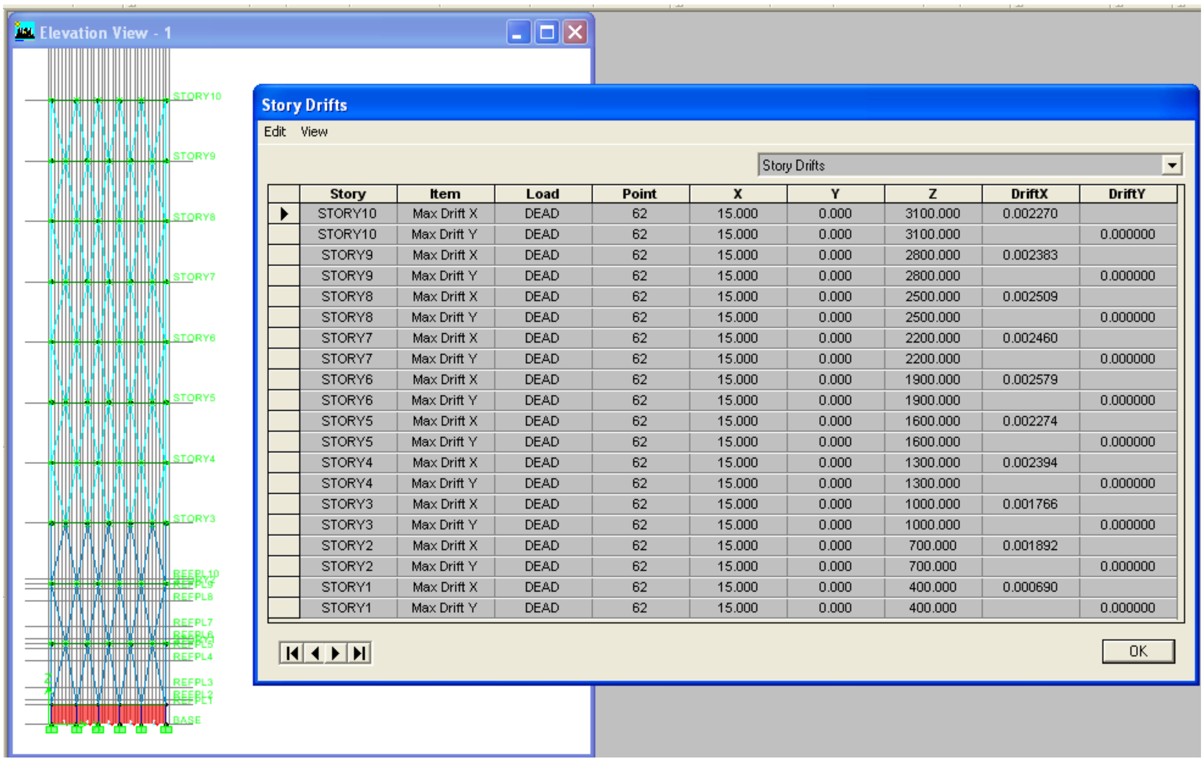
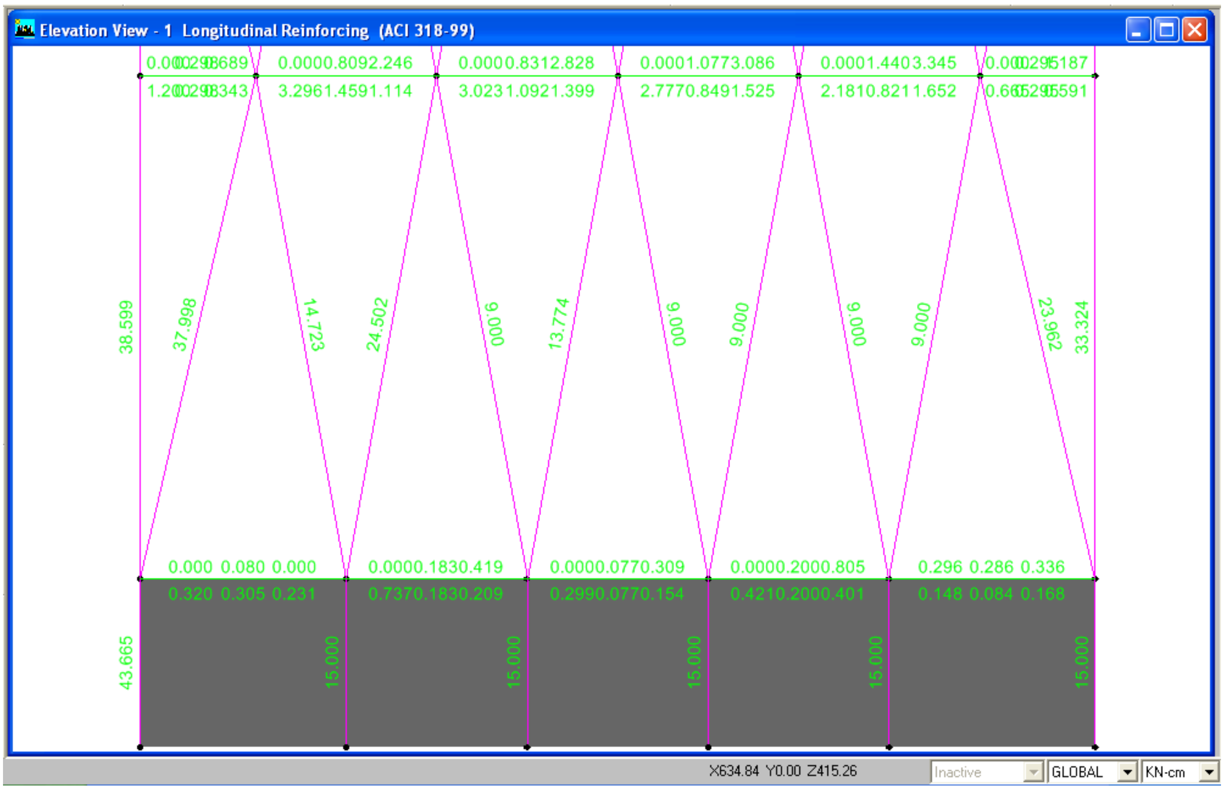
STORY10	Max Drift Y	DEAD	62	15.000	0.000	3100.000		0.000000
STORY9	Max Drift X	DEAD	62	15.000	0.000	2800.000	0.002385	
STORY9	Max Drift Y	DEAD	62	15.000	0.000	2800.000		0.000000
STORY8	Max Drift X	DEAD	63	585.000	0.000	2500.000	0.002507	
STORY8	Max Drift Y	DEAD	63	585.000	0.000	2500.000		0.000000
STORY7	Max Drift X	DEAD	62	15.000	0.000	2200.000	0.002463	
STORY7	Max Drift Y	DEAD	62	15.000	0.000	2200.000		0.000000
STORY6	Max Drift X	DEAD	63	585.000	0.000	1900.000	0.002579	
STORY6	Max Drift Y	DEAD	63	585.000	0.000	1900.000		0.000000
STORY5	Max Drift X	DEAD	62	15.000	0.000	1600.000	0.002279	
STORY5	Max Drift Y	DEAD	62	15.000	0.000	1600.000		0.000000
STORY4	Max Drift X	DEAD	63	585.000	0.000	1300.000	0.002396	
STORY4	Max Drift Y	DEAD	63	585.000	0.000	1300.000		0.000000
STORY3	Max Drift X	DEAD	62	15.000	0.000	1000.000	0.001772	
STORY3	Max Drift Y	DEAD	62	15.000	0.000	1000.000		0.000000
STORY2	Max Drift X	DEAD	63	585.000	0.000	700.000	0.001895	
STORY2	Max Drift Y	DEAD	63	585.000	0.000	700.000		0.000000
STORY1	Max Drift X	DEAD	62	15.000	0.000	400.000	0.000690	
STORY1	Max Drift Y	DEAD	62	15.000	0.000	400.000		0.000000

7.12 Story Drifts for d) wall modeling with frame elements

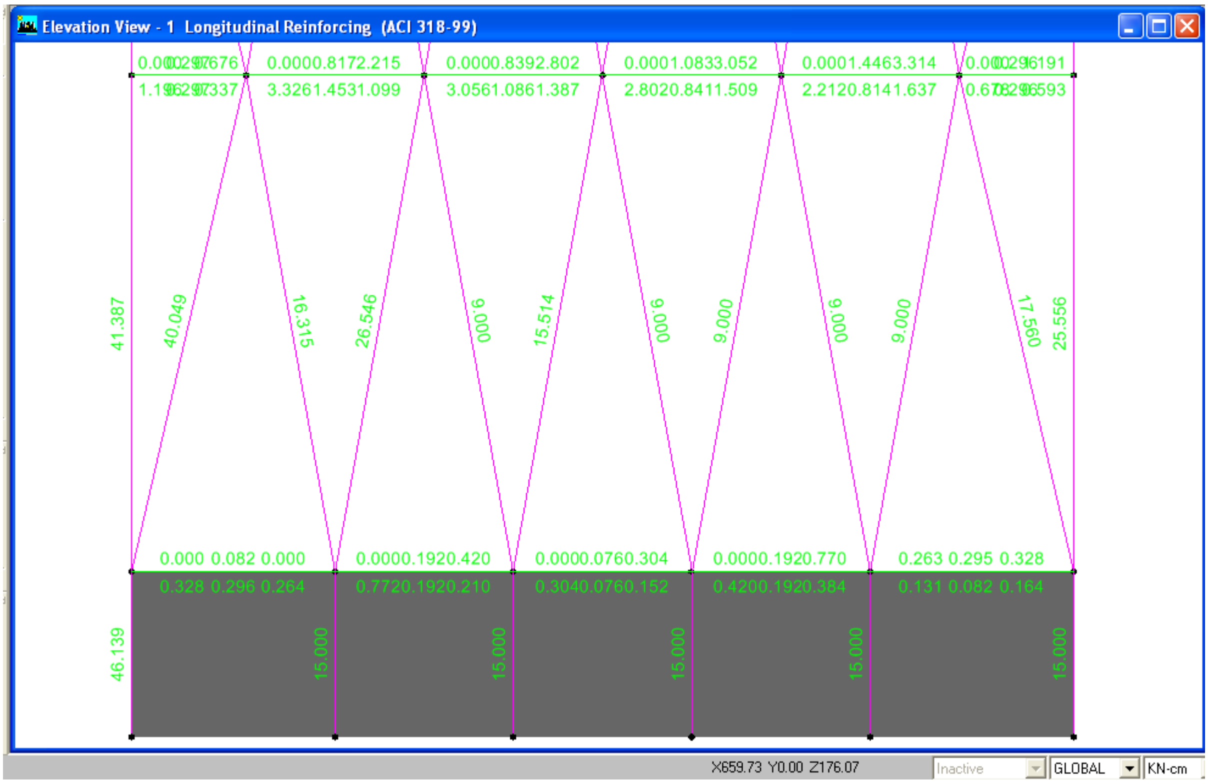


Story	Item	Load	Point	X	Y	Z	DriftX	DriftY
STORY10	Max Drift X	DEAD	62	15.000	0.000	3100.000	0.002270	
STORY10	Max Drift Y	DEAD	62	15.000	0.000	3100.000		0.000000
STORY9	Max Drift X	DEAD	62	15.000	0.000	2800.000	0.002383	
STORY9	Max Drift Y	DEAD	62	15.000	0.000	2800.000		0.000000
STORY8	Max Drift X	DEAD	62	15.000	0.000	2500.000	0.002509	
STORY8	Max Drift Y	DEAD	62	15.000	0.000	2500.000		0.000000
STORY7	Max Drift X	DEAD	62	15.000	0.000	2200.000	0.002460	
STORY7	Max Drift Y	DEAD	62	15.000	0.000	2200.000		0.000000
STORY6	Max Drift X	DEAD	62	15.000	0.000	1900.000	0.002579	
STORY6	Max Drift Y	DEAD	62	15.000	0.000	1900.000		0.000000
STORY5	Max Drift X	DEAD	62	15.000	0.000	1600.000	0.002274	
STORY5	Max Drift Y	DEAD	62	15.000	0.000	1600.000		0.000000
STORY4	Max Drift X	DEAD	62	15.000	0.000	1300.000	0.002394	
STORY4	Max Drift Y	DEAD	62	15.000	0.000	1300.000		0.000000
STORY3	Max Drift X	DEAD	62	15.000	0.000	1000.000	0.001766	
STORY3	Max Drift Y	DEAD	62	15.000	0.000	1000.000		0.000000
STORY2	Max Drift X	DEAD	62	15.000	0.000	700.000	0.001892	
STORY2	Max Drift Y	DEAD	62	15.000	0.000	700.000		0.000000
STORY1	Max Drift X	DEAD	62	15.000	0.000	400.000	0.000690	
STORY1	Max Drift Y	DEAD	62	15.000	0.000	400.000		0.000000

