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# FEM strategies for Large Scale Thermo-Mechanical Simulations with Material Non-linearity

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**Abstract.** Numerical techniques based on the Finite Element Method (FEM) are mature to provide computational tools that permit multi-physical problems to be dealt with. A relevant case concerns thermo-mechanical simulations of industrial components and processes. Nevertheless, a thermo-mechanical FEM model generally requires a transient non-linear analysis where the variation of material properties with temperature, as well as plasticity and creep, have to be considered. It follows that large scale models are often obtained and unfeasible computational time is thus required. The aim of this work is to put in evidence the possible scale reduction that can be achieved introducing model simplifications based on a practical engineering approach.

## 1. Introduction

The Finite Element Method is a powerful tool to investigate the thermo-mechanical behavior of industrial components and processes. The main computational aspects have been examined in depth [1] and several commercial codes are available (i.e. see [2]). Nevertheless, the scientific literature still lacks of practical guidelines to deal with large-scale problems. In fact, such simulations, as a matter of principle, require a transient analysis of a three-dimensional model, where several non-linearities have to be taken into account (variation of the material properties with temperature, plasticity and creep) [3]. It follows that, quite often, unfeasible computational time is required. The aim of this work is to present practical modelling strategies suitable to reduce significantly the scale of the problem.

A few representative examples are here discussed. It is shown that in certain circumstances a transient analysis can be replaced with a steady state simulation. Nevertheless, if a transient analysis cannot be avoided, a huge reduction of the problem dimensionality can sometimes be achieved by referring to harmonic models or, when cyclic plasticity has to be considered, by applying a useful acceleration technique based on an appropriate correction of the stabilization speed in a combined non-linear kinematic and isotropic model.

## 2. Transient or Steady State Analysis

A thermo-mechanical simulation generally consists of a transient thermal analysis followed by a mechanical analysis. Considering the non-linearities due to the variation of material properties with temperature (conductivity, modulus of elasticity and yield strength), the simulation time can be quite long, especially when the virtual prototyping approach is implemented in the design phase and several

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simulations, according to different configurations, are required. It is thus a useful practice to check preliminarily if a steady state thermal analysis is able to give acceptable results. As an example, the case of fire door is here presented. Such component must comply with product certification requirements, which usually need a fire test, where one side of the component is heated by means of a prescribed temperature-time relationship. Throughout the duration of the test, the component must fulfill specific thermal and mechanical requirements. In particular, the mean temperature on the cold side (not exposed to the fire) should not exceed a prescribed value and the maximum gap between panels and frame should not allow flame and/or smoke to propagate. Recently it has been observed [4, 5], that an uncoupled thermo-mechanical FEM analysis is able to assess accurately the distortion induced by the thermal loads.

A fire door is constituted by two thin steel plates with an insulating material (e.g. rock wool) in between, which is able to act as a thermal barrier that prevents heat flow.

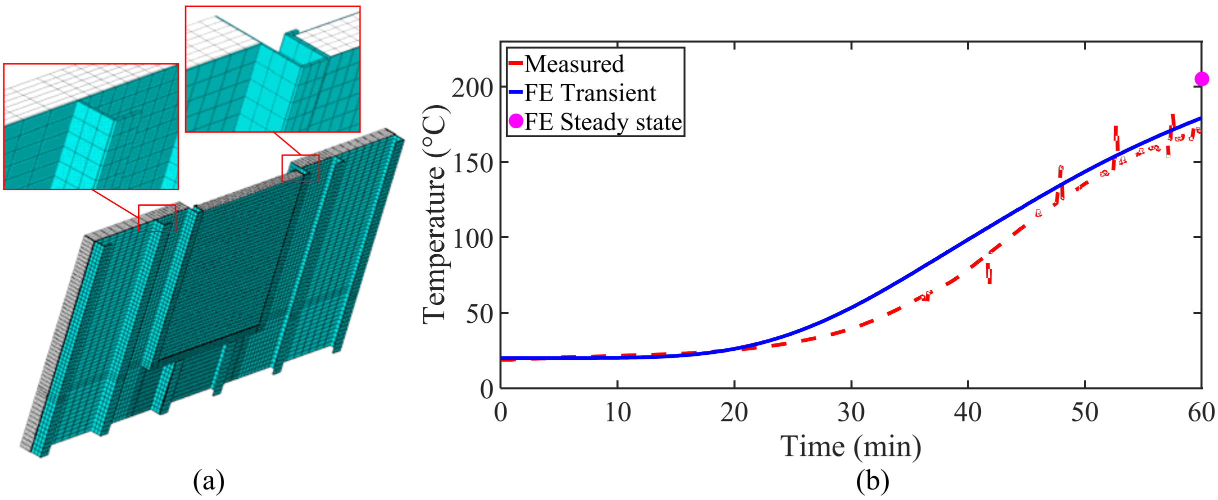


**Figure 1.** FEM simulation: fire door FEM model (a) comparison between the steady state and the transient cases with measurements (b).

