A NEW F.E. TANGENT DAMAGE MODEL MODEV FOR CONCRETE STRUCTURES

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ABSTRACT

The present work deals with the general frame work of the study of the concrete behaviour. It has for objective the development of a new model which permits to predict with F.E approach the behaviour of concrete structures. After the analysis of different existent models, an analysis of the physical mechanisms of the concrete degradation has been achieved and permitted to develop the new damage model MODEV. The model is written within the framework of non standard generalised materials in incremental tangent formulation and implemented in the general finite element code SYMPHONIE. The new deviatoric damage model MODEV considers two damage mechanisms: extension and sliding. The model considers also that the relative tangent displacement between micro cracks lips is responsible of the strain irreversibility. Thus, the rate of inelastic strain becomes function of the damage and the heterogeneity index of the material. The unilateral effect is taken into account as non-linear elastic hardening or softening process according to re-closing or re-opening of cracks. The numerical simulation of elementary and structural test cases with MODEV has shown a reliable consistency with the experimental results in terms of cracking profile and load-displacement curve.

1 INTRODUCTION

The concrete has a complex behaviour difficult to represent by a single homogeneous macroscopic law. This difficulty comes notably from its strong heterogeneousness on one hand and a composite aspect due to the existence of aggregates, cement and cavities on the other hand. In addition, the concrete has an unpredictable and random state of presence of micro-cracks even in the state called virgin before any external loading. So the representation of the behaviour can not be made with a single mechanism of deformation. According to the nature and the intensity of stress, the concrete could be deformed in a complex way producing one or more combinations of elementary mechanisms: elasticity, damage, sliding, friction, cracking... Many researches have been led on the national and international level since several years in order to elaborate a reliable and robust model to predict the behaviour of the concrete structures. Isotropic or anisotropic models of damage in particular ones of (Mazars [7]; La Borderie [5], Ramtani [15]...), models of multiple, fixed or discrete cracking based on the smeared crack theory, the micro - plans model (Olzbolt [14]; Bazant [1]), the models based on the plasticity theory (Reynoaurd [16])... were carried out. However, the major difficulty lies in the development of a sufficiently reliable model to represent the complex of concrete behaviour. But such model must be relatively simple to be used in an industrial context in order to predict the behaviour of the concrete structures.
From this report, the choice to develop a new model was adopted. New model is based on hypotheses of the mechanisms of deformation relative to the heterogeneous aspect of the concrete and the sensibility of cracking regarding the deviator strains tensor. After the implementation of the new damage model in to SYMPHONIE FE code, its results has been tested and compared with experimental and theoretical ones on various scenarios found in the literature.

2.1 Damage mechanisms

Because of the heterogeneous nature of the concrete material, the model takes into account the existence of several elementary mechanisms of degradation. On beside of the mode I due to extensions that we usually meet, the Bertacchi's triaxial tests (Bertacchi, 1972) show, even without extension, that degradation appears. We suppose that this one is due to sliding effect.

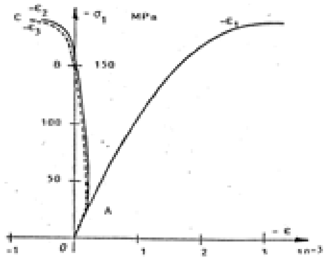

Figure 1 : Experimental curve of Bertacchi and Belotti [2]

So, the model considers the simultaneous existence of 2 damage modes: "extension mode" and "sliding mode". Adopting a multiplicative damage combination in the potential energy [6]:

$$\rho\psi = \rho\psi\left(\underline{\underline{\varepsilon}}, d, T\right) = \frac{1}{2}(1-d_s)(1-d_d)\underline{\underline{\underline{D}}} : \left(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}\right) : \left(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}\right) \quad (1)$$

Where $d_s ; d_d$ are the variables of damage by extension and by sliding respectively.

And $\underline{\underline{\varepsilon}}^{an}$ eventually represents the inelastic strain tensor.