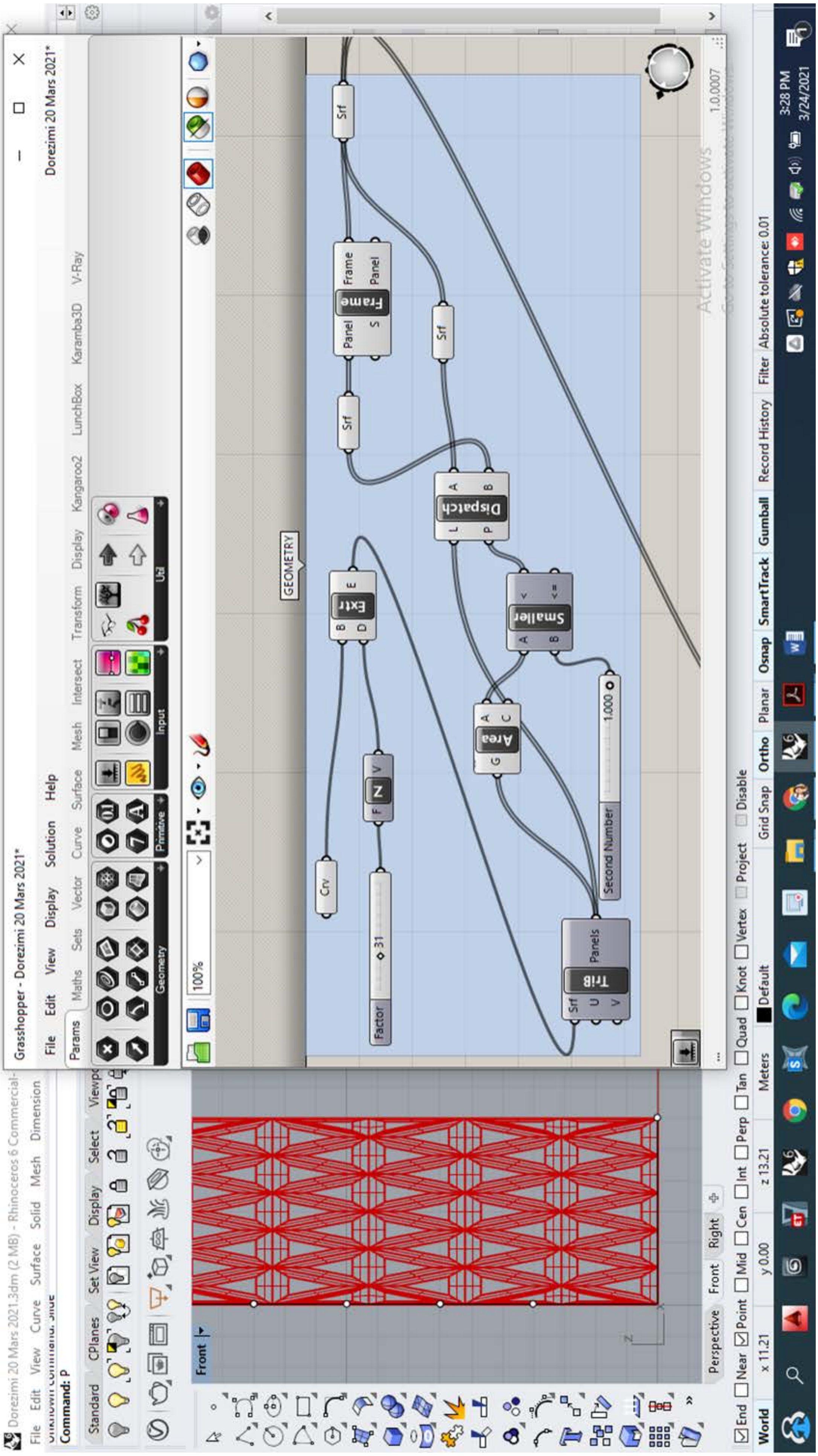
7.13 Longitudinal Reinforcing in (cm^2) for c) wall modeling with frame elements



7.14 Longitudinal Reinforcing in (cm^2) for d) wall modeling with frame elements



8 Appendix B: The procedural Analysis for Building the Model Code for Generating Innovative Perforated Pattern for Structural Wall Element


Grasshopper - Dorezimi 20 Mars 2021*
Dorezimi 20 Mars 2021 3dm (2 MB) - Rhinoceros 6 Commercial
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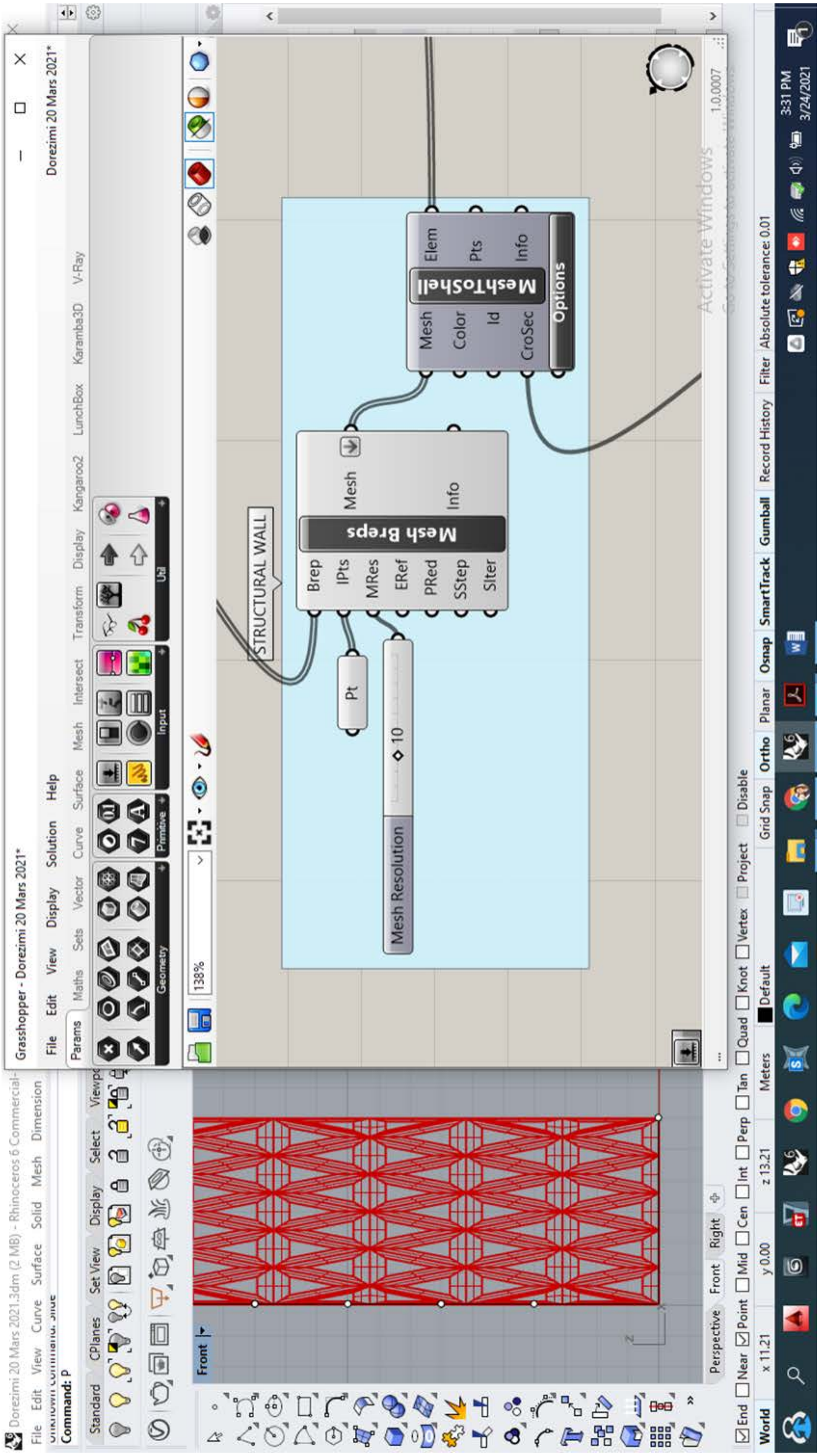
3/24/2021


