COUPLED MESO-MACRO SIMULATION OF MASONRY CRACKING

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Summary: A multi-scale framework is proposed for the representation of the complex non-linear behaviour of planar masonry structures. A standard continuum approach is used at the macroscale with embedded finite width localisation bands. A methodology to introduce homogenised material response snap-backs stemming from the finite size of the representative volume elements in the originally strain driven scale transition is proposed. Numerical examples are used to show the numerical robustness of the method.

INTRODUCTION

Ensuring the safety of historical buildings requires careful analysis of the residual strength of the (possibly damaged) structures and of the effect of repair operations. Finite element modelling of the failure process may be extremely useful in such analyses. Conventional finite element analyses require a constitutive model of the building material. For masonry, however, the formulation of closed-form constitutive relations which can accurately describe the aggregate degradation behaviour of bricks and mortar joints is a formidable challenge. Not only may both individual constituents and their bonding be degraded, these degradation processes also strongly influence each other, resulting in a range of possible failure mechanisms [1]. These failure modes and the mechanical responses associated with them are dominated by the mesostructure of the material, i.e. by the geometric arrangement of the bricks and mortar and by their individual properties. Most notably, cracks often follow the mortar joints and thus follow preferential directions which are set by the mesostructure. This results in the possible appearance of complex damage-induced anisotropy effects.

COUPLED MESO-MACRO MODELLING

Realistic predictions of strength and failure modes of masonry may be obtained from mesoscopic modelling, in which the geometry of the bricks and mortar joints is explicitly modelled, and homogeneous material behaviour is assumed for each of the phases [2]. Even if relatively simple constitutive relations are used for the brick and for the mortar materials, such models show a complex overall behaviour which agrees well with experimental observations. Furthermore, they allow to investigate the influence of brick shape, stacking mode, mortar strength, etc. on the overall response. Modelling the full mesostructure of entire walls or structures, however, may quickly become prohibitively expensive.
A compromise between computational cost and mesostructural detail can be obtained by using a coupled mesoscopic-macroscopic modelling approach. This means that walls are modelled using an homogenised continuum description, but the constitutive behaviour of the masonry material is determined on-line by mesoscopic analyses. In a finite element context, in each Gauss point of the macroscopic finite element discretisation a discretised sample of the mesostructure is used to determine this material response. For this purpose the local macroscopic strain is applied in an average sense to the mesostructure and the resulting mesostructural stresses are determined by a finite element analysis. The averaging of these mesostructural stresses and the condensation of the mesostructural tangent stiffness to the homogenised tangent stiffness then furnish the macroscopic material response associated with the Gauss point. This concept, which is also known as multilevel-FEM, FE^2 or computational homogenisation has been used before to model heterogeneous polymeric systems and other materials, see e.g. [3]. Its added value in the context of masonry resides in the fact that no complex closed form constitutive relation needs to be postulated for the representation of the overall material behaviour. The complexity associated with the damaging mesostructure of the material is naturally accounted for by scale transitions. Also, material identification issues are shifted to the level of mortar joints and brick constituents.

The definition of a multilevel-FEM scheme for masonry essentially requires the definition of four ingredients: (i) a mesoscopic constitutive setting for the brick and mortar materials, (ii) the definition of a representative mesostructural sample, (iii) the choice of a macroscopic continuum representation, and (iv) the set-up of scale transitions linking macroscopic and mesoscopic quantities. These features should carefully be selected in order to allow a proper incorporation of the localisation behaviour, both at the mesoscopic and macroscopic scales. Masonry constituents are quasi-brittle materials exhibiting low fracture energies and high sensitivities to tensile stresses. A scalar implicit gradient damage framework is therefore used at the mesoscopic scale. Based on the periodicity of the initial mesostructure of masonry, periodic homogenisation concepts are used in order to build scale transitions between the mesoscopic and macroscopic scales. In this contribution, the smallest periodic mesostructural sample is selected as the representative volume element in order to limit the computational effort at the mesoscopic scale. For running bond masonry, the smallest possible unit cell is represented in Figure 1. In order to deal with localisation at the macroscopic scale, embedded localisation bands surrounded by unloadin material are introduced in a standard first order continuum description. It is shown that a material bifurcation analysis based on the homogenised acoustic tensor as proposed in [4] allows to deduce band orientations which are consistent with the mesostructural damage patterns. The band width is deduced from this orientation and the initial periodicity of the mesostructure, as illustrated in Figure 1 for a staircase crack pattern. The resulting overall energy dissipation thus becomes

