Numerical strategies for prediction of drying cracks in heterogeneous materials: Comparison upon smeared/discrete crack approach and experimental results

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Summary The behaviour of cementitious materials during drying depends on the behaviour of each phase (cement paste and aggregates mainly). Indeed, due to hygrometical imbalance with the environment, cement paste shrinkage is restrained by the aggregates. Stresses are thus induced by these strain incompatibilities at meso scale, leading to debonding at the cement paste/aggregate interfaces and to the growth of intergranular cracks. To accurately predict the durability of these structures requires the development of a powerful numerical tool to account for the influence of drying loadings on the mechanical response. The aim of this paper is to simulate this hydro-mechanical behaviour at meso scale by taken into account the heterogeneity at this scale. Two approaches (damage mechanics and truss lattice with the incorporation of displacement and strain discontinuity) are used and compared to experimental results using digital image correlations.

Introduction

During drying, concrete undergoes an apparent shrinkage called drying shrinkage It leads to self-stresses induced at different scales. At macro scale, drying at the surface of the structure generates moisture gradients inside the structure which will induce drying shrinkage gradients and thus stress gradients [2]: compression in the core and tension near the surface. This structural effect is associated with the apparition of microcracks (openings less than 50μm) near the drying surface and perpendicular to this surface [2]. At meso-scale, we have to consider the two main components of concrete: cement paste and aggregates. Cement paste shrinkage is restrained by the aggregates leading to debonding at the cement paste/aggregate interfaces (circumferential cracks) and to the growth of intergranular cracks (radial cracks). The aim of the paper is to compare different numerical strategies with experimental results on controlled cement-based materials in order to identify the most suitable approach to predict the cracking pattern. Besides, using digital correlation image software Correli-Q4, it is possible to extract the experimental displacement boundary conditions. A tool allowing imposing these boundary conditions into the finite element calculus is currently under development.

Experimental results

A cement paste with a water to cement ratio of 0.57 containing different contents of sandstone cylindrical aggregates (with different diameters) is used as a ‘‘model’’ material mix. Thin layers of these mesostructures (10 mm width) are cut from each block of mesostructure ($100 \times 100 \times 50$ mm^3) after 28 days of hydration. The position of aggregates is determined precisely so as to be able to mesh easily these mesostructures in the numerical simulations. Three thin layer mesostructures constituted of cement paste only are also cast so as to assess cement paste behaviour during drying without interaction with aggregates effects (and check that drying shrinkage gradient do not lead to cracking).

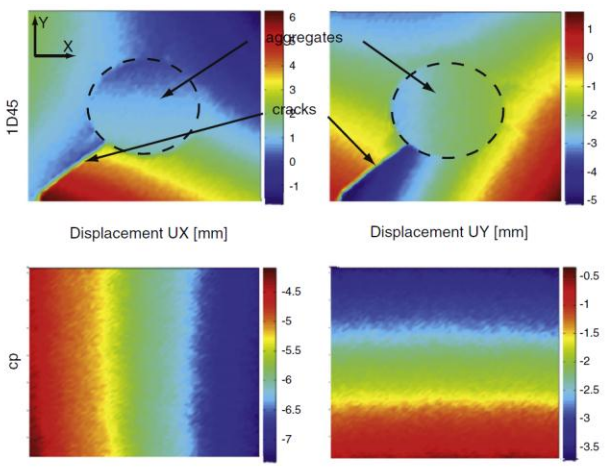

Figure 1 - Displacement fields obtained (along 2 directions) after drying for two types of mesostructures (cement paste only cp and cement paste with one inclusion of diameter 45 mm)

A monitoring of the cracking induced for the different mesostructures has been performed using a digital camera (CANON EOS 350D), at the rate of one shot every 10 min during the 48 first drying hours, on one of the drying surfaces. The evolution of the displacement field on the observed surface is determined by DIC using the Correli-Q4-LMT software [1]. The observed surface is previously recovered by a spraying paint so as to obtain a random texture in order to increase the correlation technique performance. The figure 1 represents two examples of displacement fields obtained after drying for two different mesostructures (cement paste without or with inclusion). Due to the apparition of a crack during drying, we can observe a discontinuity in the displacement field in the case of the mesostructure with one inclusion. This displacement field can thus give us access to a cracking indicator (to unveil the cracks) and to crack openings (displacement gap). However, no cracks have been detected on the cement paste alone.