Grasshopper - Dorezimi 20 Mars 2021*
STRUCTURAL WALL
Mesh Resolution
10
Pt
Mesh Breps
Brep
IPts
MRes
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MeshToShell
Mesh
Color
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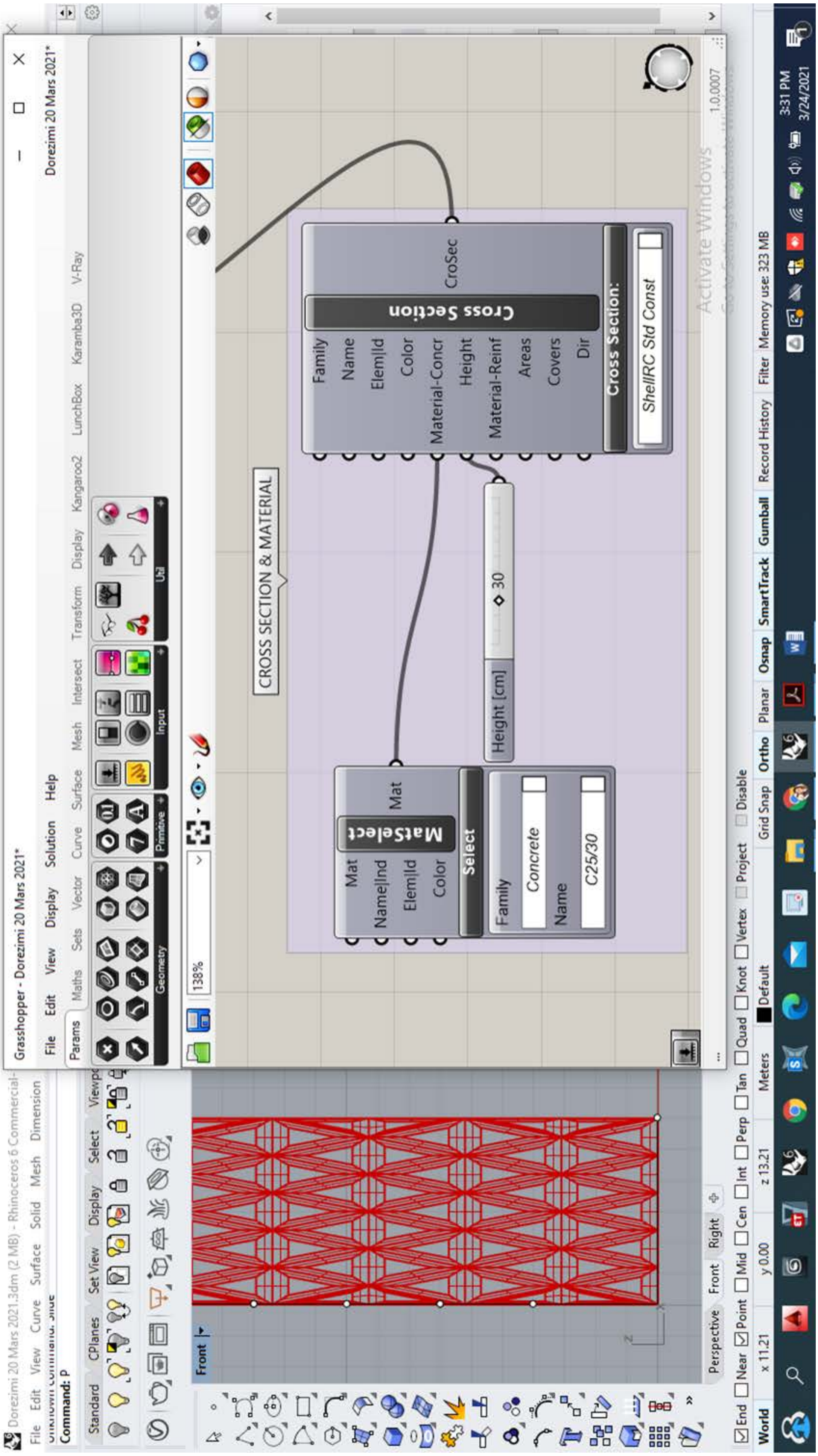
CroSec
Elem
Pts
Info
Options


Grasshopper - Dorezimi 20 Mars 2021*
CROSS SECTION & MATERIAL
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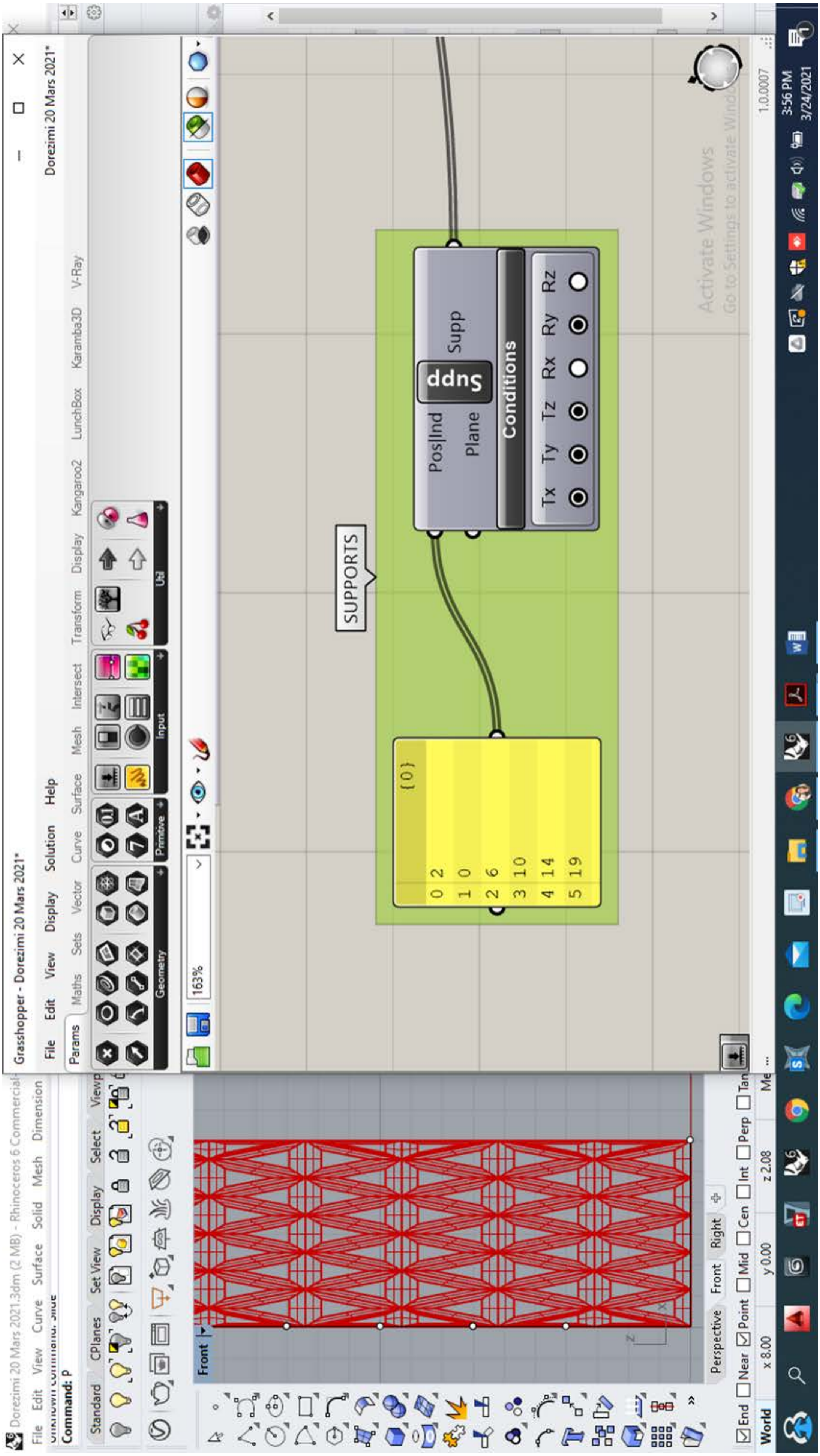
ElemId
Color
Select
Family
Concrete
Name
C25/30
Height [cm]
30
Cross Section
Family
Name
ElemId
Color
Material-Concr
Height
Material-Reinf
Areas
Covers
Dir
CroSec
Cross Section:
ShellRC Std Const


