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NUMERICAL RECREATION OF GAP TEST

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Abstract: A gap test is a new experimental and numerical test proposed by Bažant et al. Its main goal is to show that the effective mode I (opening mode) fracture energy depends on the crack-parallel normal stress. Moreover, the authors of the test believe that the FE crack band model coupled with microplane model M7 and the lattice discrete particle model allow to fit results of the laboratory gap test satisfactorily. A specimen is in form of a concrete beam with a notch. A static scheme of the specimen changes when a gap between specimen and roller supports vanishes. The authors of this paper tried to recreate numerically the gap test using the concrete damaged plasticity (CDP) model. A finite element analysis was performed using Abaqus software. Main results compared with Bažant et al. were: a force-displacement relationship and a crack pattern. The numerical test will answer the question if the CDP model allows to recreate the gap test properly. To simplify computations the specimen was divided into elastic and plastic regions. The plastic region was fine meshed and a coarse mesh was assigned to the elastic regions. The gap modeled in the test was equal to 3 mm, so a pinned and a roller supports became active only when displacements of both ends of the specimen reached 3 mm. Displacement control was chosen in the FEM model in form of a displacement imposed on a top steel pad. Bottom pads were modeled as made of polypropylene. The force-displacement relationship was established using results obtained for the top steel pad and the crack pattern was presented with the equivalent plastic strain of concrete in tension.

1 INTRODUCTION

A simple fracture test called the gap test has been recently described in a few scientific papers [1-3]. The main goal of the test is to show that the effective mode I fracture energy in concrete depends on the crack-parallel normal stress. The test has been already performed in laboratory and numerically. According to [1] only certain material models are suitable to simulate the gap test numerically, namely: the FE crack band model coupled with microplane model M7 and the lattice discrete particle model.

The gap test consists of two steps, which differ in boundary conditions. In the first step (see Fig. 1) a notched concrete specimen is only supported with pads made of polypropylene with near-perfect plastic yielding. A gap between the specimen and rigid end supports is introduced. In the second step of the test yielding of the pads occurs exactly when both ends of the specimen touch the end supports. The test continues until the specimen's failure.

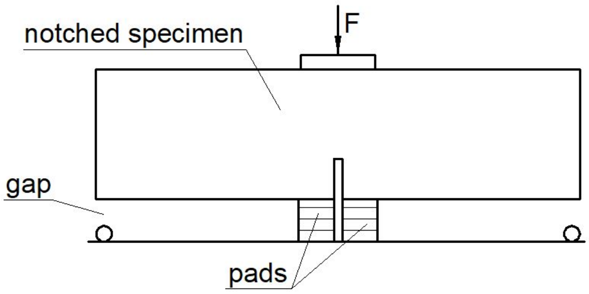

Figure 1: Set up of the gap test.

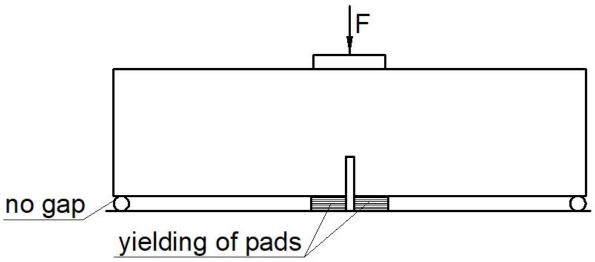

Figure 2: Yielding of pads.

The authors of this paper decided to recreate the gap test using Concrete Damaged Plasticity (CDP) model of concrete in ABAQUS finite element software [4]. The model is widely used for simulation of various concrete elements, e.g. [5]. Result of a numerical analysis were compared with laboratory test presented in [1]. The main goal of the authors was to assess if the CDP model is able to reproduce the gap test in satisfactory way.

