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SHOCK WAVE LOADING ON REINFORCED CONCRETE PLATES: EXPERIMENTAL RESULTS AND COMPARISONS WITH EXPLICIT DAMAGE MODEL PREDICTIONS

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Abstract

In order to determine the vulnerability of reinforced concrete structures submitted to accidental loading, the Centre d' Etudes de Gramat (C.E.G.) has developed an explicit damage model for concrete where the stress tensor can be obtained in terms on the strain tensor without any iterative process. Such an explicit formulation is recommended when dynamic response must be obtained on complex two or three dimensional structures. The new model uses two scalar damage variables to represent material stiffness with opened or closed cracks. Inelastic strains are also included in the constitutive equations. Strain rate effects are introduced in the model as well as friction in order to simulate stress strain hysteresis during unloading and reloading.

At the same time experimental facilities have been developed in order to test reinforced concrete plates under shock wave effects. The concrete plates have a diameter of 1.3 meter and a thickness of 10 centimeters. The plates are supported on their external edges and they are submitted to calibrate shock wave loading inducing large permanent deflection and yielding of the steel reinforcement. Dynamic displacements are measured on the plate. Strain gages located on the steel reinforcement bars give the strain history during tests.

Numerical simulations of these experiments are done using a finite element program with the developed damage model. Comparisons between numerical simulations and experimental results are presented and discussed.

1 Introduction

In order to determine the vulnerability of reinforced concrete structures under severe accidental loading, the Centre d'Etudes de Gramat (C.E.G.) has to simulate, on complex two or three dimensional structures, dynamic response and failure of reinforced concrete targets. Such numerical simulations take a long time to run and convergence problems often induce fatal numerical difficulties. More over the complex behaviour of brittle material like concrete is not easy to model when qualitative and quantitative results are expected. The following essential physical mechanisms should be considered for reasonable numerical predictions in dynamic and highly non linear problems:

- Correct description of tension and compression strength.
- Description of the crack closure effect.
- Introduction of inelastic strain.
- Strain rate effect on tension and compression strength.
- Friction phenomena.

In order to take into account these physical mechanisms it was necessary to develop a new model and to introduce it in the well known finite element program ABAQUS Explicit. A particular attention should be devoted to numerical integration of the constitutive equations. Computation procedure of the stress tensor has to be written with an explicit form for better numerical efficiency.

Validation of the new model on realistic experiments is necessary to be sure that numerical predictions are correct. A specific experimental facility needs to be developed for this purpose. Dynamic tests with shock wave applied to large size concrete specimens are able to give experimental results close to realistic problems. The dynamic loading should induce large deflection and severe damage on the structures. Failure of the tested specimens has to be performed and to be compared with numerical simulations for validation including a large loading range. In order to get interesting experimental results, dynamic measurements should be obtained on the concrete specimens and on the steel reinforcements. Detailed comparisons on measured and computed values are necessary to be confident with the new developed model.

2 Concrete damage model

2.1 General damage model characteristics

A damage model mainly developed for reverse loading of concrete specimen is proposed. The new model can be presented as an extension of the J. Mazars' damage model (Mazars, 1984). Two scalar damage variables are used instead of one for the first model. These scalar variables are internal state variables that give the material stiffness with opened and respectively with closed cracks. The scalar D_t is introduced to represent the loss of material stiffness when cracks induced by extensions are opened. The scalar D_c refers to loss of material stiffness when compressive loading is applied at the material point.

Inelastic or irrecoverable strains are introduced in the constitutive equations. These strains are related to the damage variables D_t and D_c. As damage grows, inelastic strain increases. They are associated to frictional effects in cracked zone which induce permanent strains even for zero loading.

Figure 1 shows the stress strain relation for uni-axial and cyclic tension or compression loads. Cyclic loading can be simulated in this way with the present model.