Grasshopper - Dorezimi 20 Mars 2021*
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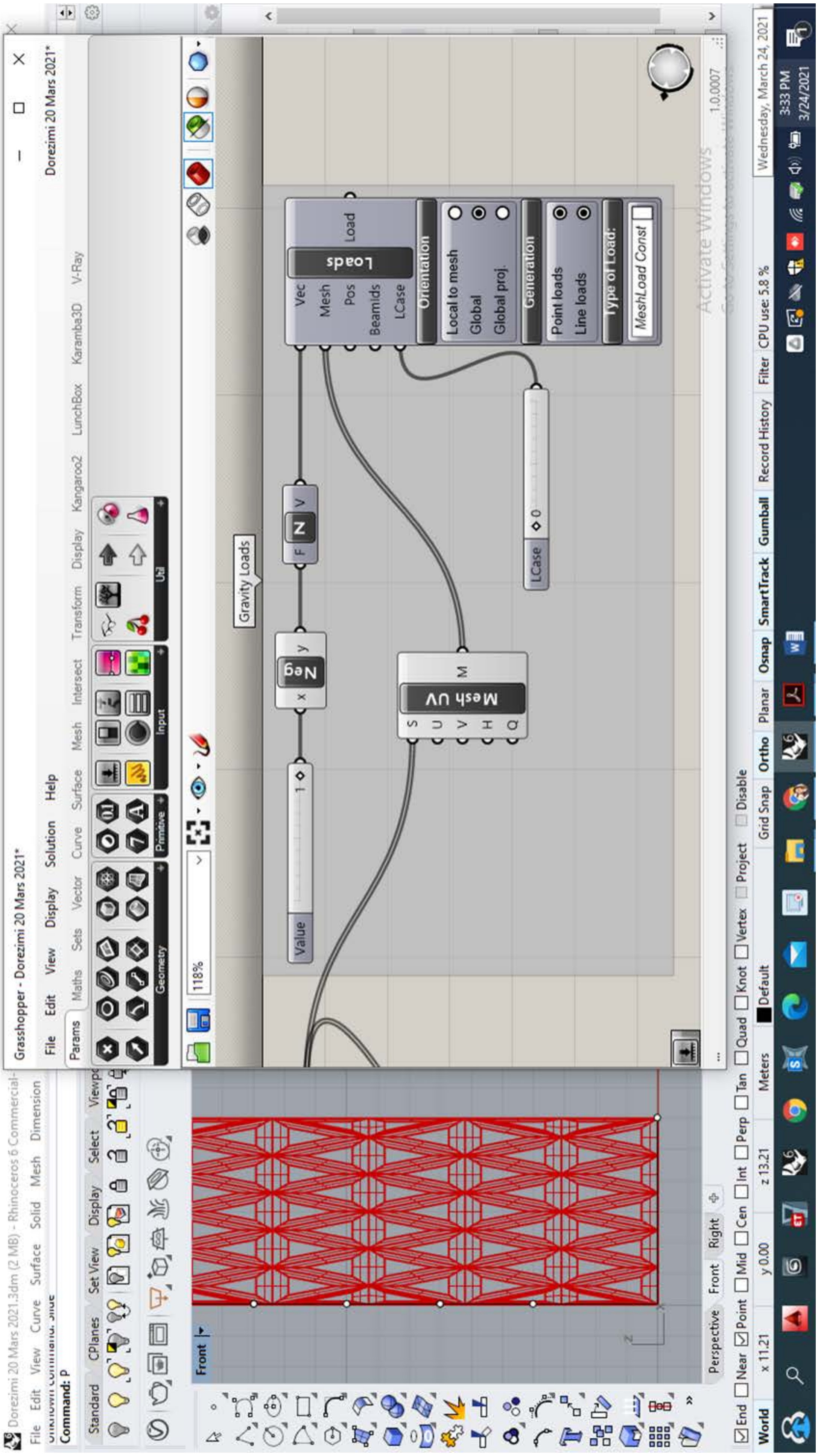
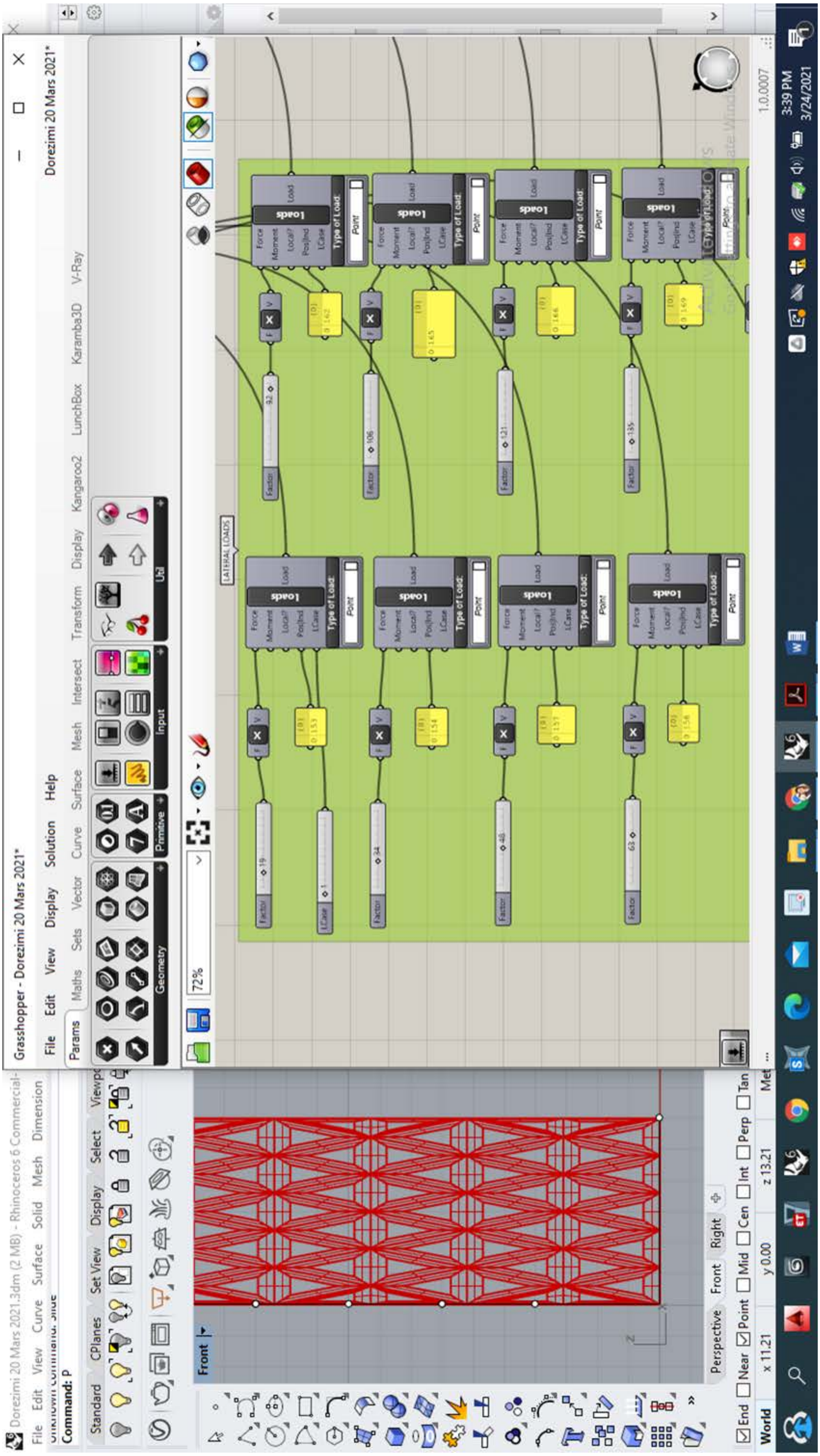
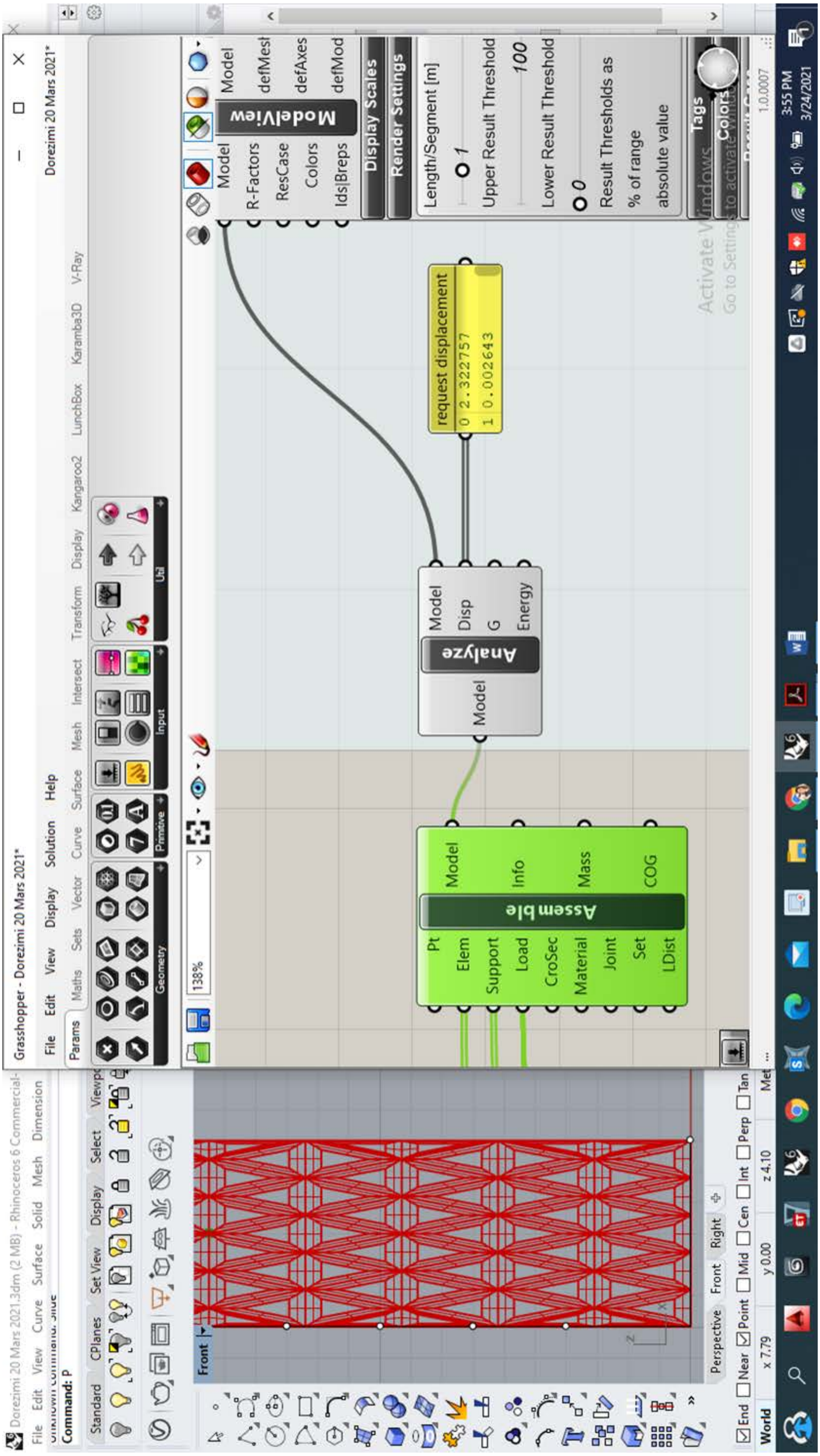
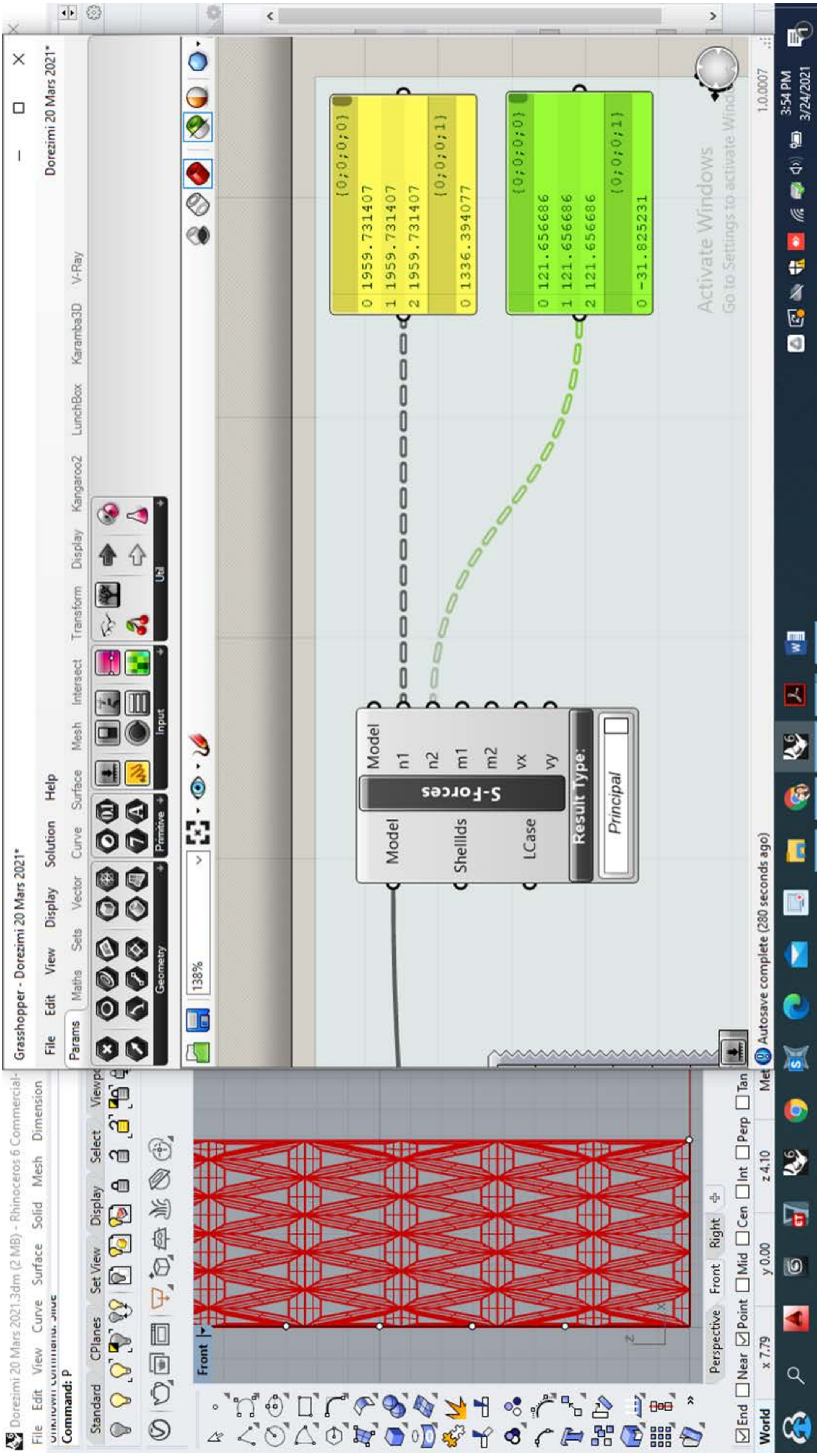
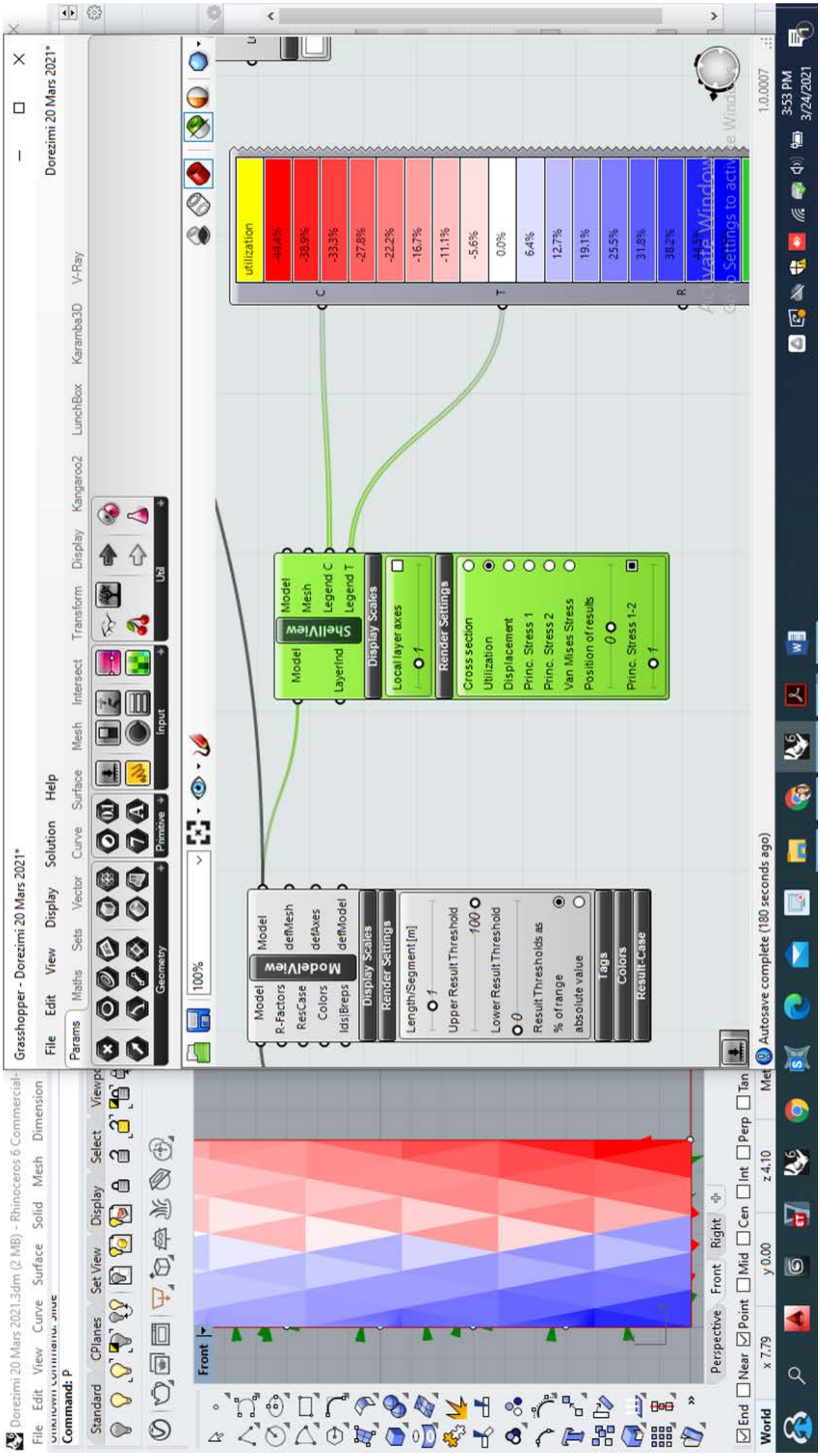
2 6
3 10
4 14
5 19


