Oral reference : ICF100425OR

AN IMPACT DAMAGE MODEL FOR CEMENTITIOUS COMPOSITES

Patricia VERLEYSEN[1] and Joris DEGRIECK[2]

[1] Doctor-Assistent, Ghent University, Faculty of Engineering,
Department of Mechanical Construction and Production,
Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium
[2] Full Professor, Ghent University, Department of Mechanical Construction and Production.

ABSTRACT

Although in recent years a lot of research has been spent on the dynamic, tensile behaviour of cementitious composites, such as concrete, less attention has been paid to the modelling of this behaviour. In this contribution a model, developed within the framework of the continuum damage mechanics, is presented and the determination of the model parameters is dealt with. One of the essential characteristics of the approach is that the model distinguishes two stages : a first stage during which nucleation of damage is dominant and a second during which the existent damage propagates. The model was implemented in a finite element program, which was subsequently used for the simulation of split Hopkinson bar experiments. To validate the proposed material model and to determine the material parameters a series of experiments on concrete were performed. Comparison of the experimental and numerical results showed an excellent agreement for rates of deformation ranging from 1/s to 300/s.

KEYWORDS

cementitious composites, impact, damage model

INTRODUCTION

When a quasi-brittle material such as concrete is subjected to an increasing tensile stress, the initial linear elastic behaviour will soon be abandoned because of the creation of microcracks. The microstructure of the material will gradually degrade by the nucleation and propagation of these microcracks. In the beginning, the process of nucleation of microcracks is dominant; this is a stable stage. When the stress is further increased new microcracks develop and the size of the existing cracks grows. After a while propagation of existent microcracks becomes dominant; an equilibrium between stress and damage is only possible under decreasing stress. This process is unstable.

The dynamic, tensile behaviour of concrete differs significantly from its static behaviour; in experiments higher strengths, higher deformation capacities and higher energy-absorbing properties are observed at higher rates of strain [1][2][3][4][5]. This can be explained by the fact that, when the load is applied very slowly, the final rupture has the time to choose the way of least resistance; tougher aggregates are avoided and the fracture goes through the weakest zone of the matrix. The development of microcracks in other zones is limited. In dynamic circumstances however, fracture has to develop in a very short time period. A lot of energy is put in the material in a very short time; as stresses are increasing very fast, cracks do not have the same time to search for the weakest path and have to develop along shorter paths with higher resistence; as a consequence higher strengths are observed. The high stresses in the material now also cause microcracking in other zones, resulting in higher deformations in dynamic experiments.

In this contribution a material model for the dynamic, tensile behaviour of concrete is proposed [6]. The description is based on damage mechanics. To validate the proposed material model and to determine the material parameters series of experiments on concrete were performed. Because of practical considerations a concrete 'on scale' (or microconcrete) was used. The results of the experiments are compared with simulated results, using the finite element program in which the material model is implemented.

DEVELOPMENT OF THE DYNAMIC DAMAGE MODEL FOR TENSION

One basic assumption of the continuum damage mechanics is the fact that the irreversible changes in the microstructure of a material due to the loading history and resulting in a degradation of the mechanical behaviour of the material, can be described by an internal variable (or variables); the *damage variable* d (or d_i, i=1, ..., n). Another essential assumption is that in the description of the mechanical behaviour of the material, this material can be replaced by a fictitious, homogenous and continuous material. The full set of all mathematical expressions describing the resulting mechanical behaviour of the fictitious material and the evolution of damage is a *damage model.* An adequate damage model is able to predict the onset and evolution of damage under variable circumstances.
The damage variables can be defined either in direct relation to the deficiencies which constitute the damage, or in relation to the observable reduction in mechanical properties which the damage brings about. The second, more phenomenological, approach is more often used, and was equally adopted here. In the developed one-dimensional model a scalar damage variable d is used. Its physical meaning is related to the reduction of stiffness of the damaged material, as follows :