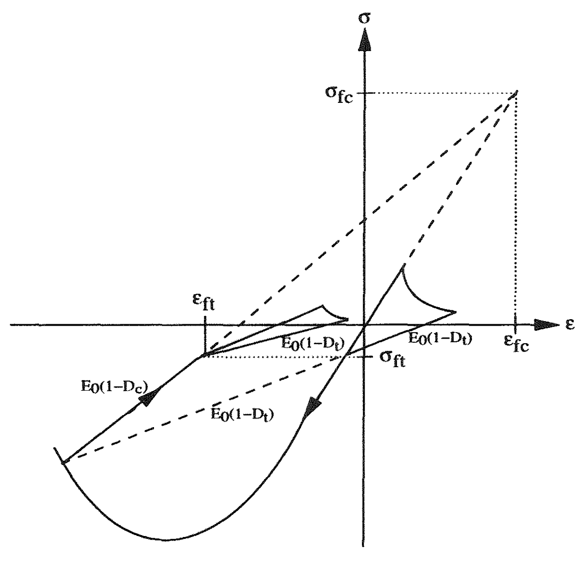


Figure 1. Cyclic behaviour of damage model under uniaxial loading

As for the J. Mazars's model an explicit formulation is adopted in the stress strain relation. The formulation gives a stress tensor expression versus the strain tensor and versus the inelastic or irreversible strain tensor.

Details of the present model are given in reference (Pontiroli, 1995). Only general characteristics are shown here.

The stress strain relation is given by:

$$\underline{\underline{\sigma}} - \underline{\underline{\sigma}}_{ft} = (1-D_t)\,\alpha_t \left[\lambda_0 \mathrm{Trace}\,(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}_{ft})\,\underline{\underline{I}} + 2\,\mu_0\,(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}_{ft}) \right] + (1-D_c)\,\alpha_c \left[\lambda_0 \mathrm{Trace}\,(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}_{ft})\,\underline{\underline{I}} + 2\,\mu_0\,(\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}_{ft}) \right] \quad (1)$$

λ_0 and μ_0 are the Lame coefficients.

$\underline{\underline{\sigma}}_{ft}$ is the closure stress tensor, $\underline{\underline{\varepsilon}}_{ft}$ the associated closure strain tensor.

D_t and D_c are the damage variables (scalar values).

Evolution laws for D_t and D_c are controlled by an equivalent strain $\tilde{\varepsilon}$ which depends, like in the J. Mazars's model, on positive principal strain components.

α_c and α_t are scalar values between 0 and 1 which give the compressive and tensile part of a given loading ($\alpha_c + \alpha_t = 1$).

2.2 Strain rate effects

Experimental results, obtained on dynamic tensile and compressive tests, show that the concrete strength is strain rate dependent (Toulemonde 1995, Suaris and Shah 1985). This effect is significant specially on tensile tests where a strain rate equal to 1 s^{-1} can double the maximum concrete strength. In order to simulate this phenomena, damage evolution laws are strain rate dependent. The damage threshold that governs damage evolution law is written as follows:

$$\varepsilon_0 = \alpha_t \varepsilon_0^t + \alpha_c \varepsilon_0^c \quad (2)$$

ε_0^t and ε_0^c are tensile and compressive damage threshold. These threshold are strain rate dependent as follows:

$$\varepsilon_0^t = \varepsilon_0^{ts}\left[1 + a_t (\dot{\varepsilon})^{b_t}\right]$$
$$\varepsilon_0^c = \varepsilon_0^{cs}\left[1 + a_c (\dot{\varepsilon})^{b_c}\right] \quad (3)$$

ε_0^{ts} and ε_0^{cs} are respectively static tensile and static compressive threshold.

a_t, b_t, a_c, b_c are material coefficients which are obtained from dynamic tensile and compressive tests.

$\dot{\varepsilon}$ is a scalar measure of the strain rate calculated from octahedral strain (Liu and Owen, 1986).

This method introduces different strain rate sensitivity coefficients between tension and compression.

2.3 Friction effect

An additive friction stress, $\underline{\underline{\sigma}}_{fric}$ is introduced in the formulation. This stress generates hysteresis in the stress strain relation during unloading and reloading response with constant and non zero damage variables. Dissipate energy is simulated in the elastic range for damaged material. This effect introduces a damping in the concrete structure response which is strain rate independent.

