Computational performances optimization of a non-linear mechanical behaviour model for geomaterials

Alain SELLIER[1], Pierre MORENON[1,2], Nathalie DOMEDE[1]

[1] *Université de Toulouse, UPS, INSA, LMDC (Laboratoire Matériaux et Durabilité des Constructions), 135, avenue de Rangueil, F-31 077 Toulouse Cedex 04, France)*

[2] *Toulouse Tech Transfer, 118 route de Narbonne, CS 24246, 31432 Toulouse Cedex 04, France*

RESUME Modelling large civil engineering structures with complex shapes, such as gothic vaults, arch dams, nuclear containment vessels, requires 3D nonlinear numerical models usable in finite element codes, discrete elements codes and codes coupling them both. Concerning the finite element formulation, many models based on plasticity are particularly well adapted to soil-mechanics, while damage theory is widely used to model concrete fracture. In the case of the building heritage masonry, in which natural geomaterials are combined with lime mortar, the mechanical behaviour law of the components presents a first stage with microcracking closure under low compression, a second stage of hardening, and finally a softening stage with a significant dilatancy and a damage induced by its crushing. In tension, the cracks appear mainly in principal tensile direction, with a highly orthotropic damage induced. This paper gives principles used to couple all these phenomena in a single model with the objective to enhance the accuracy and minimize the computational cost. These improvements are based on a computing process avoiding to resort to iterative solving methods at the integration points.

Mots-clefs: plasticity, damage, orthotropy, cracking, settlement, modelling, computing

I. INTRODUCTION

Facing ecological transition will pass by conservation as long as possible of civil engineering structures, simply because avoiding their destruction and replacement save thousands tons of CO_2 needed to treat induced wastes, create new materials, bring them to the construction site and rebuild a novel structure, but these structures are often altered by environment and service life, so their loading capacity are reduced, and strength reserve must resort to their nonlinear behaviour to demonstrate their operation extension. Another problem is the safety in architectural heritage for which a safety level must be shown before a possible public opening, another one is the use of traditional material such as natural health for which the natural mechanical performances are limited. In all these cases the resorting to an accurate non-linear mechanical model allows to assess a realistic loading capacity, which in turn allows to optimize safety factors and justifies the maintain of operation or access. Supplying robust and accurate non-linear models to code users is from this point of view a challenge. Our experience in the domain, at LMDC Toulouse, lead us since two decades to adopt some basic principles which enhance significantly the robustness, the accuracy and reduce the computational cost of behaviour laws usable for construction materials. This paper gives these principles to help researcher reaching a behaviour law robustness compatible with an engineering use.

II. Causes of computing performances loss and proposed solutions

A. Causes of performances losses when model resolving at integration points of a finite element

Usually, the non-linear hardening is modelled in the framework of plasticity theory. In case of non-linearity, a tangent hardening modulus allows to predict the solution, a residue is computed from this prediction and cancelled by an increment of plastic strain thanks to a return mapping algorithm (Simo and Taylor, 1985). This iterative method is the main cause of time consuming during the local solving procedure (i.e. at the Gauss integration points of each finite element).

In civil engineering, geomaterials used as construction materials present also a post peak softening behaviour often modelled by a damage model. The well-known Mazar's model (Mazars, 1986) is very useful because it allows to compute an isotropic damage variable reducing the Young modulus explicitly from elastic strain, what avoids resorting to an iterative procedure at the integration point of the finite element.

A natural method could be to chain a plastic law with a damage model based on elastic strain. Unfortunately, the real material behaviour shows that permanent strains and damages are correlated. In fact, in most cases, the damage appears as a consequence of anelastic strains. The physical origin is the heterogeneity of material at micro scale which leads to micro heterogeneity in the plastic flow leading to void nucleation. Once they are created with a sufficient density, their coalescence leads to a micro crack, and the propagation of this crack leads to stress concentrations, straining more and more the material and giving the appearance of Young modulus reduction, known as "mechanical damage". Thanks to the contribution of (Lemaitre and Chaboche, 1985), the concept of effective stress (the mean value of the local stresses around voids) allows to consider simply these stress concentration.

