Focussed on Steels and Composites for Engineering Structures

Visual Abstract

A nonlinear concrete damaged plasticity model for simulation reinforced concrete structures using ABAQUS

Thanh Cuong-Le*, Hoang-Le Minh, Thanh Sang-To
Faculty of Civil Engineering, Ho Chi Minh City Open University, Ho Chi Minh City, Viet Nam
cuong.lt@ou.edu.vn, hoang.lm@ou.edu.vn, sang.tt@ou.edu.vn

ABSTRACT. The reinforced concrete structure is typical and widely used in many fields. The behavior of concrete is nonlinear and complex. Especially, when cracks/crushings occurred in softening phase. Thus, It is important to find a damaged model of concrete with high reliability in the numerical simulation. The nonlinear behavior of concrete is the most feature used in the simulation. This characteristic is expressed through the parameters defining the yield surface, the flow potential, and the nonlinear relationship of stress-strain in the cases of tension and compression. This paper introduces a damaged concrete model that applies to the simulation of reinforced concrete structures. The reinforced concrete beam and flat slab are selected as examples to evaluate the reliability of the model presented. Through the results achieved, the model used in this paper shows high reliability and can be used to simulate more complex reinforced concrete structures.

KEYWORDS. Nonlinear behavior; Concrete material; Numerical simulation; Concrete damaged plasticity.

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INTRODUCTION

Because of the complicated nonlinear behavior of concrete material. There are many theories about the damaged model in a finite element method (FEM) analysis reported in the literature. Among the damaged models, the concrete damaged plasticity (CDP) model is considered the most reliable use in simulation. Based on this model, by using many other techniques, many damaged models have been proposed. Most improved techniques are based on developing a new stress-strain relationship in both compression and tension or proposing a novel function to calculate damaged parameters in compression dc and tension (*dt*). Lubliner *et al.* [1] was proposed a novel constitutive model lied on plasticity theory for the non-linear analysis of concrete. A new yield criterion was presented which accounts for both elastic and plastic stiffness degradations effects. Comparing results between numerical simulation and experimental methods showed that the model responded well to applications. Carol *et al.* [2] was presented as a formulation for tensile damage. One of the important advantages of the model is that closed-form solutions are possible for some loading cases. Damaged models which are based on presenting a novel curve of stress-strain in three dimensions stress can find in reports of. Ahmed *et al.* [3]. were proposed a damaged model based on the novel stress accounting for damaged shear. The new stress makes further decompose tensile and compressive parts into pure biaxial shear and pure tensile/compressive biaxial stresses. The theory of Lubliner theory [1] was employed to develop a new method to modify the damaged concrete model by Lee *et al.* [4]. Thus, this proposed model was accounted for confinement having a uniform and non-uniform conditions. Jason *et al.* [5] introduced the new function to calculate the damaged elastic-plastic. This model has overcome the limitations of pure elastic-plastic damage in the case un-loading phase. Grassl *et al.* [6] were used the combination of damage mechanics and plasticity flow to investigate the concrete structure under dynamic loading conditions, etc. In this paper, the concrete damaged plasticity model (CDP) in combination with the tensile damage variable (*dt*) and compressive damage variable (*dc*) were followed by Birtel and Mark [7]. This model is employed to simulate the test of a reinforced concrete beam namely C3 in tests of Vecchio và Shim (2004) [8] and a reinforced concrete slab in test of Genikomsou and Polak [9] for reliable consideration.

A DAMAGED MODEL PRESENTED FOR CONCRETE

Material parameters for the yield function and plastic flow potential

The damaged concrete plasticity model (CDP) is employed in the ABAQUS manual. This model was improved by Lee and Fenves [4] . The model CDP based on that definition the yield function of concrete shown in Fig. 1 and the parameters of flow potential and yield surface given in Tab. 1. Where $\sigma_{b0} / \sigma_{c0}$ is the ratio between the strength of biaxial and uniaxial in compression. Kc is the ratio between the magnitudes of deviatoric stress in uniaxial tension and compression.