The condition of positivity of the intrinsic dissipation reads:

$$\xi = \underline{\underline{\sigma}} : \dot{\underline{\underline{\varepsilon}}} - \rho\dot{\psi} = -Y_d.\dot{d}_d - Y_s.\dot{d}_s + \underline{\underline{\sigma}} : \dot{\underline{\underline{\varepsilon}}}^{an} \geq 0 \quad (2)$$

With:

$$-Y_s = \frac{1}{2}(1-d_d)\underline{\underline{\underline{D}}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}) : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}) \geq 0 \; et \; -Y_d = \frac{1}{2}(1-d_s)\underline{\underline{\underline{D}}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}) : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}) \geq 0 \quad (3)$$

With regard to the damage criteria, in the model, by analogy with the equivalent deformation within the meaning of Mazars [7], we introduce two new equivalent deformation expressions. These expressions respectively representing two damage mechanisms translate the hydrostatic state of extension and the local sliding of the microscopic cracks:

$$\underline{\underline{\varepsilon}} = \underline{\underline{\varepsilon}}^d + \underline{\underline{\varepsilon}}^s = \underline{\underline{\varepsilon}}^d + \varepsilon^H \underline{\underline{I}} \quad (4)$$

$$f_s\left(\underline{\underline{\varepsilon}}, B_s\right) = \tilde{\varepsilon}^s - B_s(\beta_s) = 0 \text{ et} f_s \leq 0; f_s.\dot{d}_s = 0 \quad (5)$$

$$f_d\left(\underline{\underline{\varepsilon}}, B_d\right) = \tilde{\varepsilon}^d - B_d(\beta_d) = 0; \; f_d \leq 0 \; et \; f_d.\dot{d}_d = 0 \quad (6)$$

The equivalent spherical strain $\tilde{\varepsilon}^s$ and the equivalent deviatoric strain $\tilde{\varepsilon}^d$, are defined in the following way:

$$\tilde{\varepsilon}^S = \left\langle \varepsilon^H \right\rangle = \left(\varepsilon^H + \left| \varepsilon^H \right| \right) / 2 \quad et \quad \tilde{\varepsilon}^d = \sqrt{\left(\underline{\underline{\varepsilon}}^d - \underline{\underline{\varepsilon}}^{an}_d \right) : \left(\underline{\underline{\varepsilon}}^d - \underline{\underline{\varepsilon}}^{an}_d \right)} + \alpha \varepsilon^H \tag{7}$$

Where $\underline{\underline{\varepsilon}}^d$ and $\underline{\underline{\varepsilon}}^{an}_d$ are deviatoric tensors of total strain and inelastic ones respectively; α is coefficient of coupling between spherical – deviatoric effects representing the influence of hydrostatic strain state on the sliding.

With these definitions, we can plot the yield surface form in the principal strains reference. This surface is convex and contains the origin. It also is the case in the stress coordinates (Figure 2).

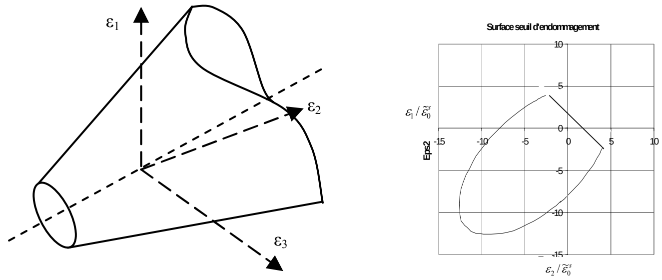

Figure 2: MODEV damage yield surface in 2D and 3D

Thus, within the framework of a non-standard generalized material, we postulated the evolution law of the damages according to the corresponding equivalent expressions:

$$d_s = 1 - \left(\frac{\tilde{\varepsilon}^s_0}{\tilde{\varepsilon}^s} \right) \exp\left[-B_t (\tilde{\varepsilon}^s - \tilde{\varepsilon}^s_0 \right] \; et \; d_d = 1 - A_C \exp\left[-B_C \left(\tilde{\varepsilon}^d - \tilde{\varepsilon}^d_0 \right) \right] - (1 - A_C) \frac{\tilde{\varepsilon}^d_0}{\tilde{\varepsilon}^d} \tag{8}$$

Where B_t, A_C, B_C, are characteristic coefficients of the damage evolution. Note that the coefficient B_t of the damage by extension is considered as a function of the crack energy $\boldsymbol{G_f}$ to assure an objectivity with regard to the finite elements meshing size during a numerical calculation.