2 CDP MODEL

The Abaqus software offers a few material models dedicated to concrete and other brittle materials. One of them is the CDP model, theoretically described by Lubliner et al. [6, 7] and developed by Lee [8] and Lee & Fenves [9]. The multiaxial behavior of concrete, the yield function and the flow potential function in the CDP model are formulated according to the following formulae:

$$\boldsymbol{\sigma} = (1-d)\mathbf{D}_{\mathbf{o}}^{\mathbf{el}} : (\varepsilon - \varepsilon_{pl}) \tag{1}$$

$$F = \frac{1}{1-\alpha}\left(\bar{q} - 3\alpha\bar{p} + \beta(\tilde{\varepsilon}_{pl})\left\langle \bar{\hat{\sigma}}_{\max} \right\rangle - \gamma\left\langle -\bar{\hat{\sigma}}_{\max} \right\rangle\right) - \overline{\sigma_c}(\tilde{\varepsilon}_{pl}) = 0 \tag{2}$$

$$G = \sqrt{\left(\varepsilon\sigma_{t0}\tan\psi\right)^2 + \bar{q}^2} - \bar{p}\tan\psi \tag{3}$$

where **σ** is a stress tensor, $\mathbf{D_o^{el}}$ is an initial elasticity matrix, d denotes a damage parameter, α, β and γ are parameters of the yield surface, $\bar{p}$ is a hydrostatic equivalent pressure stress, $\bar{q}$ is von Mises equivalent effective stress, ε is a flow potential eccentricity and ψ is a dilatation angle. The yield surface in the plane stress state is presented in the Figure 3 and the plastic potential function in the meridian plane is shown in the Figure 4.

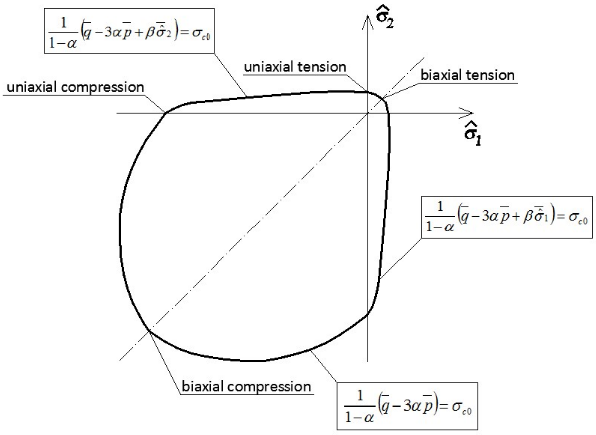

Figure 3: Yield function in the plane stress state.

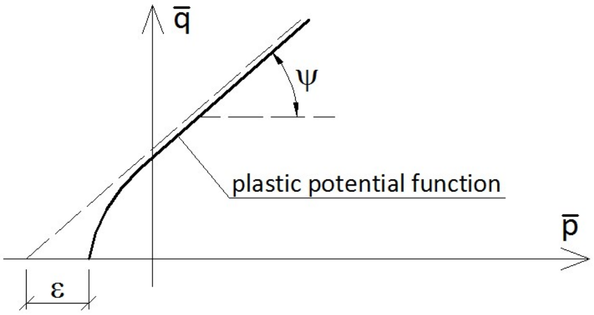

Figure 4: Plastic potential function in the meridian plane.

Viscoplastic regularization in the CDP model can be introduced according to Duvaut-Lions [10] approach. A rate of change of plastic viscous strains is defined as:

$$\dot{\varepsilon}_v^{pl} = \frac{1}{\mu}\left(\varepsilon^{pl} - \varepsilon_v^{pl}\right) \tag{4}$$

where μ denotes relaxation time.

The tension behavior of concrete in the post-critical range in the CDP model can be defined in three different ways: by defining the $\sigma-\varepsilon_{in}$ or $\sigma-u_{cr}$ relationship (a lower index "in" means inelastic and "cr" denotes cracking), or by inputting the fracture energy G_f. The compressive behavior is defined with the $\sigma-\varepsilon$ relationship for the compression of concrete. The proper choice of the dilatation angle and the relaxation time was discussed by the authors in their previous work [11].