The total stress tensor is given by:

$$\begin{aligned} \underline{\underline{\sigma}} &= \underline{\underline{\sigma}} + \underline{\underline{\sigma}}_{fric} && \text{if} \quad \dot{D}_t = 0 \text{ and } \dot{D}_C = 0 \\ \underline{\underline{\sigma}} &= \underline{\underline{\sigma}} && \text{if} \quad \dot{D}_t \neq 0 \text{ or } \dot{D}_C \neq 0 \end{aligned} \tag{4}$$

2.4 Regularization method

In order to reduce mesh size effects on results, the regularization concept proposed by Hillerborg et al. (1976) is used. When crack localization appears in the material, large strains take place along a finite element band. The energy dissipated in the localization band is mesh size dependent. In order to get a constant dissipated energy for any mesh, the equivalent tensile strain $\tilde{\varepsilon}$ is replaced by the corrected strain tensor $\tilde{\varepsilon}^*$ defined by:

$$\tilde{\varepsilon}^* = \tilde{\varepsilon} \qquad \text{if} \quad \tilde{\varepsilon} \leq \varepsilon_p \tag{5}$$

$$\tilde{\varepsilon}^* = \varepsilon_p + (\tilde{\varepsilon} - \varepsilon_p)\frac{L_e}{L_c} \qquad \text{if} \quad \tilde{\varepsilon} \geq \varepsilon_p \tag{6}$$

L_e is the finite element characteristic length (the square root of the element area).

L_c is a material internal length.

ε_p is the equivalent tensile strain obtained at the peak stress.

For a given loading, we can write:

$$\varepsilon_p = \alpha_t \varepsilon_p^t + \alpha_c \varepsilon_p^c \tag{7}$$

ε_p^t and ε_p^c are respectively strains at the peak tensile and compressive stress.

The regularization method modifies the post peak stress strain relation. It has an effect on tensile and compressive part of the material behaviour.

3 Experimental procedure

3.1 Reinforced concrete specimens

The circular concrete slabs which have been tested have a diameter of 1.3 meter and a thickness of 10 centimeters.

These slabs are orthogonally reinforced in the top and bottom positions, at 1.5 cm of each surface. The diameter of the steel bars is d = 6 mm.

3.2 Shock tube facility

The slabs have been tested with the blast simulator of C.E.G. In the shock tube, a quasi plane shock wave is generated by bursting the diaphragm which separates the reservoir filled with compressed air from the expansion zone (figure 2).

The concrete plates are placed at the end of the tube, perpendicularly to the shock wave direction (figure 2).

The size of the tube (diameter = 2.4 m) allows to load the samples with a maximum pressure of 6.6 bars.

3.3 Boundary conditions of concrete specimens

Two different boundary conditions have been studied (figure 3.(a) and 3.(b)):

- (a) corresponds practically to a embedded slab due to the ring's rigidity
- (b) corresponds practically to a simply supported slab