Grasshopper - Dorezimi 20 Mars 2021*
Gravity Loads
Value
Neg
Mesh UV
LCase
Loads
Vec
Mesh
Pos
BeamIds
LCase
Load
Orientation
Local to mesh
Global
Global proj.
Generation
Point loads
Line loads
Type of Load:
MeshLoad Const

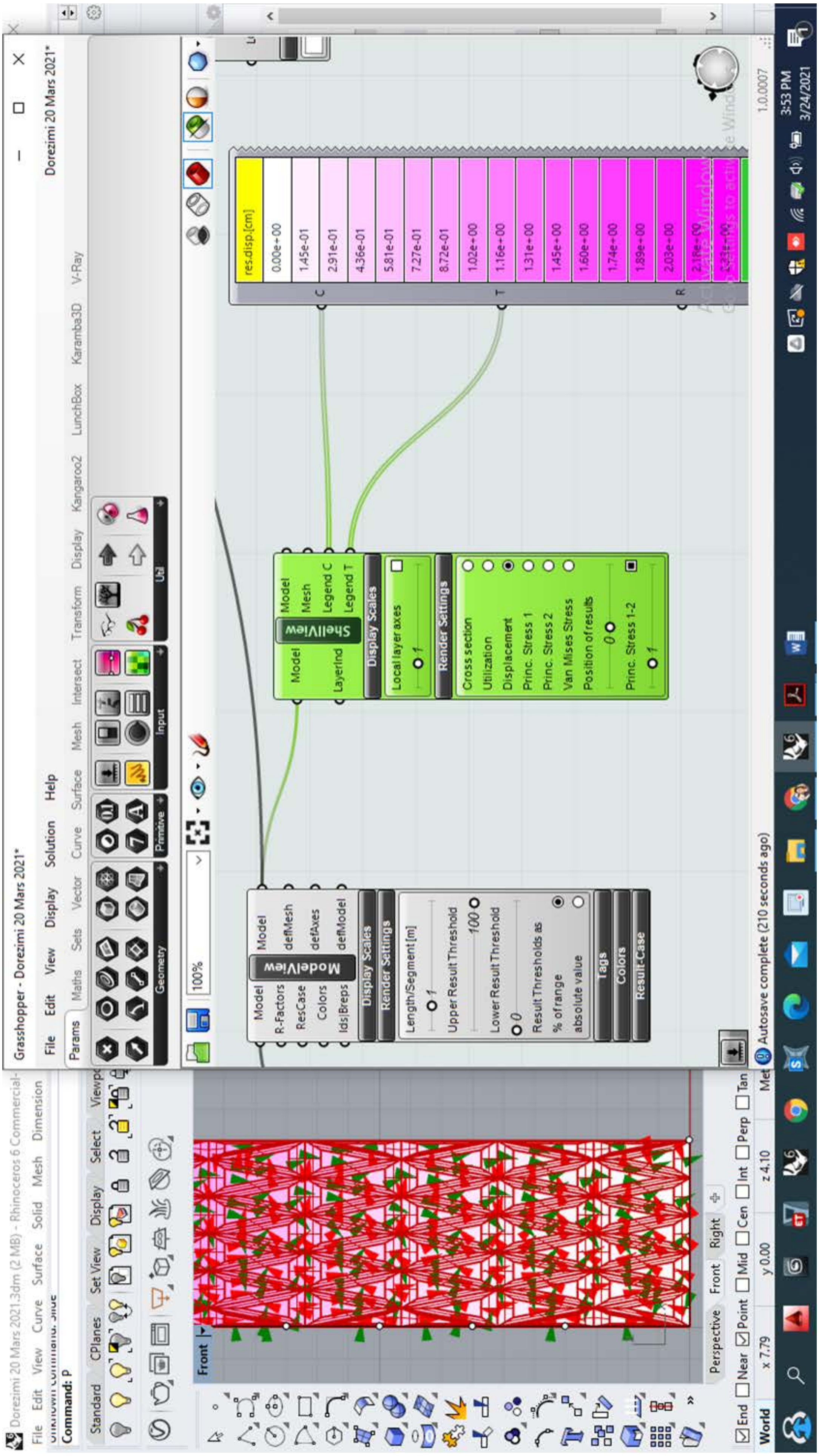

Grasshopper - Dorezimi 20 Mars 2021*
File Edit View Display Solution Help
Params Maths Sets Vector Curve Surface Mesh Intersect Transform Display Kangaroo2 LunchBox Karamba3D V-Ray
Geometry
Primitive
Input
Util
72%
LATERAL LOADS
Loads
Type of Load:
Point
Perspective Front Right
World
3:39 PM
3/24/2021

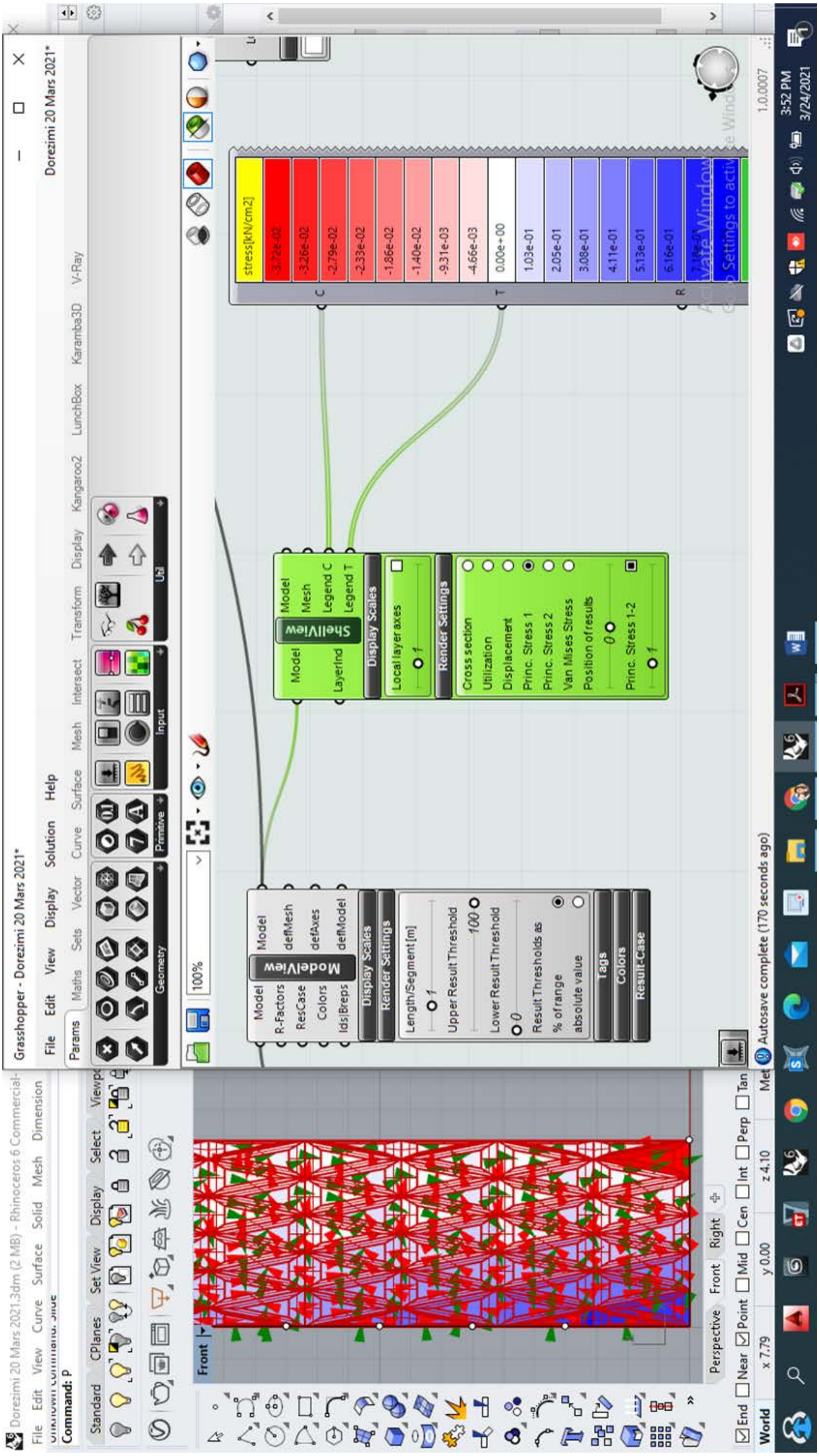

Grasshopper - Dorezimi 20 Mars 2021*
Assemble
Pt
Elem
Support
Load
CroSec
Material
Joint
Set
LDist
Model
Info
Mass
COG
Analyze
Model
Disp
G
Energy
request displacement
0 2.322757
1 0.002643
ModelView
R-Factors
ResCase
Colors
Ids|Breps
defMesh
defAxes
defMod
Display Scales
Render Settings
Length/Segment [m]
Upper Result Threshold
Lower Result Threshold
Result Thresholds as
% of range
absolute value