$$E = E_0(1 - d) \,, \qquad \sigma = E\,\varepsilon \tag{1}$$

with E_0 the modulus of elasticity of the undamaged material, E the modulus of the damaged material, σ the uniaxial stress and ε the strain. Because of the irreversible nature of the degradation process d is always increasing, and its value is obviously limited to the interval [0, 1].
Next to the choice of an appropriate damage variable, a law describing the evolution of this variable is necessary : the *damage law.* The dynamic damage law presented in this paper starts from a static model. Essential is also the fact that damage growth consists of two distinct contributions : a nucleation part describing the creation of new microcracks and a propagation part describing the growth of the existent damage.
In [7] Lemaitre-Chaboche proposed the following function for the increment of damage of concrete :

$$\begin{aligned} &\mathrm{d}(d) = \left(\frac{\varepsilon}{\varepsilon_0}\right)^s d\varepsilon && \text{if } \varepsilon > \varepsilon_{tr} \text{ and } d\varepsilon > 0\,, \\ &\mathrm{d}(d) = 0 && \text{in other cases.} \end{aligned} \tag{2}$$

ε_{tr} is a threshold value for the strain; below that value of the strain, no damage will occur. ε_0 and s are material constants.

When the strain is monotonicly increasing, the relation between stress and damage becomes :

$$\sigma = E_0(1 - d)\left(\varepsilon_0^s\,(s + 1)d + \varepsilon_{tr}^{s+1}\right)^{1/(s+1)} \tag{3}$$

This equation gives a unique relationship between applied stress and damage; no strain rate or other effects are taken into account. This equilibrium curve will only be followed during a static experiment with very low rates of loading and is therefore called the *static curve* (see figure 1).

In a dynamic situation the point representing the state of stress and damage in figure 1 will no longer be situated on the equilibrium curve, but above it; the damage evolution can't follow the stress. The point will tend to move down towards this curve. The higher the stress, or rather, the higher the available elastic energy, the faster this motion will be. It is therefore reasonable to take the rate of damage proportional to the difference in the square of the actual stress and the square of the stress of the equilibrium curve, both at the same amount of damage of course. Introducing the parameters C_1 and C_2 to scale the process of nucleation and propagation, this gives the following equation for the time derivate of the damage variable d :

$$\dot{d} = \dot{d}_{nucleatie} + \dot{d}_{propagatie}$$

$$= C_1 \left\langle \left(\frac{\sigma}{\sigma_{max}}\right)^2 - \left(\frac{\sigma_{stat}}{\sigma_{max}}\right)^2 \right\rangle + C_2 \left\langle \left(\frac{\sigma}{\sigma_{max}}\right)^2 - \left(\frac{\sigma_{stat}}{\sigma_{max}}\right)^2 \right\rangle \cdot d \tag{4}$$

σ is the actual stress, σ_{stat} is the value of the static curve corresponding with the actual damage d and σ_{max} is the maximum value of the static curve (see figure 1). The brackets ⟨ ⟩ mean that negative values are replaced by zero, thus guaranteeing that only points above the static curve will cause damage growth.
The second term, the propagation term, is multiplied by a factor d, to express the simple fact that the more damage is already present, the greater the possibility for growth. This allows to take into account the instability of the growth process. Both terms are represented in figure 2 for a loading rate of 10/s. As can be seen, after a while the propagation term dominates the damage process.

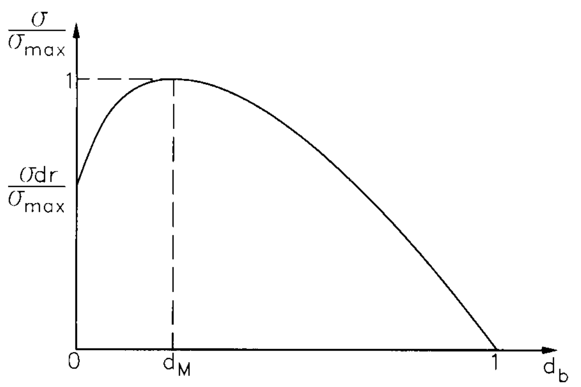

Figure 1: Static tensile curve for concrete derived from the model presented in [7].