2.2 *Inelastic effect*

We postulate that the sliding between rigorous lips of micro cracks which prevents total re-closing of these cracks is at the origin of the irreversible strain. Because of the important heterogeneous nature of concrete, this sliding occurs under hydrostatic and\or shear strain state. So we put in evident the existence of two parts of inelastic strain: spherical one and deviatoric one.

For the spherical part of the inelastic strain, the loading surface is supposed in the following way:

$$f^{an}_s = \frac{I_\sigma}{(1 - d_s)(1 - d_d)} - \kappa(p^s) \;\; \text{et} \;\; \dot{\underline{\underline{\varepsilon}}}^{an}_s = H(\dot{d}_s).\mu_1.f(d_s)\dot{\underline{\underline{\varepsilon}}}^s \tag{9}$$

As for the deviatoric part of the inelastic strain:

$$f^{an}_d = \frac{J_\sigma}{(1 - d_d)(1 - d_s)} - \kappa(p^d) \;\; \text{et} \;\; \dot{\underline{\underline{\varepsilon}}}^{an}_d = H(\dot{d}_d).\mu_2.f(d_d).\dot{\underline{\underline{\varepsilon}}}^d \tag{10}$$

Where $H(x) = 1$ if $x > 0$ and $H(x) = 0$ if either. The functions $f(d_s)$ and $f(d_d)$ are increasing functions which take values including between 0 and 1. Coefficients μ_i are intrinsic characteristics of the material, they represent the degree of heterogeneousness of the considered material. The positivity of the inelastic dissipation is automatically assured :

$$\underline{\underline{\sigma}}^{s} : \dot{\underline{\underline{\varepsilon}}}_{s}^{an} \geq 0 \text{ et } \underline{\underline{\sigma}}^{d} : \dot{\underline{\underline{\varepsilon}}}_{d}^{an} = H(\dot{d}_d)\mu_2\left(1-d_s\right)\left(1-d_d\right).f(d_d).\underline{\underline{D}}:\left(\underline{\underline{\varepsilon}}^{d} - \underline{\underline{\varepsilon}}_{d}^{an}\right):\dot{\underline{\underline{\varepsilon}}}^{d} \geq 0 \text{ (voir} f_d^{an}\text{)} \qquad (11)$$

2.3 *Unilatéral effect*

The new model supposes two modes of damage: extension and sliding. First mode (mode I) exists if and only if there is at least on extension direction. Whereas for the second mode of sliding (modes II and III) can be activated in compression as well as in extension. The unilateral effect is taken into account due to the physical concept of the model. Indeed, during compression, damage by extension d_s disappears by an introduction of a reversible monotonous function allocated to the stiffness. So it is important to make a distinction between the compression state and extension one. In the new model, the compression state is defined in a more general way by: $Tr(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}) < 0$

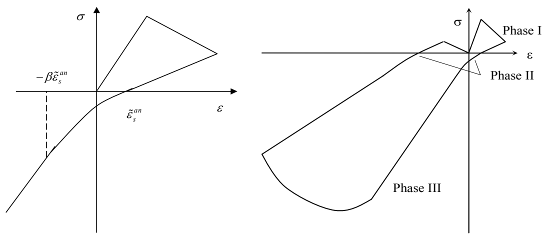

Figure 3 : Scheme of unilateral effect (phase II)

To definite the transition phase of unilaterality, we introduce a material characteristic, noted β (Figure 3). We can call it coefficient of unilateral effect, such as :

Pour $\tilde{\varepsilon}_s^{an} \geq \tilde{\varepsilon}_s \geq -\beta\tilde{\varepsilon}_s^{an}$: The material is situated in the phase of unilaterality. There is no evolution of the damage by extension, neither of the spherical inelastic strain. The change of stiffness tensor is considered as a non linear elastic process. So, we use a reversible bijective function *f*:

$$\underline{\underline{\sigma}} = \left(1-d_s\right)\left(1-d_d\right)\underline{\underline{D}}.f(d_s, \underline{\underline{\varepsilon}}, \underline{\underline{\varepsilon}}_{an}^{s}) : \left(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{an}\right) \qquad (12)$$

so : $f = 1 \; si \; \varepsilon^s = \varepsilon_s^{an} \quad et \; f = \dfrac{1}{1-d_s} \; si \; \varepsilon^s \leq -\beta\varepsilon_s^{an}$ (13)

This process is reversible in which relation between stresses and strains is bijective. The behavior law is continuous, so the potential energy is existent and continuous.