Figure 1a presents the FEM model (halved geometry, due to the symmetry with respect to a meridian horizontal plane) with a significant number of element. In figure 1b, the temperature on the cold side of the door is shown according to a transient and a steady state analysis. The comparison with measurements shows that the approximate solution gives quite satisfactory results. This is due to the fact that, in this case, the temperature variation in the oven is quite slow and, therefore, a negligible error is introduced by imposing directly the oven temperature to the hot side of the door.

## 3. Symmetry, Axi-Symmetry and Semi-Analytical FEM

In FEM modelling a well-known and widely used approach to reduce the dimension of the problem is that of exploiting any symmetry, if present. Referring to the thermo-mechanical analysis, in [6], the double symmetry along the longitudinal axis allows the behavior of a squared mold for continuous casting to be modeled by considering only one fourth of the geometry. In the case of an anode for electric arc furnace [7], the evaluation of the stress and strain induced by a thermal cycling requires also a phase change transition to be modelled; in fact, very high temperatures can be reached and it may happen that some areas undergo a partial melting. It follows that the model complexity (and consequently the computational time) strongly benefits from adopting a plane axi-symmetric model.

A less obvious and more interesting case of scale reduction is that of a work roll in hot rolling plants. If the study is not addressed to the process, but to the component, and if a durability analysis has to be carried out, a transient thermal analysis (material conductivity varies with temperature), followed by a non-linear mechanical analysis (Von Mises plasticity with kinematic hardening and material properties varying with temperature) has to be performed. Even if a plane model is adopted [8], unexpectedly, a

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huge computational time is required, in particular to perform the mechanical analysis. By observing that the work roll has an axi-symmetric geometry and is non-axisymmetric loaded (thermal flux coming from the billet and water cooling acting non-axi-symmetrically), a semi-analytical method [9] based on 1D harmonic finite elements can be adopted. Although such an approach is generally used to address three-dimensional problems, in this case it is used to make one-dimensional a two-dimensional case, as shown in figure 2. Adopting a plane model, a transient time of 43 seconds was simulated in 10 days. On the contrary, the harmonic one-dimensional model permits the mechanical behavior over a larger time interval to be easily simulated with reasonable computational times (3-4 hours).

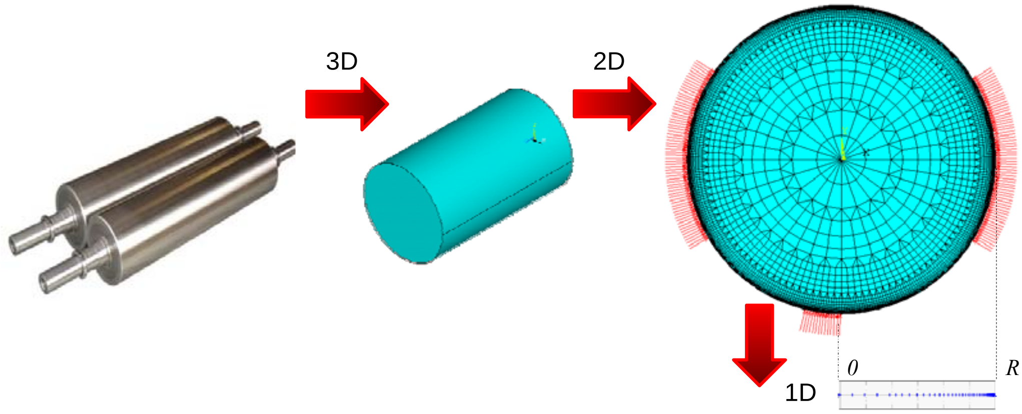


**Figure 2.** Working roll simplified model: from 3D to 1D.

## 4. Acceleration of the Simulation by Modifying Material Parameters

Often thermo-mechanical analysis is performed in the framework of a durability analysis [10], in particular when cyclic thermal loads are sufficiently high to produce plasticization in some areas of the mechanical component under investigation. In this case, it has been observed [11, 12] that the cyclic plasticity material model has to be defined accurately, generally making use of combined non-linear kinematic and non-linear isotropic models (monotonic hardening was simulated with a Chaboche model, using three pairs of $C$ and parameters, while cyclic softening phenomena was described with Voce approach). Variation of material parameters with temperature was also taken into account. Typical case is that of a mold for continuous casting of steel, which provides an initial solidification of the steel product. Molds are generally constituted by a pipe made of copper alloy and surrounded by a steel jacket. The cooling water circulates in the cavity between these two parts. Due to the presence of molten steel, the mold undergoes a high thermal flux and consequently high thermal gradients and stresses exceeding yielding are produced (see figure 3a). Moreover, during service, the component is subjected to fluctuating thermal loads because of planned switch-offs for maintenance. Such loads can lead thermal cracks to nucleate, thus reducing the component service life [13, 14]. A thermal distortion can be also observed [15, 16].