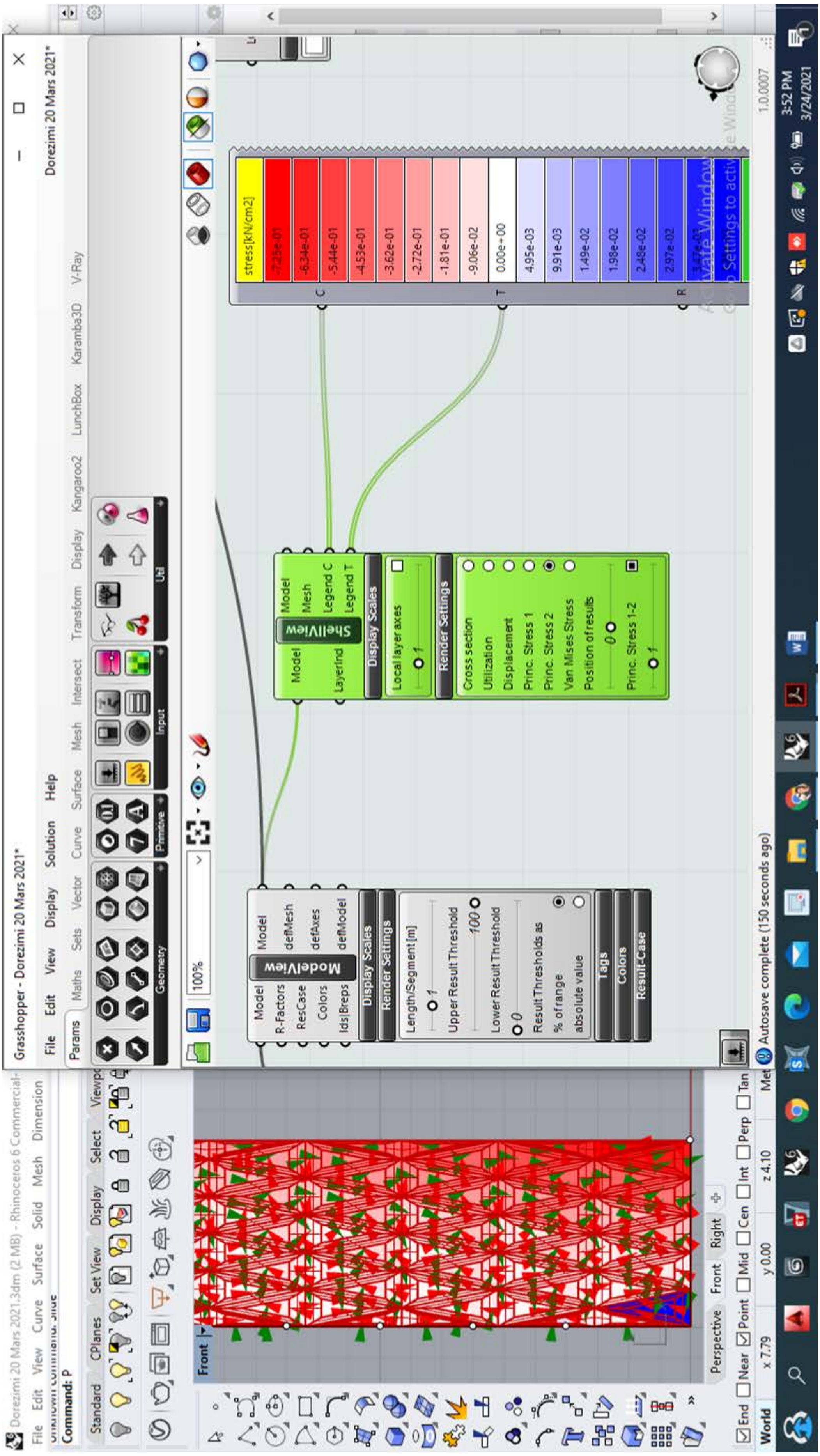

Grasshopper - Dorezimi 20 Mars 2021*
S-Forces
Model
ShellIds
LCase
Result Type:
Principal
Model
n1
n2
m1
m2
vx
vy
{0;0;0;0}
0 1959.731407
1 1959.731407
2 1959.731407
{0;0;0;1}
0 1336.394077
{0;0;0;0}
0 121.656686
1 121.656686
2 121.656686
{0;0;0;1}
0 -31.825231
Autosave complete (280 seconds ago)

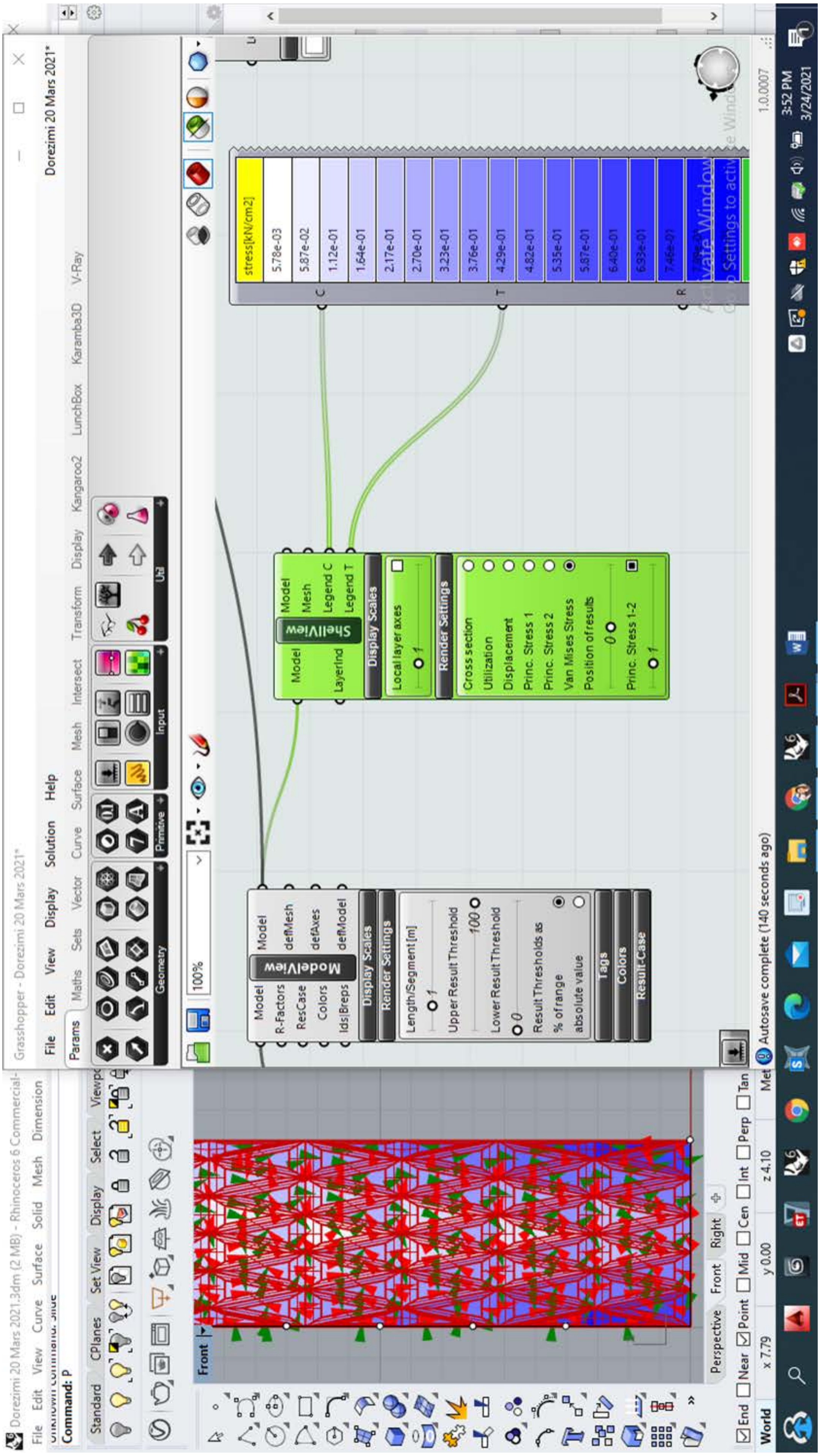


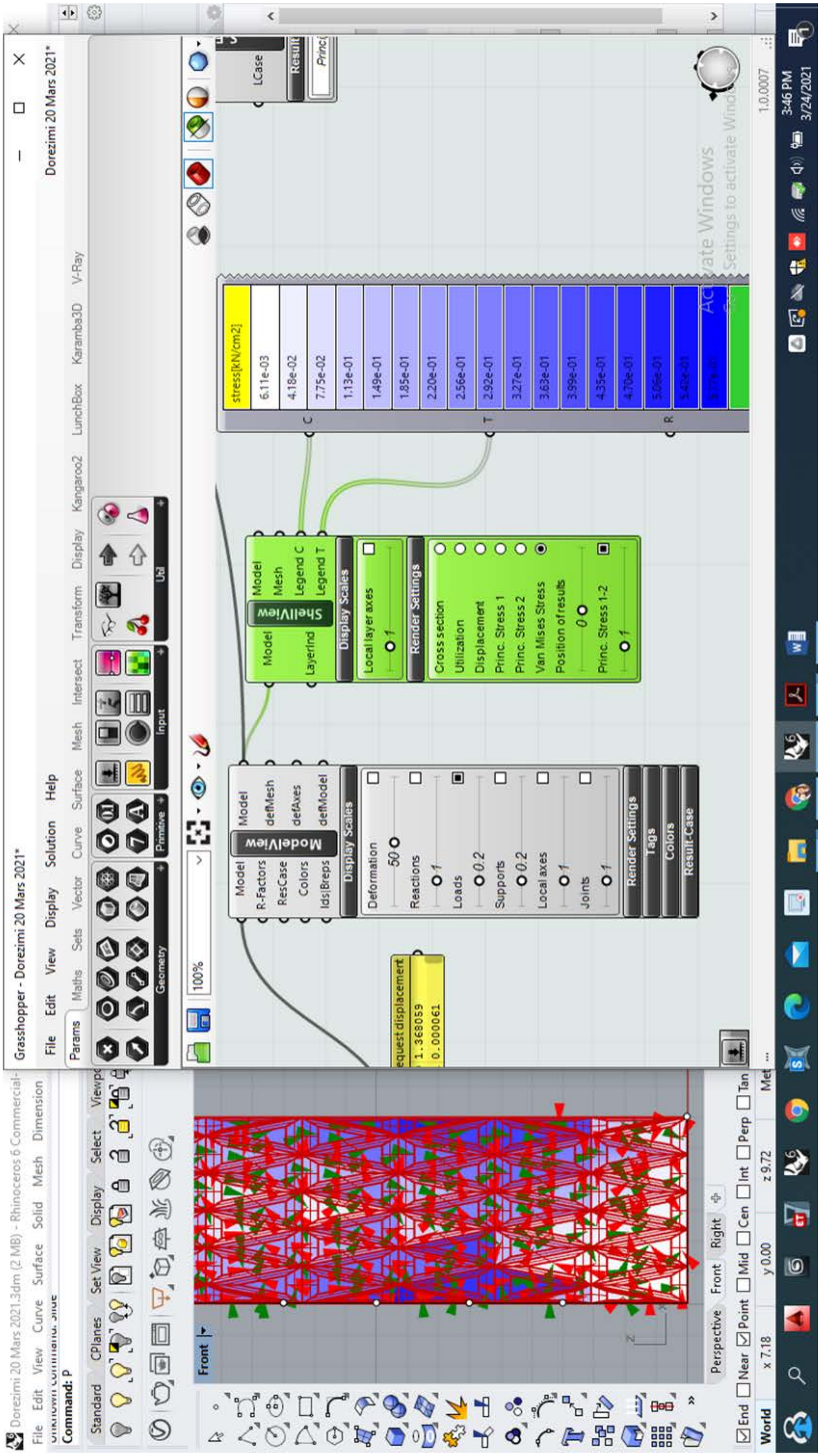
Grasshopper - Dorezimi 20 Mars 2021*
File Edit View Display Solution Help
Params Maths Sets Vector Curve Surface Mesh Intersect Transform Display Kangaroo2 LunchBox Karamba3D V-Ray
Geometry
Primitive
Input
Util
100%
ModelView
Model
R-Factors
ResCase
Colors
Ids|Breps
Model
defMesh
defAxes
defModel
Display Scales
Render Settings
Length/Segment [m]
Upper Result Threshold
Lower Result Threshold
Result Thresholds as
% of range
absolute value
Tags
Colors
Result-Case
ShellView
Model
Layerlnd
Mesh
Legend C
Legend T
Local layer axes
Cross section
Utilization
Displacement
Princ. Stress 1
Princ. Stress 2
Van Mises Stress
Position of results
Princ. Stress 1-2
utilization
-44.4%
-38.9%
-33.3%
-27.8%
-22.2%
-16.7%
-11.1%
-5.6%
0.0%
6.4%
12.7%
19.1%
25.5%
31.8%
38.2%
Autosave complete (180 seconds ago)
1.0.0007
Dorezimi 20 Mars 2021.3dm (2 MB) - Rhinoceros 6 Commercial
File Edit View Curve Surface Solid Mesh Dimension
Command: P
Standard CPlanes Set View Display Select
Front
Perspective Front Right
End Near Point Mid Cen Int Perp Tan
World x 7.79 y 0.00 z 4.10
3:53 PM
3/24/2021