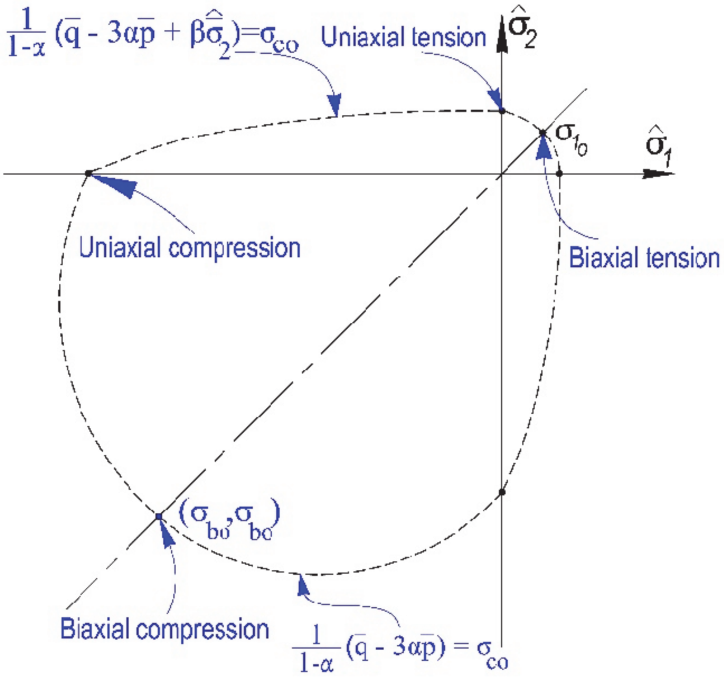

Figure 1: Concrete yield surface

Dilation angle	Eccentricity (ε)	$\sigma_{b0} / \sigma_{c0}$	K_c
$30^0 \sim 40^0$	0.1	1.16	0.667

Table 1: The material parameters in CDP model.

Compressive and tensile behavior

Behavior in compression

Uniaxial loading conditions in compression includes 3 phases shown in Fig. 2. The details of phases are described below:

Phase 1: in this phase, the relationship of stress-strain is denoted linear given in Eqn. (1). At the end of this phase registered $\sigma_c = 0.4 f_{cm}$ according to EC2.

$$\sigma_c^1 = E_0 \varepsilon_c \tag{1}$$

Phase 2: when the compressive stress is achieved $\sigma_c = 0.4 f_{cm}$, cracks begin to appear Accordingly, the relationship of stress-strain of concrete in this phase is nonlinear behavior given in Eqn. (2)

$$\sigma_c^2 = \frac{E_{ci}\dfrac{\varepsilon_c}{f_{cm}} - \left(\dfrac{\varepsilon_c}{\varepsilon_{c1}}\right)^2}{1 + \left(E_{ci}\dfrac{\varepsilon_{c1}}{f_{cm}} - 2\right)\dfrac{\varepsilon_c}{\varepsilon_{c1}}} f_{cm} \tag{2}$$

where E_{ci} is the modulus of elasticity of concrete.

Phase 3: The behavior of concrete in this phase is softening and determined based on the theory which is proposed by Kratzig and Polling (2004), this model is suitable for numerical analysis because the model depends on the length of mesh elements l_{eq}. Phase 3 is expressed in Eqns. (3-4).

$$\sigma_c^3 = \left(\frac{2 + \gamma_c f_{cm} \varepsilon_{c1}}{2 f_{cm}} - \gamma_c \varepsilon_c + \frac{\varepsilon_c^2 \gamma_c}{2\varepsilon_{c1}}\right)^{-1} \tag{3}$$

$$\gamma_c = \frac{\pi^2 f_{cm} \varepsilon_{c1}}{2\left[\dfrac{G_{ch}}{l_{eq}} - 0.5 f_{cm}\left(\varepsilon_{c1}(1-\mathrm{b}) + b\dfrac{f_{cm}}{E_0}\right)\right]^2}; \quad b = \frac{\varepsilon_c^{pl}}{\varepsilon_c^{in}} \tag{4}$$

where G_{ch} denotes crushing energy, ε_c^{pl} and ε_c^{in} are plastic strain and inelastic strain, respectively.

