The current European standard design code (EN 1992-1-1 (2004)) proposes empirical methods for assessing cracking risk and deducing reinforcement rates. Nevertheless, it is observed in the field that these rules sometimes lead to a non-optimal distribution of rebars in massive structures, where cracking can occur despite the fulfillment of the design rules. The problem seems to be linked to the fact that the present design rules were mainly worked out to control cracking in common slender structural elements (namely beams and columns of buildings). In large structures, phenomena like early age heating due to cement hydration or autogenous shrinkage play a major role and can no longer be neglected. Also, in large structures, the traditional simplified approaches based on approximations of the kinematics (Navier’s assumption for example) or simplified concrete behavior laws (without softening) are not sufficient and three-dimensional non-linear finite element analyses should constitute a reference background for determination of the provisions which can ensure control of cracking.

This paper presents the national state of the art in the field of non-linear finite element analysis capability applied to massive reinforced concrete structures. It includes a brief presentation of cases studied by the various French research teams having joined the National Project. Noteworthy among the cases considered are a nuclear confinement wall studied at early age, a massive cylinder subjected to a temperature gradient and several reinforced concrete beams under cyclic moisture boundary conditions. Starting from this state of the art, the project, which will last a total of four years from 2008 to 2012, aims to propose enhanced finite element modeling and its validation on large experimental structures. Results should provide a better understanding of cracking in such structures so that improvements can be suggested to the standards committee for European design rules. In the present paper, only THCM results of the benchmark are commented to point out research needed in the domain. First the moisture transfer dominant case is discussed; it is a concrete beam subjected to a time dependent moisture boundary condition. The second case concerns a massive cylinder subjected to a thermal gradient. The last one is a thick wall studied at early age.

ABSTRACT: The paper reports the state-of-the art review conducted within the French national R & D Project called CEOS.fr related to concrete cracking assessment under thermo-hydro-chemo-mechanical (TCHM) loading. The whole project also concerns static and cyclic mechanical loading but this paper deals only with THCM loads. Three types of THCM problems (Moisture effect dominant, thermal dominant and early age dominant) were studied by five French laboratories. The paper summarizes the main research needs pointed out by the benchmark.
2. BEAMS UNDER TIME DEPENDENT MOISTURE BOUNDARY CONDITION

2.1 Geometry and boundary conditions

The tests were carried out by Multon et al. (Multon et Toutlemonde, 2004, Multon et al., 2006). The history of the boundary conditions of the beams and their geometry are given in Figure 1.

![Figure 1: Beam geometry (dimension in mm) and moisture boundary condition variations](image)

2.2 Results analysis

A first step consisted in fitting the model parameters on a series of experimental results on cylinders kept in the same conservation conditions. The objective was to find the mass variation and displacements of the beams versus time. Figure 2 shows the mass variation simulated by the five teams (LMDC Toulouse, LMT Cachan, EDF-CIH Cambéry, CEA-LECBA Saclay, CSTB-MOCAD Champs sur Marne). Despite a good prediction during the drying period, an underestimation of the mass regained and a discrepancy of simulations increasing with time were noticed from the change of the top boundary condition (just after 14 months). The inadequacies of this modeling were attributed to the non-consideration of hysteresis in the water retention curve and to an underestimation of the relative water permeability coefficient in this phase.

![Figure 2: Mass variation prediction compared with experimental results](image)

In addition to the mass variation, the beam displacement had to be predicted. Figure 3 shows the results. Rather good simulation can be observed during the drying phase, but a large discrepancy of the response appears during the second phase (wetting of the top of the beam). Among the various responses, two models give a total return from the deflection: the CSTB...
and the CEA models (although the phenomenon is delayed for the latter). These two models are based on hydro-mechanical formulations without creep, unlike the other models (EDF and LMDC), which include a creep module in their constitutive equation. This case shows the necessity of taking creep strains into account for a long term hydro-mechanical simulation. Analyses of the predicted damage pattern and of the stress state at the end of the test also showed that neglecting creep led to an over-estimation of the stress and consequently of the damage state.

