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MULTISCALE SIMULATION OF THE THERMOMECHANICAL BEHAVIOR OF CONTAINMENT BUILDINGS OF NUCLEAR POWER PLANTS

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Abstract: The prediction of the leakage rate of containment vessels in double-walled nuclear power plants is of particular importance given the role of the structure. As the third containment barrier, it must indeed guarantee a certain level of leak tightness in order to perform its function fully. Traditionally, the estimation of the leakage rate is based on simulation and includes a good knowledge of the hydric state (degree of saturation) and of the potential mechanical disorders (potential cracks). These quantities are then associated with transfer laws (generally damage - or crack opening - permeability) in a chained (thermo)hydric/mechanical approach. This paper describes the evolutions in the methodology used to predict the mechanical behavior of containment buildings, for which numerous developments have been made in recent years. After introducing a brief history of mechanical behavior simulation practices at this scale (direct application of damage mechanics for example), significant improvements, in terms of representativeness and performance of the mechanical calculation, will be discussed. A particular attention will be paid to scale change using evolving static condensation, from the containment buildings to Representative Structural Volume, on which the application of more refined approaches become possible. Finally, discussions on open issues are proposed towards simulating the behavior of a real structure.

1 INTRODUCTION

Reinforced and prestressed concrete containment buildings represent the third passive barrier in nuclear power plants (defense-in-depth concept). They thus play a key role in plant safety by limiting potential releases to the environment in the event of an accident [1]. For these structures, a loss of tightness during operation or during an accident would have a major impact. That is why they are closely monitored, particularly during ten-yearly inspections, which decide whether to extend reactor operation for a further ten years.

Reinforced concrete is a material whose properties change over time, either “naturally” (drying inducing a change in the degree of saturation, endogenous shrinkage, desiccation, etc.), through interaction with the environment (corrosion…) or under the effect of external stresses (prestressing loading inducing creep, pressurization of the structure during ten-yearly inspections, accident situations, etc.). All these coupled thermo-hygro-mechanical phenomena have an impact on the macroscopic properties of the material, leading in some cases to the appearance of homogeneous (micro-cracking) or even localized (macro-cracking) mechanical degradation. This mechanical degradation has a direct impact on the transfer properties that characterize the tightness of the structure [2].

This issue is particularly central to the containment systems of 1300 and 1450 MWe reactors in France (Figure 1). Contrary to single-wall containments with steel liner (900 MWe reactors), in double-walled system, it is the reinforced and prestressed concrete of the inner vessel that ensures the structure's tightness. It must therefore provide guarantees that its functionality will be maintained over time.

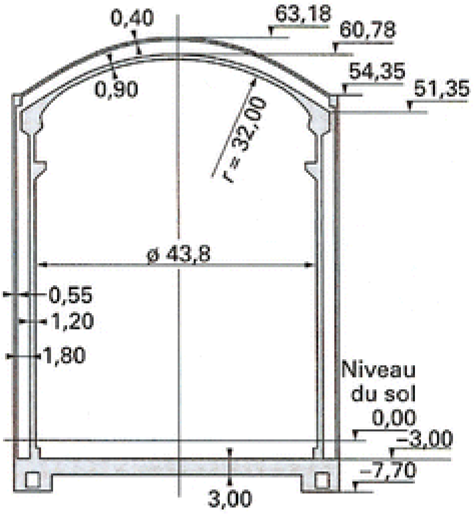

Figure 1. Principle and dimensions of double-wall containment [1]

Figure 2. Indian containment buidling mockup [3]

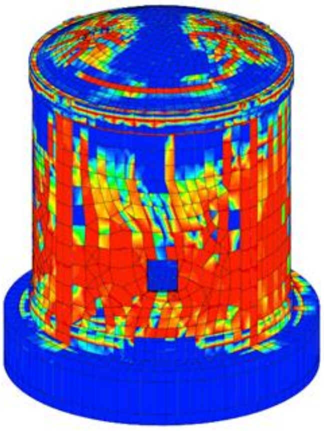

Figure 3. Example of direct application of damage mechanics to Indian BARCOM mockup [4]. Red zones are the most damaged ones