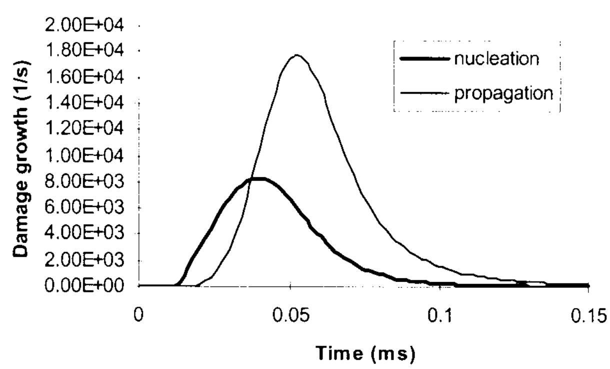

Figure 2: History of the contribution of the nucleation and propagation to the growth of damage. The rate of deformation is 10/s.

DETERMINATION OF THE MATERIAL PARAMETERS

The presented damage model contains 6 material parameters : E_0, ε_{tr}, ε_0 and s associated with the static behaviour, C_1 and C_2 related to the dynamic behaviour.
The static parameters were determined as follows : the value of E_0 is derived from a static uniaxial tensile test, for s the value 2 proposed in [7] is adopted, the value of ε_{tr} is derived from the value of the maximum stress σ_{max} observed in the static experiments. Indeed, during the static experiments an almost perfect linear behaviour is observed until 60 % of the maximum stress is reached. So, it can be concluded that under that limit no damage of any importance will appear. A good estimate of ε_{tr} was found to be :

$$\varepsilon_{tr} = \frac{0.6\,\sigma_{max}}{E_0} \tag{5}$$

ε_0 is also deduced from the maximum value of the stress. Indeed, the maximum stress σ_{max} can be written as a function of s, ε_{tr}, ε_0 and E_0 :

$$\sigma_{max} = E_0 \cdot \varepsilon_0^{\frac{s}{s+1}} \cdot \left(\frac{1 + s + \left(\frac{\varepsilon_{tr}}{\varepsilon_0} \right)^s \cdot \varepsilon_{tr}}{s + 2} \right)^{\frac{2+s}{s+1}} \quad (6)$$

For each set of values for s, ε_{tr}, σ_{max} and E_0 more than one value of ε_0 can be calculated from this expression, but only one ε_0 gives a value for d_M (damage corresponding with σ_{max}, see figure 1) in the interval [0, 1].

The damage model consisting of the equations (1) and (2) was implemented in the finite element program IMPACT. IMPACT is a one dimensional program using an unconditionally stable time integration algorithm. The program allows simulation of one-dimensional wave propagation problems. This enabled us to simulate the behaviour of a specimen during a split Hopkinson experiment. During such an experiment the specimen is subjected to a dynamic, uniaxial tensile load.
After incorporation in an optimisation routine, the simulated time histories were compared with experimental results, and the initial values of the dynamic material model parameters C_1 and C_2 are iteratively adapted [6]. Table 1 gives the values of the parameters for the microconcrete used in this study. With these parameters an excellent agreement with the experiments is observed with loading rates in the range of 2/s to 300/s, as will be shown in §4.

TABLE 1
MATERIAL MODEL PARAMETERS AND VALUE FOR σ_{max} DERIVED FROM STATIC AND DYNAMIC EXPERIMENTS

E_0 (MPa)	29 850	ε_0	5.436 10^{-6}
σ_{max} (MPa)	6.5	ε_{tr}	1.306 10^{-4}
C1	7 500	C2	45 000

EXPERIMENTAL TIME HISTORIES VERSUS NUMERICAL SIMULATIONS

As mentioned above split Hopkinson tensile bar experiments were performed on microconcrete specimen. During an experiment, a cylindrical disk of microconcrete is glued between two long bars, the Hopkinson bars, with the same diameter of the specimen. At the free end of one of the Hopkinson bars a tensile wave is generated. This wave travels through the bar towards the specimen. Once the wave reaches the specimen, the specimen is subjected to a dynamic, tensile stress, which is supposed to be purely uniaxial.