Grasshopper - Dorezimi 20 Mars 2021*
File Edit View Display Solution Help
Params Maths Sets Vector Curve Surface Mesh Intersect Transform Display Kangaroo2 LunchBox Karamba3D V-Ray
ModelView
Model
R-Factors
ResCase
Colors
Ids|Breps
defMesh
defAxes
defModel
Display Scales
Render Settings
Length/Segment [m]
Upper Result Threshold
Lower Result Threshold
Result Thresholds as
% of range
absolute value
Tags
Colors
Result-Case
ShellView
Mesh
LayerInd
Legend C
Legend T
Local layer axes
Cross section
Utilization
Displacement
Princ. Stress 1
Princ. Stress 2
Van Mises Stress
Position of results
Princ. Stress 1-2
res.disp.[cm]
0.00e+00
1.45e-01
2.91e-01
4.36e-01
5.81e-01
7.27e-01
8.72e-01
1.02e+00
1.16e+00
1.31e+00
1.45e+00
1.60e+00
1.74e+00
1.89e+00
2.03e+00
Autosave complete (210 seconds ago)
Dorezimi 20 Mars 2021.3dm (2 MB) - Rhinoceros 6 Commercial
Command: P
Front
Perspective Front Right
3:53 PM
3/24/2021

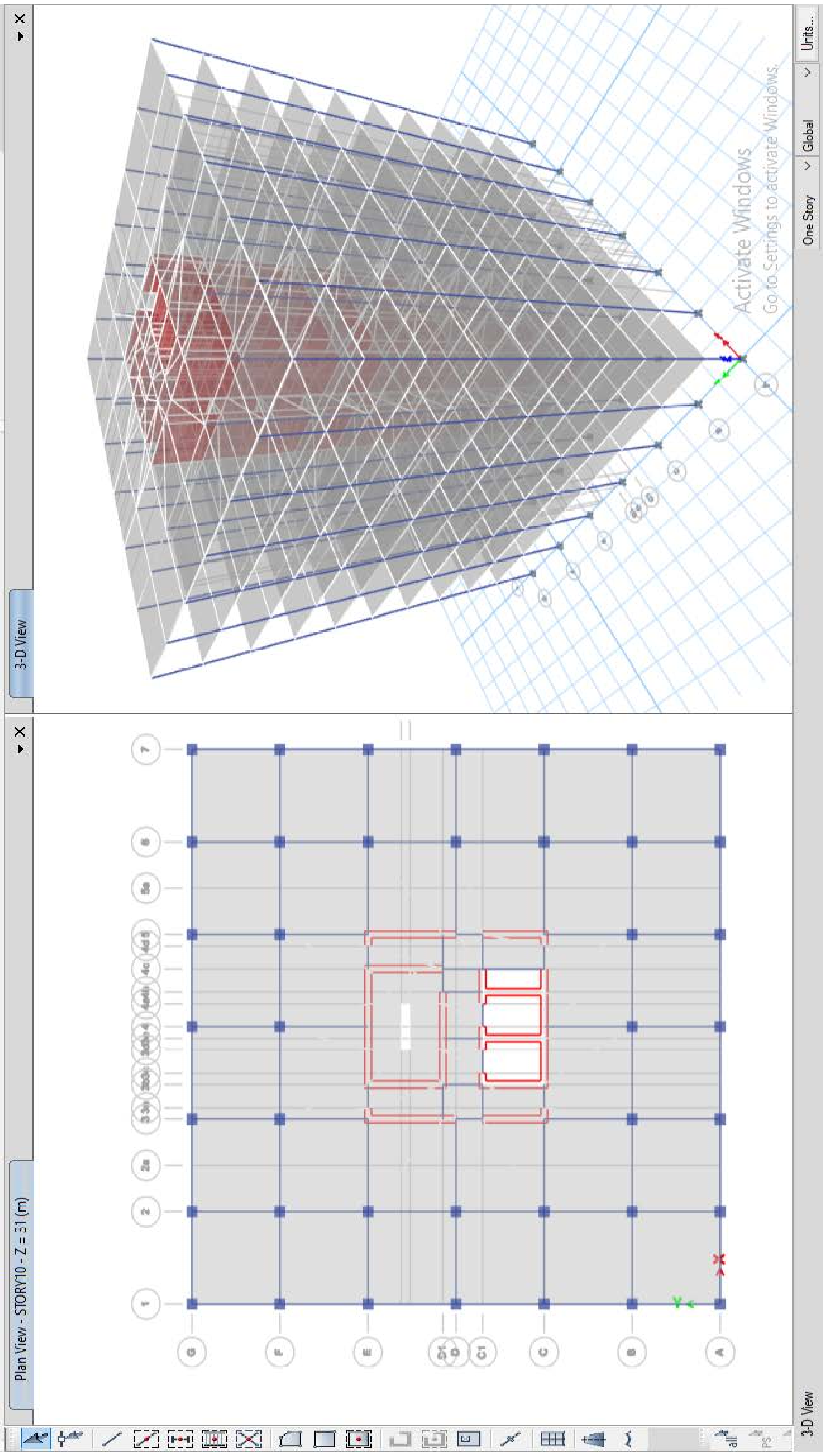

Grasshopper - Dorezimi 20 Mars 2021*
ModelView
ShellView
Display Scales
Render Settings
Cross section
Utilization
Displacement
Princ. Stress 1
Princ. Stress 2
Van Mises Stress
Position of results
Princ. Stress 1-2
Upper Result Threshold
Lower Result Threshold
Result Thresholds as
% of range
absolute value
Tags
Colors
Result-Case
stress[kN/cm2]
-3.72e-02
-3.26e-02
-2.79e-02
-2.33e-02
-1.86e-02
-1.40e-02
-9.31e-03
-4.66e-03
0.00e+00
1.03e-01
2.05e-01
3.08e-01
4.11e-01
5.13e-01
6.16e-01
Autosave complete (170 seconds ago)
3:52 PM
3/24/2021

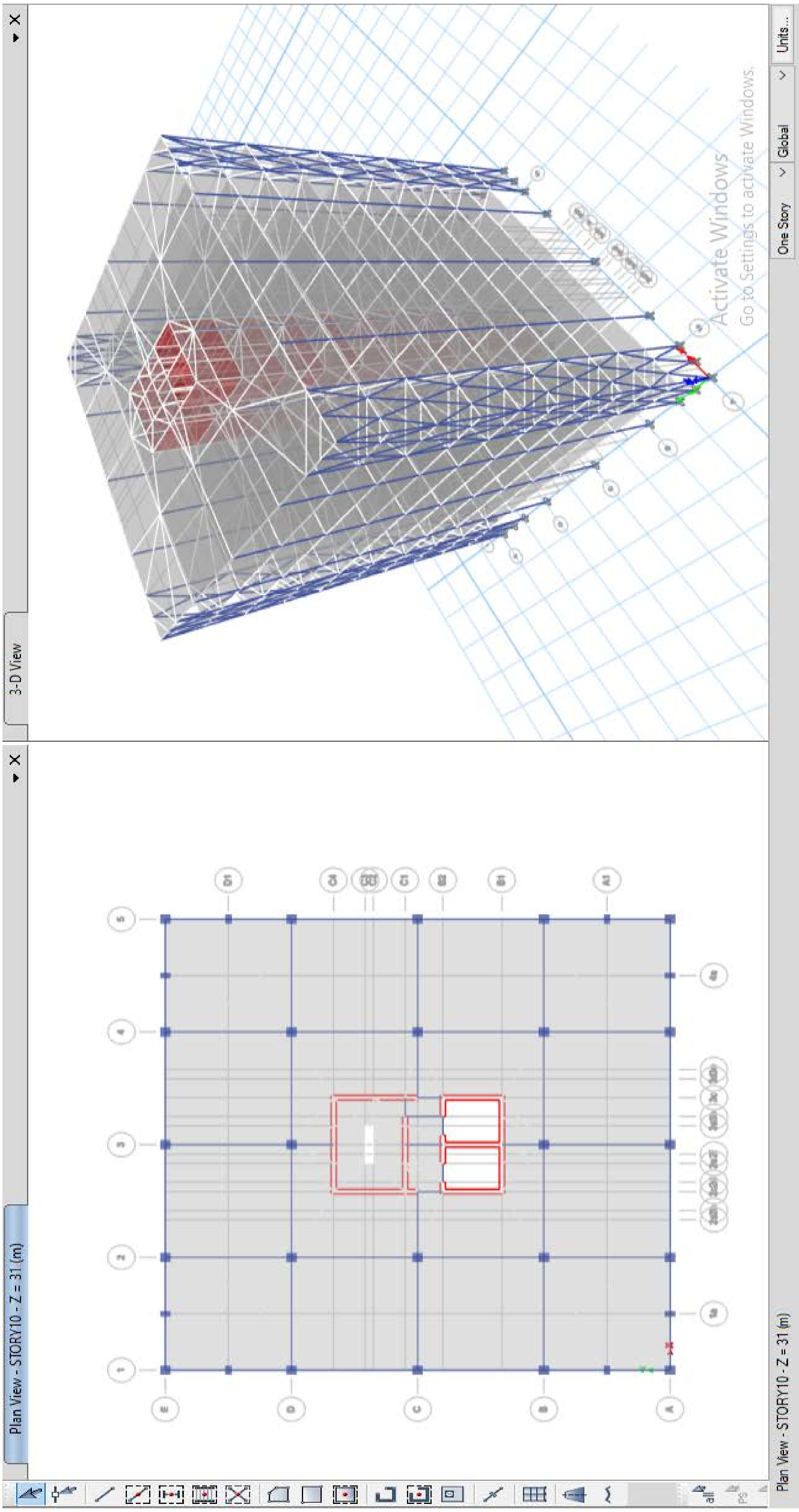

Grasshopper - Dorezimi 20 Mars 2021*
ModelView
ShellView
Display Scales
Render Settings
Cross section
Utilization
Displacement
Princ. Stress 1
Princ. Stress 2
Van Mises Stress
Position of results
Princ. Stress 1-2
stress[kN/cm2]
-7.25e-01
-6.34e-01
-5.44e-01
-4.53e-01
-3.62e-01
-2.72e-01
-1.81e-01
-9.06e-02
0.00e+00
4.95e-03
9.91e-03
1.49e-02
1.98e-02
2.48e-02
2.97e-02
Autosave complete (150 seconds ago)