The size of the containment and its role in reactor safety almost preclude any on-site experiments that might compromise its integrity. Numerical tools are therefore preferred for assessing mechanical behavior and its evolution over time. To achieve these objectives, however, two problems have to be solved that are hardly compatible: characterizing local information (damage or crack opening - characteristic order of magnitude close to ten micrometers) with tools that can be applied on the scale of a large structure (characteristic magnitude greater than ten meters). The example of the direct application of damage models to an Indian reactor containment mock-up (Figure 2) is a good illustration of this difficulty. While the overall mechanical behavior can be correctly reproduced by simulation (maximum admissible pressure, overall deformation, etc.), it is difficult, at this scale, to define the state of cracking from the distribution of internal variables alone (Figure 3). At best, averaged information within a mesh element (characteristic size of several centimetres) is obtained, but this information is not sufficient to guarantee a good description of hydraulic transfers. Thus, characterizing the mechanical behaviour of a containment vessel, and consequently assessing its degree of tightness, logically implies the use of a multi-scale modelling strategy, first to validate the numerical tools and then to obtain adapted information about the cracking. In this contribution, different scales will be described, along with some numerical developments at each scale. Application to VERCORS mockup will be presented, to highlight the progress at the target containment scale. Finally, necessary remaining developments to relate all the scales will be discussed in the conclusions.

2 DEFINITION OF MODELING SCALES

Based on the very nature of the concrete material, several scales can then be defined (Figure 4), depending on the finesse of the phenomena studied:

Figure 4. Definition of the different scales for concrete

- The scale of the reference structure, in this case the containment vessel of a nuclear power plant (characteristic size more than ten meters). At this scale, numerical tools are essentially aimed at characterizing the overall behavior of the structure, as numerical costs are prohibitive for fine characterization of mechanical degradation,
- The scale of the structural element (characteristic size of the order of a meter), for which it becomes possible to use representative and robust numerical approaches. The models remain global, but can include interactions between different components (e.g. evolution of the bond between steel and concrete in the case of reinforced concrete),
- The scale of the laboratory specimen (characteristic size of the order of ten centimeters) from which global models can be calibrated. This is typically the scale at which macroscopic behavior laws are written and validated,
- Finally, the scale of the material component (or mesoscopic scale), essentially used to identify local mechanisms, understand the physics or help calibrate macroscopic evolution laws.

In the following sections, illustrations of recent developments at different scales will be proposed including “scaling” approaches to link scales together.

2.1 From mesoscopic to macroscopic scales: the example of the bond slip law

Classically, the introduction of steel bars into concrete is intended to provide the whole structure with greater tensile strength than concrete alone, and more ductile behavior. In the event of concrete cracking, the reinforcements allow stresses to be transferred from the concrete to the steel, then redistributed around the crack from the steel to the concrete. If cracking properties (opening and spacing) are to be correctly represented, the interactions between the two materials need to be modeled. Considering these mechanisms at the scale of the structural element requires the use of simplified models, as an explicit representation of the steel-concrete interface is difficult to achieve (mesh complexity, numerical cost...). The most common are interface elements, associated with evolution laws linking bond stress to steel-concrete slip [5]. Given the complexity of these input laws, which are generally empirical [6], the mesoscopic scale may be considered in order to better understand local phenomena and help calibrate the interface model. Figure 5 and Figure 6 [7] illustrate the use of the mesoscopic scale to better understand the local evolution of the mechanical degradation around a steel bar, when subjected to pullout tests.

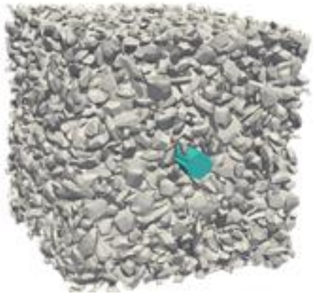

Figure 5. Mesoscopic representation of a concrete volumen including a steel bar

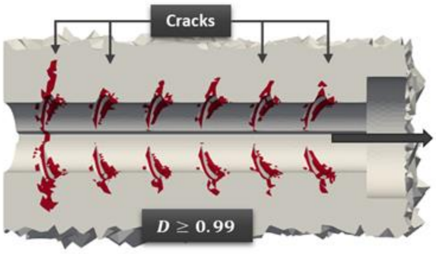

Figure 6. Damage distribution at the steel – concrete boundaries using the mesocopic scale [7]

Figure 7. Application of the adaptive static condensation to a mockup of a containment building (VERCORS) [11]

Steel and concrete are modeled using classical constitutive laws (plasticity and damage models respectively), while the steel-concrete bound is represented through dedicated interface elements. This makes it possible not only to analyze local behaviors (potential effect of the aggregates, sensitivity analysis on the material properties…), but also to provide input for the determination of a bond stress-bond slip law, which can then be integrated into a dedicated macroscopic model. In this sense, it naturally illustrates the relation between mesoscopic and macroscopic scales.