Numerical simulations

Two numerical strategies are compared (in terms of cracks representation and quantification). The general framework of the modelling of drying shrinkage is the same for both models. However, the mesh (one is adapted and the other is not-adapted), the mechanical model and the displacement/strain interpolation are different [2,3].
The first approach uses a classical smeared crack approach (based on a damage model) developed in Cast3m finite element code. Both cement paste and aggregates are meshed explicitly assuming a perfect bond between these two phases. Since cement paste undergoes softening during cracking, dissipation of energy is regularized using internal length depending on the mesh size [2].
The second approach uses kinematics enhancements adding a discontinuity within its strain field (‘‘weak discontinuity’’) between the 2 phases (separated by “cut-elements”) using incompatible modes method [3]. In order to model these isotropic media, a tridimensional truss built on the spatial Delaunay triangulation and its corresponding Voronoi tessellation is used. The model has been developed in co-Feap.
Figure 2 shows respectively the damage field for the smeared crack model (a) and the cracks opening field for the discrete crack representation (b). On the numerical point of view, it is quite clear that the smeared cracking model is not able to represent the cracks localization. The damage field is greatly diffuse and equal to 1 on large parts of the specimen surface. Obviously this is not representative of the experimental crack pattern. Moreover, there is no clear way to access to the crack openings, although several different attempts have recently been made. Contrary to the smeared damage model, the discrete crack representation through displacements discontinuities leads to more accurate and concluding results in terms of crack patterns. Actually the mesoscopic cracks are mostly localized around the inclusions (where the stresses are concentrated) and, afterwards, some bridges appear between the aggregates and also from the aggregates to the specimen edges. Comparing to DIC results, this approach thus seems quite adapted in order to describe the failure mechanisms due to drying shrinkage and the aggregates–cement paste incompatibility.

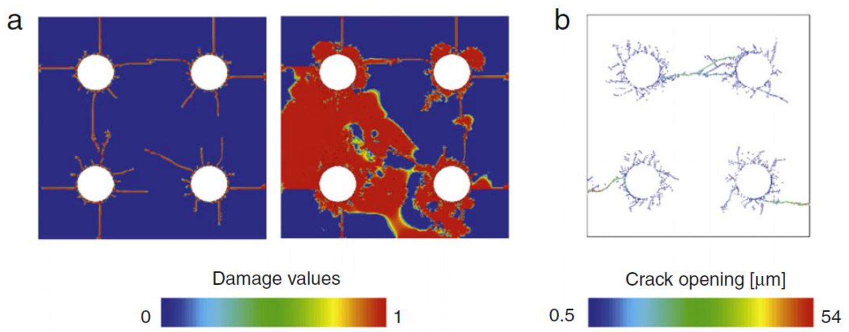

Figure 2 - Numerical cracking patterns for a mesostructure after 48 h of drying: (a) smeared crack model (at two time steps: just before 48 h and at 48 h, with appearing of numerical instabilities), (b) discrete crack representation model

CONCLUSIONS

Dealing with shrinkage and materials incompatibilities, two complementary experimental and numerical tools are presented in this paper. The digital image correlation technique Correli-Q4-LMTLMT [1] allows a cracking quantification during drying. This quantification may be used as input and validation data for numerical simulations. The numerical study leads us to underline the suitable description ability of discrete cracks model [3]. The smeared cracking classical model generates localization problems [2]. Some numerical simulations are currently undertaken to apply directly experimental boundary conditions in order to asses more efficiently the ability of both approaches.

References

[1] G. Besnard, F. Hild, S. Roux, "Finite-element" displacement fields analysis from digital images: Application to Portevin-Le Châtelier bands, Exp. Mech. 46 (2006) 789-804.

[2] De Sa C, Benboudjema F, Thiery M, Sicard J. Analysis of microcracking induced by differential drying shrinkage. Cem Concr Compos 2008;30:947–56.

[3] Benkemoun N, Hautefeuille M, Colliat JB, Ibrahimbegovic A. Failure of heterogeneous materials: 3D meso-scale FE models with embedded discontinuities. Internat J Numer Methods Engrg 2010;82:1671–88.