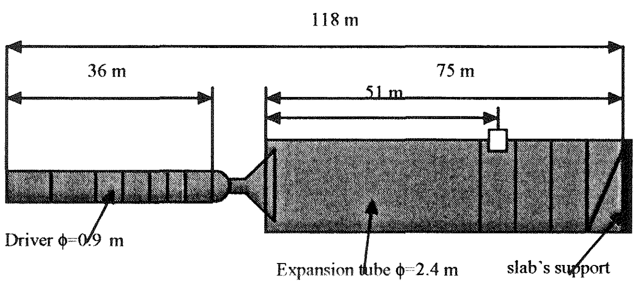


Figure 2. Blast simulator lay-out

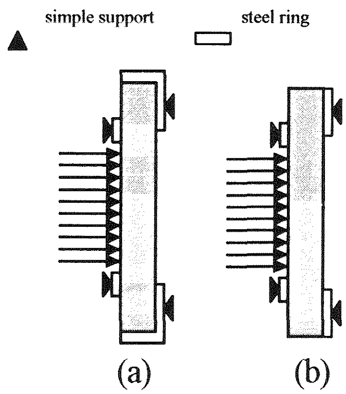


Figure 3. Boundary conditions

3.4 Dynamic measurements

- two pressure sensors in the slab plane allow to measure load profile. These pressures versus time are introduced as data in numerical simulations.
- acceleration sensors on slab, shock tube and support.
- slab measurements:
  * local strain measurements are carried out by gauges bonded to reinforcement.
  * four displacement sensors to measure global deformations.
  * video cameras and 16 mm fast cameras (1000 images/second) record the slab during the shock and measure the central deflection.

4 Experimental and numerical comparisons

4.1 Identification procedure

The material properties of concrete and steel have been obtained with:

- compressive tests (concrete's elastic modulus and compressive strength)
- Brazilian test and four points bending tests (concrete's tensile strength)
- tensile tests (steel's elastic modulus and yield stress)

Concrete properties:
Young's modulus=31 GPa
Poisson's ratio=0.2
Compressive strength=-32 MPa
Tensile strength=3 MPa
σ_{ft}=crack closure stress= -3 MPa
Density=2323 Kg/m^3

Steel properties:
Young's modulus=207 GPa
Poisson's ratio=0.3
Yield stress=660 MPa
Strain at failure=2.5 %
Density=7850 Kg/m^3

Strain rate parameters are identified from experimental results given by Suaris and Shah (1985) : a_t=1., a_c=0.3, b_t=b_c=0.21

4.2 Finite elements model

Computations are conducted using ABAQUS Explicit finite element code.

As an axisymmetric problem, slabs with rings are modelled using 40 axisymmetric layered shell elements in which each element is composed of 3 concrete layers and 2 steel layers. The number of concrete integration points through the thickness of the slab is set to nine to ensure the development of concrete's failure.

Steel behaviour is supposed to be elasto-plastic with perfect plasticity and a perfect adhesion between concrete and steel bars is considered.

Boundary conditions are applied on rings and unilateral contacts between reinforced concrete slab and steel rings are introduced (figure 3).

4.3 Comparisons

Experimental and numerical comparisons are presented for two reinforced concrete slab with same geometries and material properties but with different boundary conditions (figure 3 shows conditions (a) and (b)).

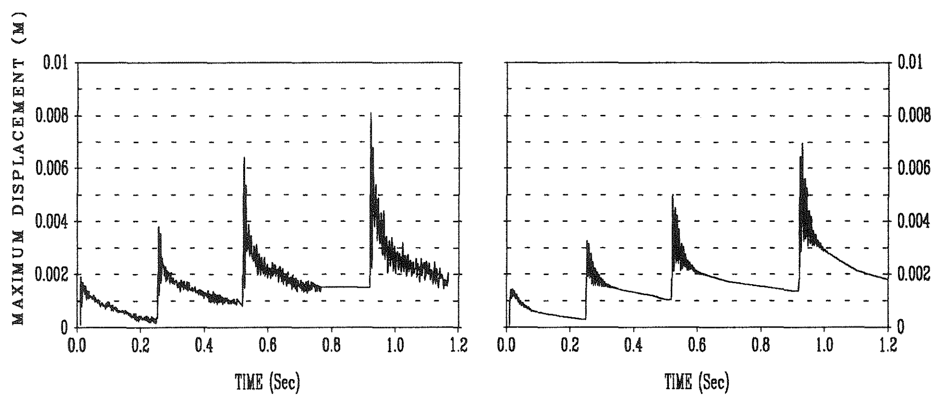
Successive shots with increasing maximum incident over-pressure allow to reach progressively the value of the ultimate structure load and to follow the evolution of its damage and failure pattern.

- boundary conditions (figure 3 a):

Figures 4 and 5 show central deflection versus time and central steel strain versus time for 4 successive shots at 1.7, 2.2, 3 and 4 bars.