2.2 From structural element to reference structure: the example of the adaptive static condensation

Given the significant dimensions of the containment buildings, one of the major challenges is to reduce numerically the size of the system from the scale of the reference structure to that of a structural element (Figure 8), whose dimensions are more suitable for nonlinear simulations.

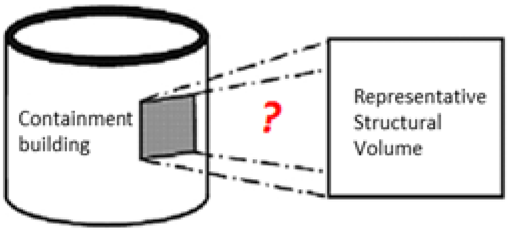

Figure 8. Principle of the Representative Structural Volume

Various approaches can be envisaged for this purpose. For example, domain decomposition, combined with the use of parallelization techniques [8], makes it possible to calculate several structural volumes simultaneously, which are then “reassembled” to obtain the complete response. The overall numerical cost is therefore reduced by the use of parallelization. However, in certain situations, this solution may not be optimal, as it requires the calculation of mechanical behavior over the entire structure. In the case of assessing leakage through localized cracks, the area concerned by non-linear behavior is spatially limited. It does not make sense to model the mechanical behavior of the entire structure, but rather to concentrate the numerical effort on the zone(s) of interest (crack development zone). This is the principle behind the adaptive static condensation method [9]. This method is based on a decomposition of the structure into zones of interest and condensed zones. Degrees of freedom in the condensed zones are “eliminated” using the static condensation method [10] and by defining equivalent rigidities and loadings at the boundaries of the zone of interest. During calculation, criteria for propagation and the creation of new zones are tested. If one or more of these criteria are met, the system evolves (“adaptive condensation”) with new zones of interest. Under these conditions, it becomes possible to simulate the mechanical behavior of the structure while significantly limiting the numerical cost.

Figure 7 illustrates the results obtained on a simplified pressurized enclosure model. Only the non-linear behavior of the colored zones (damage distribution) is actually calculated, thus reducing the load and overall calculation time. The figure shows a concentration of mechanical degradation around the openings, which represent geometric heterogeneities.

3 PROGRESS AT THE CONTAINMENT SCALE

In parallel with developments at the intermediate scales that have been illustrated in the previous sections, progress has also been made for the simulation of the behavior of the containment directly. The more significant example is probably the recent VERCORS benchmark. VERCORS mock-up is a double wall containment building (Figure 9), and the inner vessel is designed as prestressed reinforced concrete structure. To accelerate aging effect, which results from drying process in concrete, the mock-up is reduced at 1/3 scale compared to a real containment building. The total height is 19.8 m; 7.7 m for the radius; 0.4 m for the thickness of the wall and 0.7 m for the bottom thickness of the gusset. This reduction scale speeds up the drying in concrete approximately by a factor of 9 in comparison with the real containment building. The structure was built by EDF. To support the experimental campaign, numerical benchmark have been launched. In this context, a numerical methodology was developed to assess the mechanical behavior and the tightness of the reinforced and prestressed structure.

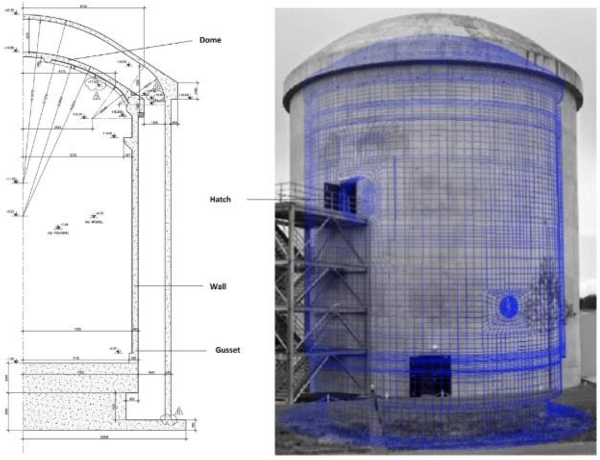

Figure 9. Principle of VECORS mockup [12]

Contrary to the past simulations (see section 1), which supposed the direct application of the damage mechanics on the structure, the proposed methodology is done in two main steps:

- a thermohydromechanical (THM) analysis to reproduce the initial cracks in the gusset. It includes classical thermal and hydric models, weakly coupled to a mechanical part, taking into account thermal expansion, drying shrinkage and resulting mechanical damage [13].
- then, prestressing and pressurization phases, at the scale of the whole mockup, considering the initial state from the first analysis, are modeled. The rest of the structure, i.e. the cylindrical wall, the raft foundation and the dome are then included. At the beginning of prestressing, the full-scale simulation is started with the initial damage state in the gusset that is obtained from the previous THM analysis, whereas new added structures are considered as zero damage. A simplified model, based on [14] is considered for delayed strains (creep and shrinkage). Prestress losses are modeled. The mechanical degradation is tackled through the same constitutive law as in the first step.