2.4 *Intégration in symphonie f.e. code*

This model named MODEV, is integrated into the SYMPHONIE code of the CSTB [9] in total formulation and incremental tangent formulation, namely:

$$\boldsymbol{\sigma} = \left(1-d_s\right)\left(1-d_d\right)\mathbf{D}\left(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^{an}\right) \text{ and } \dot{\boldsymbol{\sigma}} = (1-d_s)(1-d_d)\mathbf{D}\left[\mathbf{I} - \mathbf{M}_S - \mathbf{M}_D - \mathbf{A}_S - \mathbf{A}_D\right]\dot{\boldsymbol{\varepsilon}} \qquad (14)$$

Where $\mathbf{M}_S$, $\mathbf{M}_D$ represent effect of damages, $\mathbf{A}_S$, $\mathbf{A}_D$ represent the influence of the inelastic effect on the tangent stiffness tensor of the material.

2.5 Validation

2.5.1 Validation of the continuity of the model

The validation of the continuity of the model is shown through a case of triaxial loading by imposing a history of principle deformations *eps1* , *eps2* , *eps3* which form a loxodromy. All the points of the loading are situated on a half-sphere of radius 0.0004. The answer *sig1-sig2* in the plan *sig3=0* show us a complete continuity of the model.

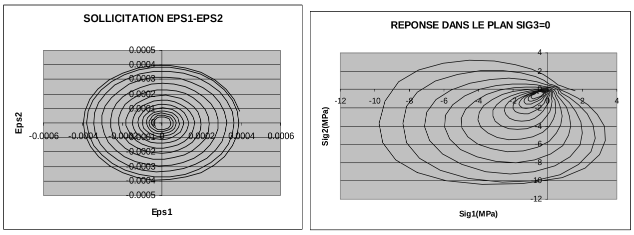

Figure 4 : Validation of the continuity of the model

2.5.2 Case of structure under cyclic loading

We consider a concrete beam subjected to a cyclic flexural loading. This test was realized by La Borderie [5]. Comparison between experimental and numeric results presented in Figure 5, shows the good agreement between the numerical results of the model and the experience.

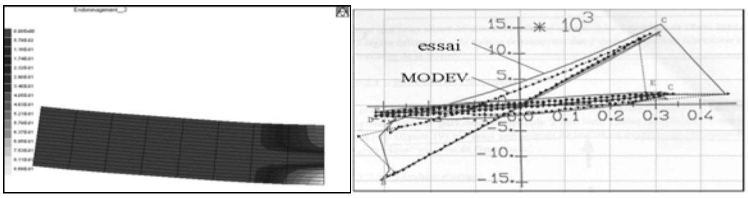

Figure 5 : Damage profil, load (N)- displ(mm) curve

2.5.3 Industrial application to anchor bolt in concrete:

In this 3D case we consider a metal anchor imbedded in a concrete slab near to the edge. The top of the metal anchor is subjected to a tangent shear load [3]. The Figure 6 presents the final mode of failure obtained by simulations and the comparison with experimental results. This figure shows a good qualitative and quantitative agreement between experimental and simulation results.

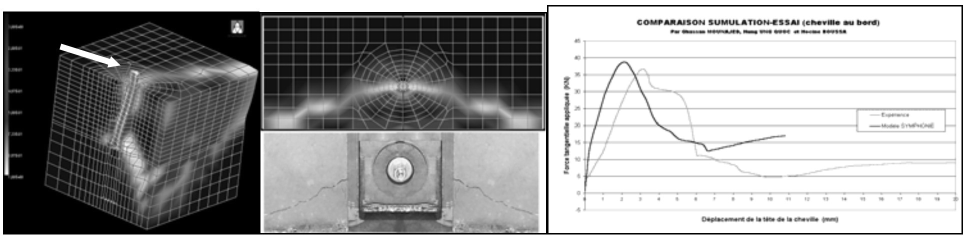

Figure 6 : Failure mode et load - displacement curve at the head of the ankle (simulation, test)