3 SETUP OF NUMERICAL MODEL

The notched specimen was defined in the ABAQUS software in a plane stress state. Boundary conditions are shown in the Figure 5. The specimen's dimensions were assumed following [1]: width L = 381 mm, height D = 101.6 mm, pads: 25 x 30 mm, notch depth 0.3D = 30.48 mm and width 3 mm. A vertical displacement imposed on the top of the mid-span was equal to 20 mm.

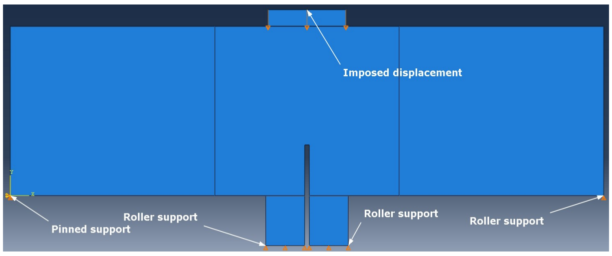

Figure 5: Geometry and boundary condition of the specimen.

The specimen was meshed with four-node bilinear plane stress quadrilateral finite elements with reduced integration and enhanced hourglass control (CPS4R in the ABAQUS code). Meshing of the specimen in shown in the Figure 6. Average mesh size was as follows: 2x2 mm for a fine and 2x5 mm for a coarse mesh.

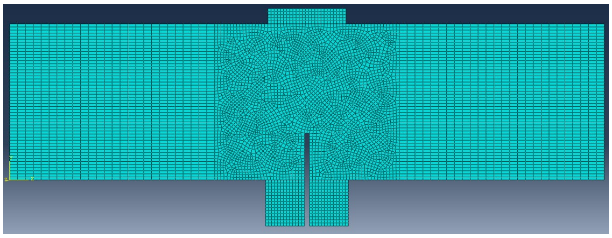

Figure 6: Meshing of the specimen.

As mentioned before, the CDP model was applied for concrete. Polypropylene pads were defined with the use of the classical von Mises plasticity, according to [1]. Main material constants and input data are listed in the Tables 1 to 3. The authors of this paper decided to vary the value of the dilatancy angle, as presented in the Table 1.

Table 1: Input data of concrete

Elastic modulus	35 GPa
Poisson's ratio	0.167
Dilatancy angle	15°, 20°, 25°
Yield stress	3.5 MPa
Fracture energy	142 Nm^{-1}
K	0.667
f_{b0}/f_{c0}	1.16
ε	0.1
Relaxation time	10^{-4} s

Table 2: Compressive behaviour of concrete

Yield stress [MPa]	Inelastic strain
16.2	0
40.5	0.001837
32.4	0.003037

Table 3: Input data of polypropylene

Elastic modulus	1.74 GPa
Poisson's ratio	0.38

Two consecutive static steps of the FEM analysis were defined in ABAQUS: first with the 3 mm gap between the specimen and the end supports and the second step without the gap (as shown in the Figure 5).

4 RESULTS

Results of the FEM calculations presented in this paper are: equivalent plastic strain in tension (abbreviated as PEEQT in the ABAQUS code) and a force-displacement relationship. The PEEQT output parameter allows to track a cracking pattern of the specimen. The force-displacement relationship (established for the displacement imposed on the top of the mid-span of the specimen) can be compared with the laboratory test, presented in [1]. Results for the PEEQT parameter (with dilatancy angle equal to 15°; for the rest of assumed angles the results differ slightly) are presented in the Figures 7-9 and the force-displacement relationship – in the Figure 10. Please note, that the whole FEM analysis was divided into two different steps (as described in the previous section) and the “step time” indicates an increment in the FEM analysis of a non-linear problem. An exponential notation in the Abaqus software needs to be explained with an example: “e-01” denotes 10^{-1} and so on.