The history of the stress, the strain and the strain rate in a specimen during such an experiment is determined by the applied tensile wave and by the mechanical properties of the Hopkinson bars and of the specimen. The strain rate, strain and stress in a specimen during the experiment can be deduced from measurements on the Hopkinson bars [8][9]. Figure 3 gives a typical history of the strain rate for (micro)concrete. Notice that the strain rate is far from being constant in time. Figure 4 gives the corresponding strain. When loading of the specimen is started, strain and strain rate will be homogeneous over the length of the specimen, after a while the damage will concentrate in a small zone of the specimen, where also the deformation will localise. Thus, the measured strain and strain rate of figures 3 and 4 have to be seen as mean values over the length of the specimen. Figure 5 gives the stress history in the specimen. Figure 6 gives the corresponding stress-strain curve.

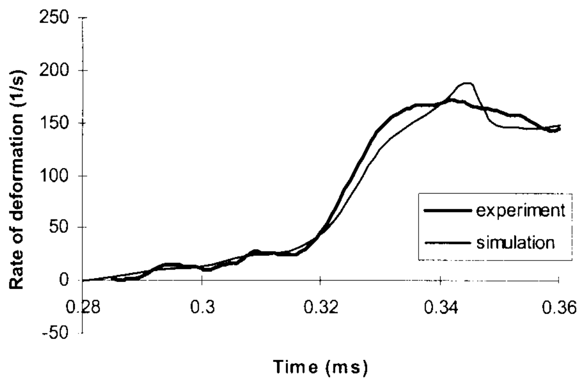

Figure 3: Simulated and experimental history of the rate of deformation in a specimen during a split Hopkinson bar tensile experiment.

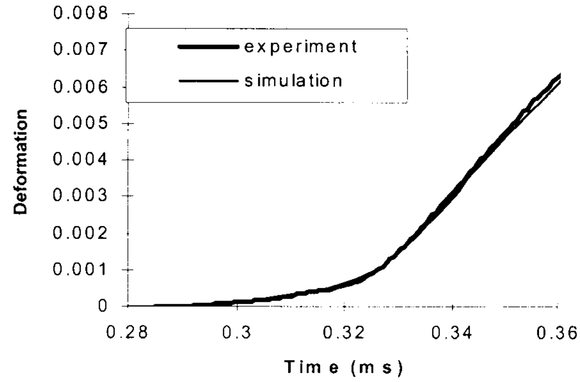

Figure 4: Simulated and experimental history of the deformation in a specimen during a split Hopkinson bar tensile experiment.

Next to the experimental values, in figures 3 to 6 also the simulated values are plotted. These simulations are obtained with the material constants mentioned in table 1 and 2. As can be seen an excellent agreement can be observed. A simular agreement between experiments and numerical simulations can be demonstrated for experiments conducted in other circumstances, and so other rates of deformation [6].

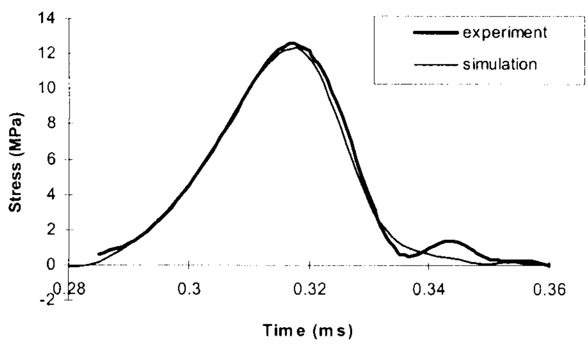

Figure 5: Simulated and experimental history of the stress in a specimen during a split Hopkinson bar tensile experiment.

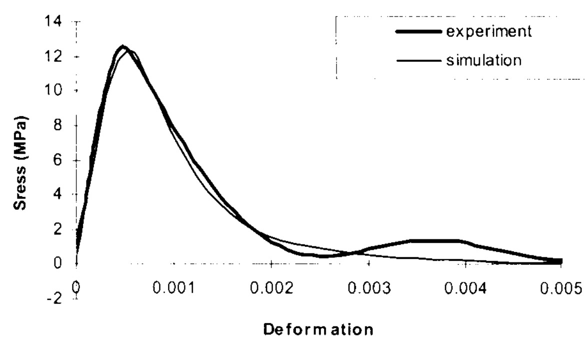

Figure 6: Simulated and experimental history of the stress as a function of the deformation in a specimen during a split Hopkinson bar tensile experiment.