![Figure 3: Deflection of the beams versus time](image)

3 CYLINDER UNDER THERMAL GRADIENT

3.1 Geometry and boundary conditions

The concrete cylinder characteristics are given in (Ranc et al. 2003) and summarized in Figure 4. The concrete structure under study (called MAQBETH by its designers) was not fully characterized so the participants had some latitude in fitting some terms of their model on published results. Two teams carried out the related numerical analysis: CEA-LECBA and CSTB. Both used a fully coupled hydro-mechanical formulation using a damage model to describe the cracking. The gas and water transfers were linked to the damage state.

![Figure 4: Cylinder under thermal gradient (dimension in m)](image)

3.2 Results analysis

Although the models used were able to reproduce the temperature profile (Figure 5), the gas pressure in the pores (Figure 6) and the relative humidity profiles (Figure 7) were more difficult to obtain. This is particularly visible on the RH profile in Figure 7 where it can be seen that, on the heated face, CEA-LECBA gives an RH equal to zero while CSTB found a value of 50%.
In fact, both teams had difficulty in obtaining a correct RH profile in zone (a) (Figure 7). The CSTB model underestimated the RH in this zone and compensated by moving the corresponding boundary condition up. In contrast, the CEA overestimated the RH in the same zone and consequently moved the boundary condition down to obtain a better fit. Finally, both models had difficulties predicting the RH correctly in the hot zone. This was certainly due to the difficulty in precisely estimating the different terms of the water mass transfer equation in hot conditions. The water retention curve and consequently the permeability depend strongly on the temperature but this dependence is still poorly understood. For example, Poyet and Charles showed recently that the usual Kelvin-Laplace theory failed to explain the effect of the temperature on the water retention curve and could be advantageously replaced by a sorption modeling based on the Clausius-Clapeyron equation (Poyet and Charles 2009).

On the other hand, the analysis of the predicted damage pattern (given at 200 hours in Figure 8) shows that the models used lead to significant differences. Although both models predict damage in the cold zone, the CEA-LECBA model gives two localized, deep horizontal cracks not found by the CSTB model. As the damage acts on the permeability and on the water retention curve in these models, it is obvious that, from this time on, the vapor pressure fields diverge from one another in the two models. This last remark shows that, after the first significant cracking, the coupling between the damage and the water transfer properties plays a major role. For these reasons, coupling between cracking and water transfer properties needs serious enhancements.
4 THICK CONCRETE WALL AT EARLY AGE

4.1 Geometry and boundary conditions

The last case studied was a large-scale wall cast in Civaux (France) close to the nuclear power plant and representative of typical walls of this structure, 1.20 m thick and 20 m long, cast in two successive lifts, a first one 1.90 m high and a second one 0.90 m high. Temperature measurements were taken at the numbered points given in Figure 9 (a). Two teams carried out the modeling: LMDC at “Université de Toulouse” and LMT at “ENS Cachan”. LMT used two different meshes, a two-dimensional one in plain strains and a three dimensional one. LMDC used a single, more detailed mesh (consideration of soil and pre-stressed reservations). The characteristics of the material, from (Nectoux 1992) and (Granger 1996) were supplied to the participants.

Figure 9 : Civaux’s thick wall geometry and modeling for early age cracking assessment
4.2 Analysis of results

The first objective was to find the temperature evolutions versus time in different locations and to compare them with the measurements made on instrumented points of the wall. Both teams succeeded in this part as illustrated in Figure 10. Note that the LMT prediction was less accurate near the foundation due to the fact that the soil was not meshed in their modeling. Both teams used a hydration model coupling chemical advancement and thermal analysis, allowing a realistic thermal activation of the hydration reactions to be considered.