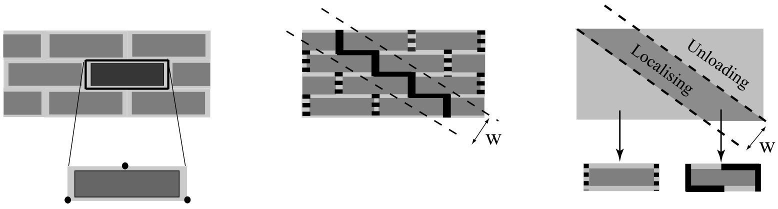

Figure 1: Identification of a mesostructural unit cell (left), and of a macroscopic localisation band (center and right)

sensitive to the ratio between mesostructural and structural sizes. Moreover, mesoscopic damage localisation in weaker zones of the order of a thin mortar joint may lead to snap-backs in the retrieved homogenised material response used at the macroscopic scale. Since the mesostructural problem is deformation-driven, an adaptation of the framework is introduced to handle such snap-backs. This enhancement consists in steering the mesostructural computation on the snap-back path. This is achieved where needed by forcing further mesoscopic energy dissipation through selected mesoscopic non-local strain unknowns which are transferred to the macroscopic solution procedure together with a non-local residual equation.

APPLICATION

The proposed multilevel scheme was implemented using parallel computing facilities. The capacities of the proposed approach are shown by means of structural computations. A typical structural application consists in a confined sheared wall as illustrated in Figure 2 with the associated mesoscopic damage patterns.

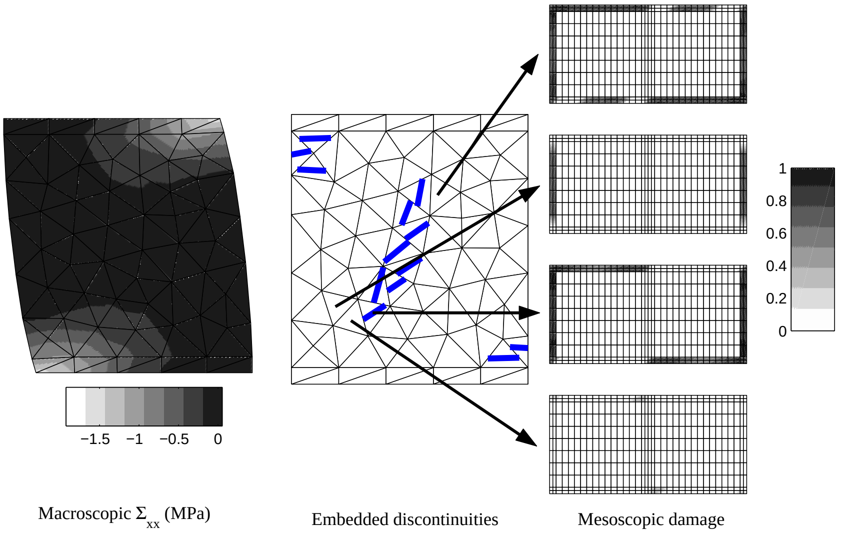

Figure 2: Application of the coupled meso-macro method to a masonry wall segment.

CLOSING REMARKS

FE^2 methodology proves to be a valuable tool for the investigation of masonry structures. In particular, it allows to account for the strong coupling between the structural response and the underlying mesostructural features of the material. In order to further exploit this methodology on large scale computations, it could still be improved in terms of performance. In this regard, improvement could be reached by the use of interface elements to represent mortar joints at the mesoscopic scale or by a restricting the use of mesoscopic on-line computations the damaging zones where degradation progresses.

References

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