3 CONCLUSIONS ET PERSPECTIVES

In this research, we proposed a new model MODEV based on the theory of the damage and on the thermodynamics of irreversible processes. According to the type of loading several types of damage can appear. The new MODEV model based on physical analyses and on experimental test introduces the notion of equivalent deviatoric strain responsible for the damage by sliding. The model was validated with several cases by comparison with experimental results found in the literature. The proposed model proves also its capacity to predict correctly the global behaviour (load-displacement curves), the shape of cracking and the mode of failure.
The model could be adapted to different fragile materials. Studies of coupling between the mechanical damage and thermal, chemical phenomena…could be investigated with the model MODEV.

4 REFERENCES

[1] Bazant Z. P (1984) "Microplane model for strain controlled inelastic behaviour". *Mechanics of engineering materials*, Desai C.S. et al., John Wiley Ed, Chichester. NY. 45-59.

[2] Bertacchi P., Belotti R. (1972) « Experimental research on deformation and failure of concrete under triaxial loads », *ProceedingInt. Symposium RILEM*, pp. 35-38, Cannes.

[3] CSTB (1996) "Rapport d'essai n° 41114 concernant les chevilles de fixations »

[4] Gerard G. Hasselwander (1988), "*Anchorage to Concrete*" (315p), ACI, SP-103.

[5] La Borderie C. (1991) « Phénomènes unilatéraux dans un matériau endommageable : Modélisation et Application à l'analyse des structures en béton », Thèse doctorale, Paris 6.

[6] Lemaître J., Chaboche J.-L. (1988) « *Mécanique des matériaux solides* », Dunod.

[7] Mazars J. (1984) « Application de la mécanique de l'endommagement au comportement non-linéaire et à a rupture du béton de structure », Thèse de Doctorat d'Etat, Paris 6.

[8] Mesureur B., Mounajed G., El Dalati R. (1998) « Etude de la capacité résistante des ancrages avec chevilles de fixation soumis à des sollicitations tangentes », *Rapport* confidentiel CSTB.

[9] Mounajed G. (1991) « Code EF SYMPHONIE. SYMPHONIE, Code de calcul général aux éléments finis", CSTB.

[10] Mounajed G., Ung Quoc H. & Boussa H. (2003) « Elaboration d'un nouveau modèle d'endommagement dans le code de calcul SYMPHONIE-CSTB», Numéro spécial de *Revue Française de Génie Civil*, Edition Hermes.

[11] Mounajed G., Ung Quoc H. & Boussa H. (2002) « Elaboration of a new model of damage for concrete. Application to the modelling of metal anchors », *First International Conference on Applications of Porous Media* Jerba, Tunisia.

[12] Mounajed G., Ung Quoc H. & Mesureur B. (2002) « New tangent formulation of the concrete damage model MODEV », *Befestigungstechnik Bewehrungstechnik und…*, Rolf Eligehausen zum 60. Geburtstag, pp. 671-684, Herausgeber: Werner F., Hans-Wolf R., Edition ibidem.

[13] Mounajed, G., Ung Quoc, H. & Boussa, H. (2002) « Development of a new concrete damage model in SYMPHONIE-CSTB. Application to metallic anchor bolts. » *Second Biot International Conference on Poromechanics,* Grenoble France.

[14] Ozbolt J. (1996) "Microplane Model for Quasibrittle Materials - Part I – Theory". Universität Stuttgart. Universität Stuttgart. Institut für Werkstoffe im Bauwesen. Bericht Nr. 96-1a/AF.

[15] Ramtani S. (1990) "Contribution à la modélisation du comportement multiaxial du béton endommagé avec description du caractère unilatéral", Thèse de Doctorat d'Etat, Paris 6.

[16] Reynouard J.-M. (1974) « Structures planes en béton armé. Elaboration d'un modèle du comportement jusqu'à la ruine et résolution numérique », Thèse de Doctorat, Unv. Claude-Bernard de Lyon.

[17] Rots J. G., Blaauwendraad J. (1989) "Crack models for concrete:Discrete or smeared? Fixed, Multi - directional or rotating?" *HERON* Vol,34, no.1.