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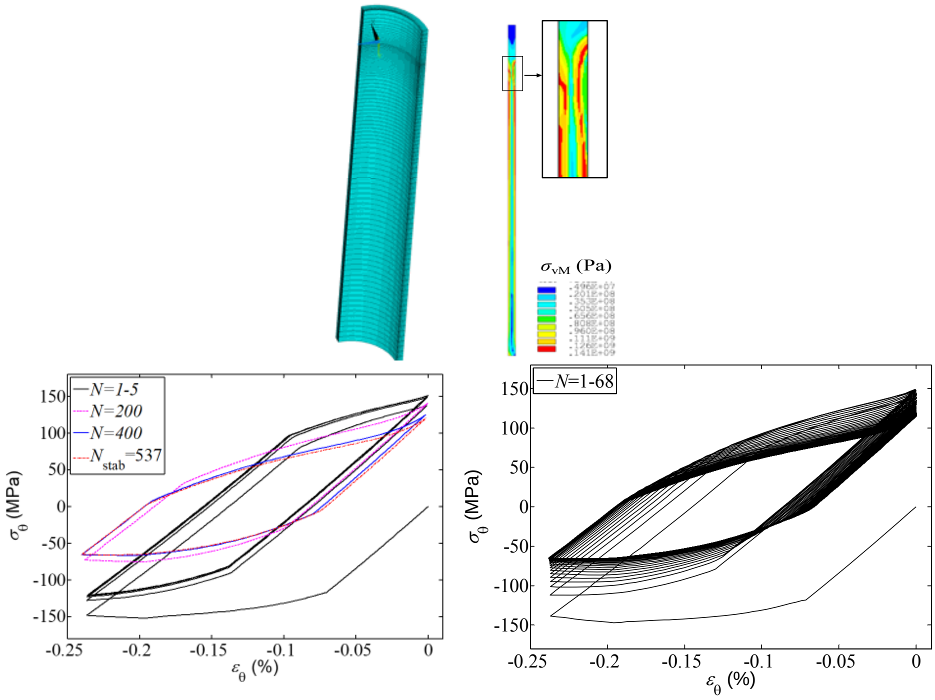


(a) (b) (c)

**Figure 3.** FEM model and von Mises stress distribution (a), evolution of the hoop stress-strain curves: combined (b) and accelerated (c) models.

To perform a durability analysis, it is necessary to estimate accurately the stress-strain evolution caused by the fluctuating thermal flux up to stabilization. In certain circumstances (material characteristics, amount of plastic strain range induced by thermal loads, etc.), the number of cycles to reach stabilization could be very high, and therefore the simulation could be unfeasible. An acceleration technique has been proposed in [17, 18] to speed-up the analysis, this approach being based on a fictitious increment of the parameter governing the speed of stabilization in the isotropic model. Figure 3b displays the stress-strain evolution that occurs in the most stressed part of the mold. It can be observed that stabilization is reached after 537 cycles, which means that a huge number of heating and cooling cycles have to be simulated. Figure 3c shows the same case, where the isotropic model was corrected by increasing the parameter controlling the speed of stabilization, in order to reach stabilized conditions only after 68 cycles. This approach permits a strong reduction of the computational time without affecting significantly the equivalent strain range in stabilized condition and therefore permitting a correct durability analysis to be subsequently performed [19].

## 5. Discussion and Conclusions

In this work several engineering applications requiring a thermo-mechanical FEM simulation were discussed. Although such models generally imply a very high computational time, possible strategies to shorten the analysis, without affecting significantly the results, were presented. Tab. 1 summarizes the results; in the presented cases it can be observed that a drastic reduction of the computational time, up to 80%, is always achieved. In particular, substituting a transient with a steady state analysis permits a 95% reduction of the computational time. When a durability analysis has to be performed and the component is subjected to thermal cycles which induce plasticity and, therefore, a thermal fatigue analysis has to be performed, acceleration techniques based on combined non-linear kinematic and isotropic models seem providing quite promising results (88%-time reduction). Even higher scale reduction (98%) can be achieved by using harmonic elements.

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**Table 1.** Comparison between the presented cases.

| Case | Type of model-analysis | Computational time | Time reduction (%) |
|---|---|---|---|
| Fire test | Transient | 20 min | 95 |
| | Steady state | 1 min | |
| Roll mill | Plane model | 10 days | 98 |
| | 1D Harmonic model | 4 hours | |
| Mold | Combined model | 108 min | 88 |
| | Accelerated model | 14 min | |

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