Discussion of the results begins with the PEEQT output parameter. A crack pattern arranged into a characteristic “X” sign in almost all steps and increments. In the second step of the numerical calculations we can see a disappearance of the “X”-pattern and a relatively small propagation of a concurrent crack in the tip of the notch.

The force-displacement relationship seemed to be different from the one obtained in the experiment [1]. The maximal force both in the experiment and in the numerical simulations is comparable, but the initial stiffness for the simulations is lower. The value of the assumed dilatancy angle did not significantly affect the numerical results.

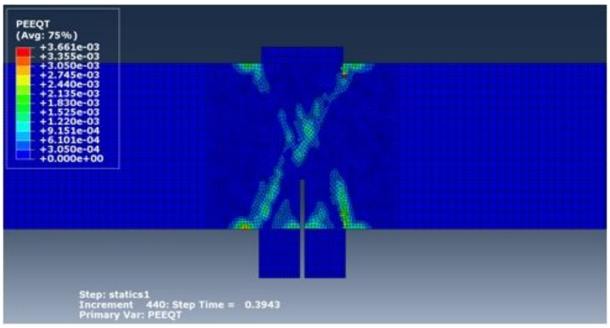

Figure 7: PEEQT, 1st step, step time 0.3943.

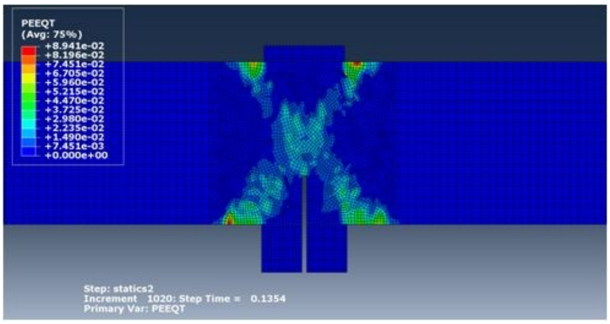

Figure 8: PEEQT, 2nd step, step time 0.1354.

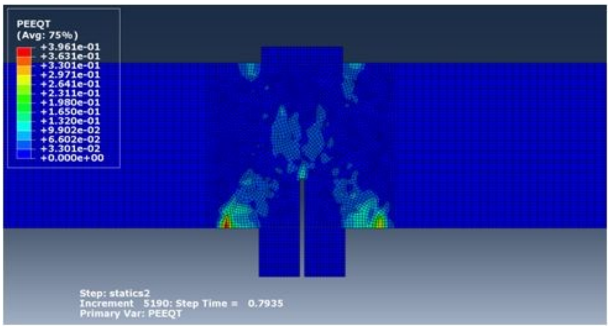

Figure 9: PEEQT, 2nd step, step time 0.7935.

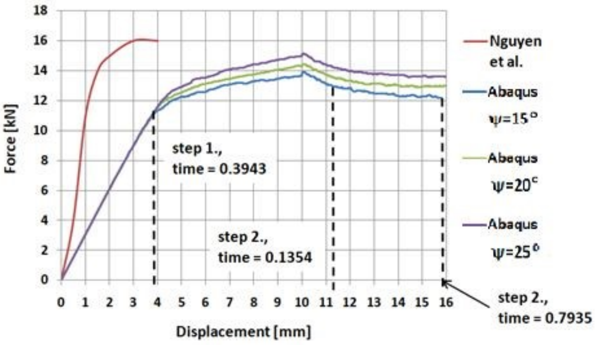

Figure 10: Force-displacement relationship.

5 CONCLUSIONS

The presented results of the authors’ work lead to the following conclusions:

- the gap test simulated in Abaqus with the use of the CDP model reproduced well the maximal force on the force-displacement path,
- the initial stiffness in the numerical simulations was lower than in the experiment,
- cracking pattern of the specimen was different than in the experiment.

Considering this, the authors decided to continue their work on the gap test to adjust numerical result to the experiment presented in [1]. However, it is also possible that the CDP model will not reproduce the gap test sufficiently.

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