Settlement, i.e. the existing microcrack or voids closure at first stage of the mechanical behaviour of brittle material, is of great interest when working on natural under-consolidated material (used in construction at higher pressure then it was in the quarry). The modified Cam-Clay model is a plastic model able to consider the hardening induced by the reduction of voids volume of a clay-based soil. It reflects the fact that the void ratio is proportional to the logarithm of the pressure. So, if the voids are used as state variable of the model to control hardening, its exponential form of the void indices could be a problem for the tangent predictor. It could under-estimates the pressure and consequently over estimates the void reduction, needing an iterative procedure to adjust the pressure to the correct void volume reduction.

B. Proposed solutions to enhance computational performances

During the development of our model, the effective stresses were defined in the sense of "computed with the equivalent strain principle proposed by (Lemaitre and Chaboche, 1985)", consisting to use the initial elastic modulus whatever the damage level already reached. The principles adopted have been as following: 1) Whatever the criteria used, elasto-plastic behaviour laws involve only positive or null linear hardening and are expressed in the bases of effectives stresses. 2) The damages are only functions of plastic-strains. 3) Damages, crack-reclosure functions, and settlement functions affect effective stresses and are the only internal variables used to manage the possible post peak softening of the stress-strain relation.

Our two first principles consist to use only a positive or null linear plastic hardening in effective stresses bases and to solve the plastic sub-problem first. As it leads to a system of linear equations, it can be solved directly, what avoids resorting to an iterative procedure during the return mapping algorithm application. Next, third principle allows to use non-linear functions as damage evolution laws without iterative procedure, since the plastic strains are already computed. Thus, the damage is a consequence of plasticity. The regularization technics (Hillerborg et al., 1976; Pijaudier-Cabot and Bazant, 1987) are implemented at this level.

III. Practicability of proposed optimization principles

A. Considered phenomena

The principles exposed above are used in the framework of the multi-criteria approach, schematized in Figure 1 drown in the pressure/deviatoric plane (b) or in the effective stresses base (c) (in the damage theory sense). There are three orthotropic Rankine criteria to manage opening and reclosure of cracks, a non-associated pressure-shear criterion to consider internal friction under deviatoric loading (Drucker and Prager, 1952) and a Cam-clay criterion for settlement (Roscoe et al., 1963). The non-linear damage in tension and shear is obtained thanks to the orthotropic evolution laws clarified in (Sellier et al., 2012) and adapted to plastic context in (Sellier and Millard, 2019). In these last papers, the functions used to manage orthotropic cracks reclosure in the context of rotating and regularized orthotropic damage are detailed.

B. Example of application

The model has been applied to the modelling of a real material (masonry composed of three granitic soil blocks and two joints (Vasconcelos, 2005)) presenting several specificities such as a settlement in the beginning of the compressive test, then a hardening stage up to the maximal strength, followed by a softening induced by a transverse dilatancy (Figure 1).

IV. Conclusion

A methodology of modelling is proposed to minimize computational cost and enhance the accuracy of non-linear models. This methodology consists in the three following principles: (1) plasticity in effective stresses bases (in the damage sense), (2) only linear positive or null plastic hardening in the space of effective stresses, (3) softening induced only by evolution laws of damages, themselves function of plastic strain tensors, reclosure and settlement functions linked only to the plastic strains. The applicability of these principles has been tested in the framework of a three different plastic-mechanisms need. Currently, a model called ENDO3D is implemented in Castem and LMGC90 in order to be applied to the calculus of the damaged zones of the cathedral

"Notre-Dame de Paris", in the context of the ANR (French National Research Agency) DEMMEFI project which we grateful thanks for its funding and for the fruitful collaboration with Dr T. Parent (I2M Bordeaux) and Dr F. Dubois (LMGC Montpellier).