Grasshopper - Dorezimi 20 Mars 2021*
File Edit View Display Solution Help
Params Maths Sets Vector Curve Surface Mesh Intersect Transform Display Kangaroo2 LunchBox Karamba3D V-Ray
ModelView
Model
R-Factors
ResCase
Colors
Ids|Breps
defMesh
defAxes
defModel
Display Scales
Render Settings
Length/Segment [m]
Upper Result Threshold
Lower Result Threshold
Result Thresholds as
% of range
absolute value
Tags
Colors
Result-Case
ShellView
Mesh
Legend C
Legend T
LayerInd
Local layer axes
Cross section
Utilization
Displacement
Princ. Stress 1
Princ. Stress 2
Van Mises Stress
Position of results
Princ. Stress 1-2
stress[kN/cm2]
5.78e-03
5.87e-02
1.12e-01
1.64e-01
2.17e-01
2.70e-01
3.23e-01
3.76e-01
4.29e-01
4.82e-01
5.35e-01
5.87e-01
6.40e-01
6.93e-01
7.46e-01
Autosave complete (140 seconds ago)
Dorezimi 20 Mars 2021.3dm (2 MB) - Rhinoceros 6 Commercial
Command: P
Perspective Front Right
End Near Point Mid Cen Int Perp Tan
3:52 PM
3/24/2021

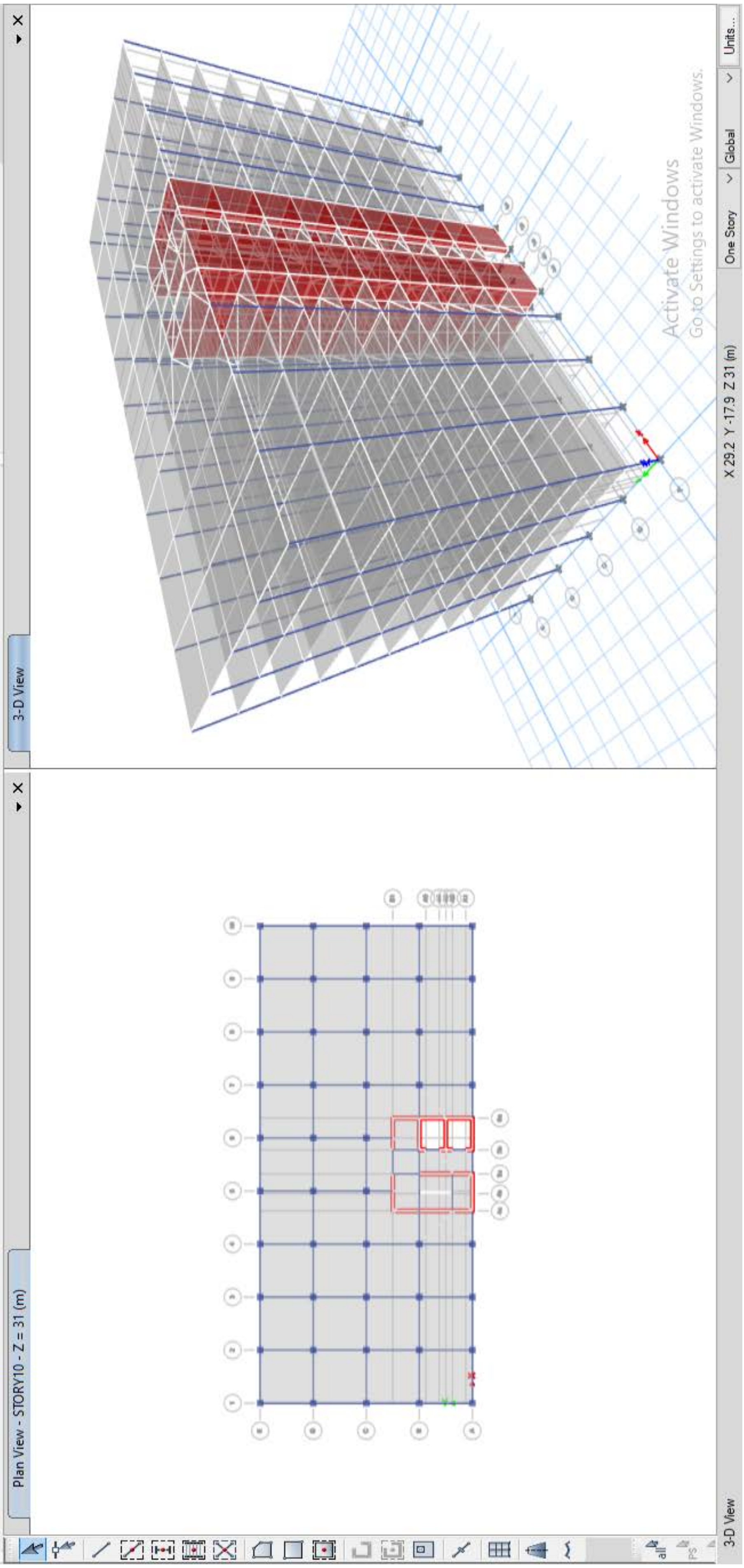

Grasshopper - Dorezimi 20 Mars 2021*
Dorezimi 20 Mars 2021.3dm (2 MB) - Rhinoceros 6 Commercial
ModelView
Model
R-Factors
ResCase
Colors
Ids|Breps
defMesh
defAxes
defModel
Display Scales
Deformation
Reactions
Loads
Supports
Local axes
Joints
Render Settings
Tags
Colors
Result-Case
ShellView
Mesh
LayerInd
Legend C
Legend T
Local layer axes
Cross section
Utilization
Displacement
Princ. Stress 1
Princ. Stress 2
Van Mises Stress
Position of results
Princ. Stress 1-2
stress[kN/cm2]
6.11e-03
4.18e-02
7.75e-02
1.13e-01
1.49e-01
1.85e-01
2.20e-01
2.56e-01
2.92e-01
3.27e-01
3.63e-01
3.99e-01
4.35e-01
4.70e-01
5.06e-01
5.42e-01
equest displacement
1.368059
0.000061
LCase
Perspective
Front
Right
3:46 PM
3/24/2021

9 Appendix C: Structural Models of Multi-Storey Building Type 1 & 2

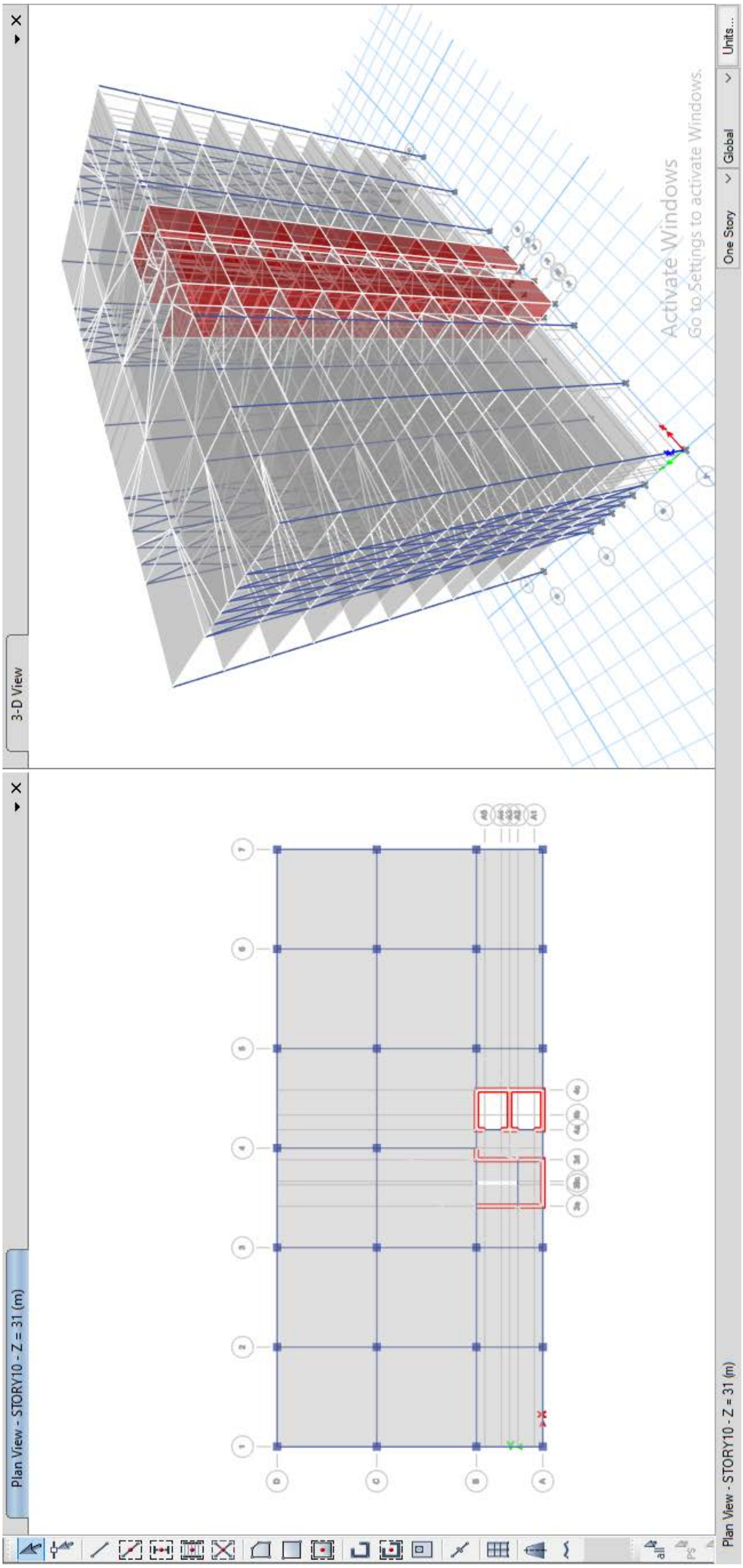

Plan View - STORY10 - Z = 31 (m)
3-D View
One Story
Global
Units...
Activate Windows
Go to Settings to activate Windows.



Plan View - STORY10 - Z = 31 (m)
3-D View
Activate Windows
Go to Settings to activate Windows.
One Story
Global
Units...



Plan View - STORY10 - Z = 31 (m)
3-D View
X 29.2 Y -17.9 Z 31 (m)
One Story
Global
Units...
Activate Windows
Go to Settings to activate Windows.


Plan View - STORY10 - Z = 31 (m)
3-D View
One Story
Global
Units...
Activate Windows
Go to Settings to activate Windows.