![Figure 10: Temperature profiles versus time, LMT’s calculations (lines) compared to measurements (dots)](image1)

The main objective was nevertheless to predict the cracking pattern and the date of the first cracking. Concerning these points, the different models led to significant differences as illustrated in Figure 12 and Figure 13. The 2D mesh used by the LMT showed an overestimation of the cracking risk, which appeared sooner than in the field, showing that the plain strain assumption was too severe with respect to the cracking risk assessment. On the other hand, the 3D mesh used by the LMT led to a single horizontal crack at the bottom of the wall just between the foundations and the first part. This crack was also initiated in the 2D LMT mesh. It was due to the high shear stress level reached in this zone during the cooling period. As the foundations constrain the thermal shrinkage of the wall, a longitudinal tensile stress appeared in the wall and was balanced by a compressive one in the foundations. The abrupt change in the stress sign at this level caused this shear stress concentration. Once the shear damage has appeared in the model, the bond between the wall and the foundation is altered and consequently the tensile stress decreases in the wall, avoiding the appearance of vertical cracks. Surprisingly, these phenomena were more limited in the LMDC modeling as shown in Figure 13. The vertical cracks obtained were, however, less numerous than in the field (Figure 14). The difference of behavior between the LMT and the LMDC modeling was not due to the constitutive laws used for the material, since they were almost the same, but to the more realistic mesh adopted by the LMDC. As can be observed in Figure 9, the LMDC meshed the soil, which provided a better
temperature prediction near the wall-foundation interface (Figure 11) and, above all, the pre-
stress vertical reservations from which the vertical cracks started as shown in Figure 13.

Figure 12: LMT Computed damage pattern obtained by the LMT

Figure 13: LMDC damage pattern

Although the LMDC mesh and boundary conditions were better than the LMT’s, the LMDC
modeling seemed, however, to underestimate the crack number (Figure 13 compared to Figure
14). This has been attributed, among other things, to the material characteristics which perhaps
were not assessed accurately enough. In particular, the basic shrinkage and the thermal dilation
coefficient evolution at very early age (around the percolation threshold transition) need to be
clarified. The reinforcement and possibly the tensile creep just after the temperature peak could
also play a major role in the global process of cracking at early age.

Figure 14: In-the-field cracking pattern

Finally, this last benchmark test shows that the cracking risk assessment at early age remains a
difficult exercise because of the need for accurate data, which is difficult to obtain for an evolv-
ing material, but also because of the strong dependence of the result on the mesh realism, which
leads to greater or less stress concentrations, which themselves control the crack pattern.

5 CONCLUSION

The first phase of the French research project CEOS.FR consisted in a numerical benchmark.
Its objective was to point out the ways research could improve the understanding of the cracking
risk in massive structures subjected to various loading types and, in the longer term, to lead
to efficient numerical tools to predict cracking in such concrete structures. Among the different
benchmarks, we have focused on the THCM ones. Each of them has effectively allowed us to
highlight particular research needs.
Concerning the long-term cracking risk under moisture effects, we have pointed out the necessity
to use a hydro mechanical formulation involving a realistic creep model. The need to model
the hysteresis aspect of water retention curves has also been underlined.
Concerning the risk of damage under high thermal gradient, the MAQBETH specimen study again shows the importance of knowing the water retention curve versus relative humidity and temperature, but also the impact of the damage on the permeability. Indeed, the coupling between permeability and damage plays a major role and can lead rapidly to a divergence between the different models after the first cracking.

The last case concerned a thick wall in early age conditions inducing a problem of differential shrinkage between the foundations and the wall. The high dependence of the predicted cracking pattern on the mesh realism and on the boundary conditions was underlined; the necessity to improve this type of modeling, especially around the temperature peak transition was noted.

The CEOS.FR project is now progressing in its second phase, which concerns the improvement of the models and their testing on large reinforced concrete specimens (more than 6 m long and 1 m² cross section). Most of the research paths pointed out in the present paper are currently being approached by the different teams of the project or have been used to build an accompanying research program dealing more specifically with the modeling aspects, the MEFISTO research program, also supported by the French national research agency (ANR) “ville durable” (sustainable development in civil engineering).

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7 REFERENCES