Figure 7 gives the stress-strain curve for an experiment where lower rates of deformation are reached. Notice the smaller value of the maximum stress, the smaller the value of the deformation corresponding with the value of the maximum stress and the smaller the ultimate deformation. The experimentally observed strain rate dependence is well reflected by the material model.

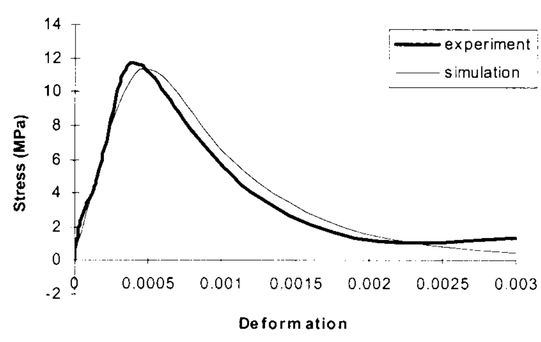

Figure 7: Simulated and experimental history of the stress as a function of the deformation in a specimen during a split Hopkinson bar tensile experiment.

CONCLUSIONS

An impact model within the framework of damage mechanics was developed for concrete. The model makes a clear distinction between the nucleation of new damage and the propagation of existent damage. The model starts from an existing static description. Future research will be performed to investigate if the approach can be extended for the description of the dynamic behaviour of other materials. After all, starting from a static curve valid for the considered material, the dynamic description can be derived in a simular way as for the concrete model presented in this paper.
The presented model is suitable for implementation in a numerical program. The model contains some parameters that were determined by means of experiments : static tensile tests allowed determination of the parameters associated with the time independent behaviour and, by means of a combination of numerical simulation and split Hopkinson tensile tests, the dynamic material parameters were determined.
The model proved to give an excellent agreement with experimental results. In the considered experiments loading rates from 1/s to 300/s were reached, thus it can be stated that the model is valid in this range of deformation rates.

ACKNOWLEDGEMENT

The presented research was performed in close collaboration with the Laboratory for Concrete Research of the Ghent University. The authors want to thank in particular prof. L. Taerwe and prof. G. De Schutter of this laboratory for the production of concrete and the static experiments.

REFERENCES

1. Ross, C.A., Thompson, P.Y. and Tedesco, J.W. (1989) Split-Hopkinson pressure-bar tests on concrete and mortar in tension and compression. *ACI mat jour* 86, nr. 5, 475-481.
2. Tang, T., Malvern, L.E. and Jenkins, D.A. (1992) Rate effects in uniaxial dynamic compression of concrete. *j. engrg. Mech.* 118, nr 1, 108-124.
3. Banthia, N., Chokri, K., Ohama,Y. and Mindess, S. (1994) Fiber-reinforced cement based composites under tensile impact. *Advn. Cem. Bas. Mat.*, 1, 131-141.
4. Rossi, P. (1994) Dynamic behaviour of concretes : from the material to the structure. *Materials and Structures*, 27, 319-32.
5. Reinhardt, H.W., Rossi, P. and Van Mier, J.G.M. (1990) Joint investigation of concrete at high rates of loading. *Mat. and Struc.*, 23, 213-216.
6. Verleysen, P.(1999) Experimental investigation and numerical modelling of the dynamic tensile behaviour of quasi-brittle and fibre reinforced quasi-brittle materials. Doctoral dissertation University of Gent (In dutch)
7. Lemaitre, J., Chaboche, J.-L. (1988) Mécanique des matériaux solides. Dunod.
8. Kolsky, H. (1949) An investigation of the mechanical properties of materials at very high rates of loading. *Proc. Phys. Soc.* Sec. B, **62**, 676-700.
9. Kolsky, H. (1963) Stress waves in solids. New York Dover Publications Inc..