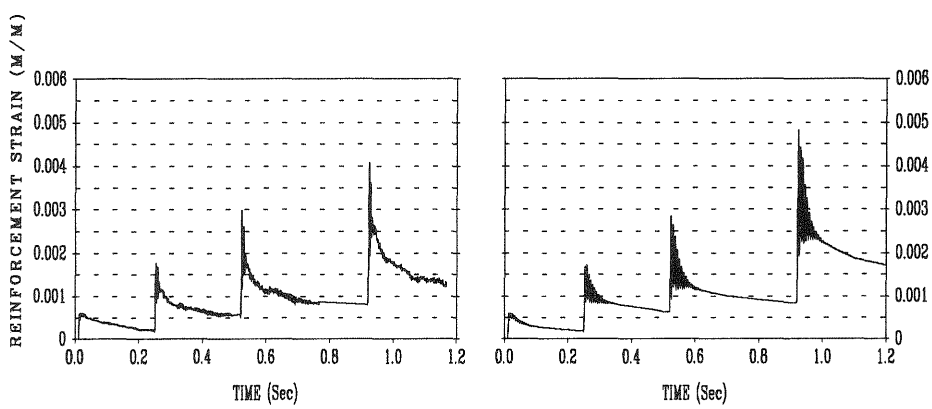
Moderate damage is obtained for these loads and numerical results give a good prediction of slab behaviour.

Permanent deflection and inelastic strain appear after each shot due to the cracking of concrete under tension. Yielding of steel reinforcement is not obtained with these loading.



Experimental results Numerical results

Figure 4. Central deflection at successive shots



Experimental results Numerical results

Figure 5. Central reinforcement deformation at successive shots

- boundary conditions (figure 3 b):
Figure 6 shows central deflection for 3 successive loads at 3.1, 3.8 and 4.8 bars.

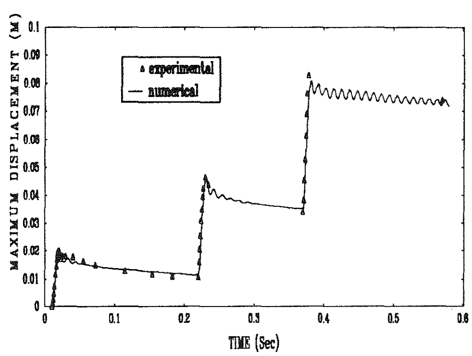


Figure 6. Central deflection for 3 shots

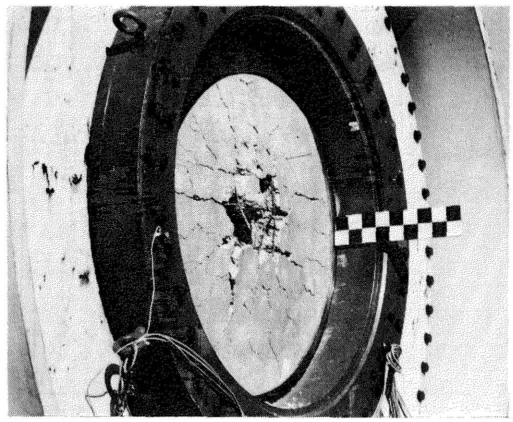


Figure 7. Cracked concrete slab

For the last load, at the center of the slab, the cracks propagate rapidly until collapse occurs as the steel bars yield (figure 7). Even after 3 impact loads, numerical central deflection obtained are in good general agreement with experimental results. Other comparisons, such as the crack patterns, the yield stress and the failure modes, are also analysed and found to be similar with the experiments.

5 Conclusions

A numerical and experimental procedure has been presented for predicting the nonlinear dynamic response of reinforced concrete slab under accidental loading.

The new material model uses a rate sensitive damage model which includes inelastic strains, crack closure and friction effects. This model is used in conjunction with the Hillerborg regularization method to limit mesh size effects.

The explicit formulation of this concrete model allows an easy implementation in a general finite element code and gives very robust computations to simulate strong instabilities due to localization phenomena.

The constitutive model outlined in this paper and considered for the dynamic behaviour of reinforced concrete slabs under impact loads seems to give a good estimate of the overall response of the structure, but requires further validation on other numerical examples.

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