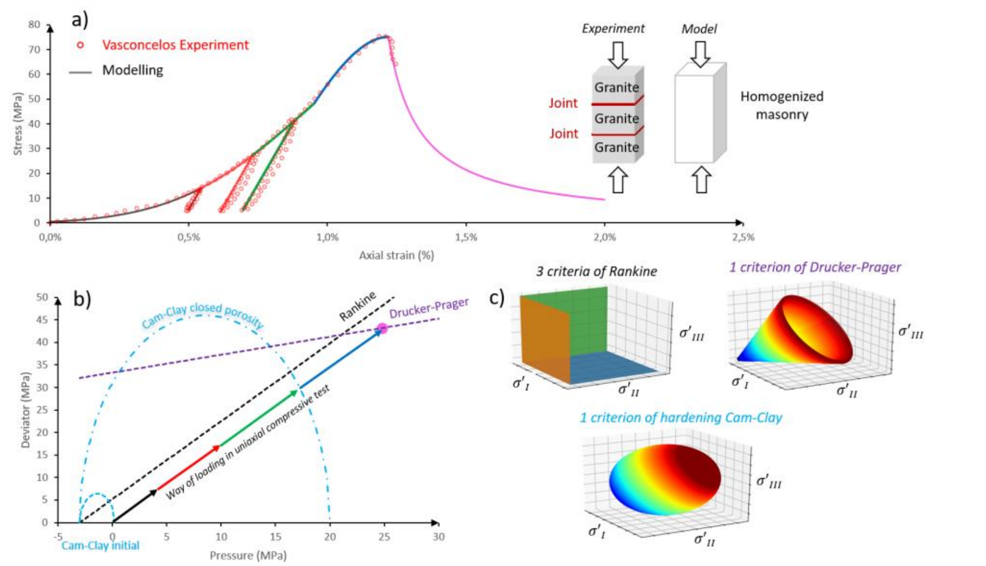

FIGURE 1. Cyclic compressive test modelling compared to experiment on a granitic masonry (Vasconcelos, 2005) : (a) Axial stress-strain curves (b) Plastic criteria used in the deviator-pressure plan (c) Plastic criteria drawn in the principal stresses base

REFERENCES

Drucker, D.C., Prager, W., 1952. Soil mechanics and plastic analysis for limit design. Q. Appl. Math. 10, 157–165.

Hillerborg, A., Modeer, M., Peterssonn, P., 1976. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cem. Concr. Res. 6, 773–782.

Lemaitre, J., Chaboche, J., 1985. Mécanique des matériaux solides.

Mazars, J., 1986. A description of micro- and macroscale damage of concrete structures,. Eng. Fract. Mech. 25, 729–737.

Pijaudier-Cabot, G., Bazant, Z., 1987. Nonlocal damage theory. J. Eng. Mech. 113, 1512–1533.

Roscoe, K.H., Schofield, A.N., Thurairajah, A., 1963. Yielding of clays in states wetter than critical. Geotechnique 13, 211–240. doi.org/10.1680/GEOT.1963.13.3.211

Sellier, A., Casaux-Ginestet, G., Buffo-Lacarrière, L., Bourbon, X., 2012. Orthotropic damage coupled with localized crack reclosure processing Part II: Applications. Eng. Fract. Mech. 97. doi.org/10.1016/j.engfracmech.2012.10.016

Sellier, A., Millard, A., 2019. A homogenized formulation to account for sliding of non-meshed reinforcements during the cracking of brittle matrix composites: Application to reinforced concrete. Eng. Fract. Mech. 213, 182–196. doi.org/10.1016/j.engfracmech.2019.04.008

Simo, J.C., Taylor, R.L., 1985. Consistent tangent operators for rate-independent elastoplasticity. Comput. Methods Appl. Mech. Eng. 48, 101–118. doi.org/10.1016/0045-7825(85)90070-2

Vasconcelos, G., 2005. Experimental investigations on the mechanics of stone masonry: Characterization of granites and behavior of ancient masonry shear walls. PhD thesis.