With these conditions, the crack opening distributions illustrated in Figure 10 are obtained. Due to THM analysis, several vertical cracks in the gusset are detected for the initial state, and those cracks are also observed experimentally. It is worth to mention that those cracks result from the displacement constrains between the extension of thermal effect (heated temperature) and contraction of shrinkage strain. Those vertical cracks are uniformly distributed due to the regular geometry and distribution of reinforcements. In prestressing phase, concrete pertains the compression stress, and the unilateral effect in the constitutive law of concrete partially closes the crack opening coming from the previous THM analysis. Aging effect of concrete, which results from the delayed strains, contributes to increase the prestress loss. As consequence, pressure test makes the crack opening re-open and even larger than those observed in the THM stage.

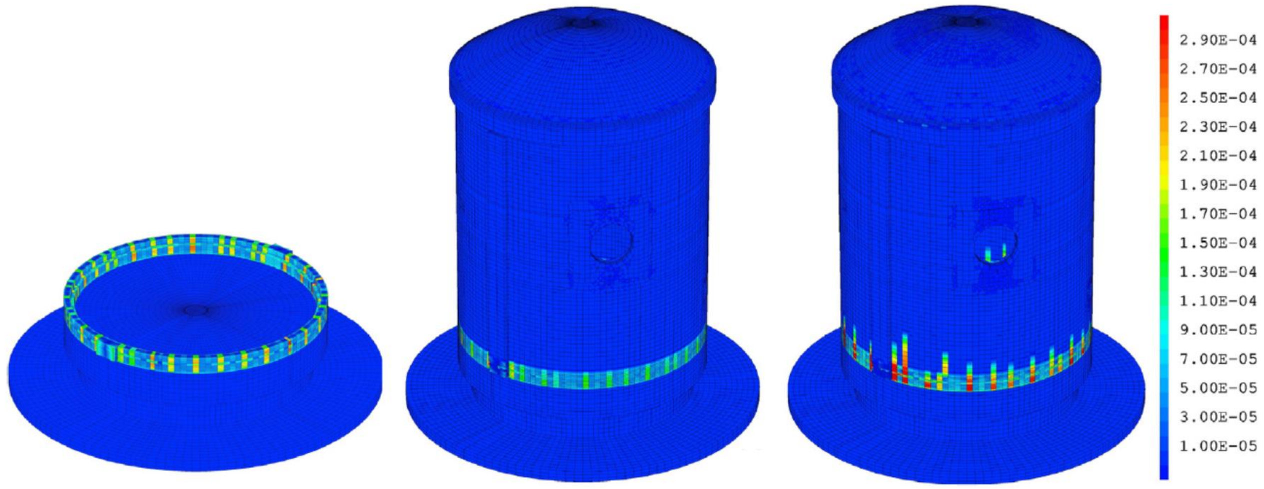

Figure 10. Distribution of the crack openings. From left to right : initial state, after prestress, after pressurization [13]

Details of the simulation results can be found in [13]

4. SUMMARY AND PERSPECTIVES

This contribution aimed at presenting the continuous progress that have been proposed in the simulation of the mechanical behavior of containment buildings (or of representative scaled mockup) since the first attempt decades ago. New methodological approaches show the improvements at the direct scale of the containment: the physical effects are better represented and post-processing methods enable to reach more interpretable quantities (like crack opening). These developments go hand in hand with work at intermediate scales, as illustrated in this contribution for steel-concrete bond or adaptive static condensation for example. At their respective scales, these tools enable to produce more representative results for quantities related to cracking: redistribution of the stress due to the bond in the first case, access to more refined meshes in the second. The next step will be to further improve the cross-functionality of these tools, so that they can be combined to achieve a fully multi-scale treatment of cracking in large-scale structures, such as containment vessels, in a thermo-hydro-mechanical context. Work in this area is currently in progress.

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