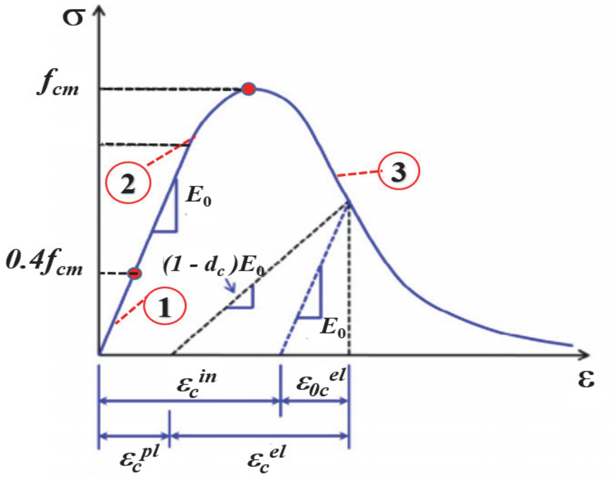

Figure 2: Behavior in compression.

Behavior in tension

The tensile nonlinear behavior of concrete is a curve showing the stress-crack opening relationship proposed by Hordijk. The characteristic of this curve is that it does not depend on the element meshing in the FEM model. The formulation of this relationship is given in Eqn. (5).

$$\frac{\sigma_t(w)}{f_{tm}} = \left[1+\left(c_1\frac{w}{w_c}\right)^3\right]e^{-c_2\frac{w}{w_c}} - \frac{w}{w_c}(1+c_1^3)e^{-c2} \tag{5}$$

where $c_1 = 3, c_2 = 6.93$ and wc is the critical crack opening which can be considered as the fracture crack opening given in Eqn. (6).

$$w_c = 5.14\frac{G_F}{f_{tm}} \tag{6}$$

Based on the curve of stress-crack opening relationship, it can be obtained a new curve having the feature of stress-strain through Eqn. (7). Thus, the strain ε_t at tensile strength ε_{tm} can be evaluated from crack opening. Where l_{eq} can consider as a length of element (meshed size). After this assumption, the stress-strain curve relationship given in Fig. 3.

$$\varepsilon_t = \varepsilon_{tm} + \frac{w}{l_{eq}} \tag{7}$$

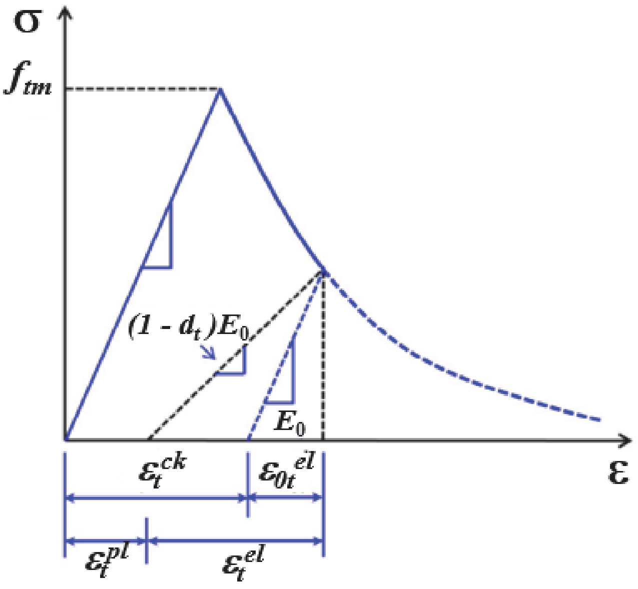

Figure 3: Behavior in tension.

Compressive damage and tension damaged component

Compression damage variable (*dc*)

This parameter is used to specify compressive stiffness degradation damage, d_c is determined through plastic strain ε_c^{pl} and a using a constant factor b_c with $0 < b_c \leq 1$.

$$d_c = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{pl}\left(1/b_c - 1\right) + \sigma_c E_c^{-1}} \tag{8}$$

In this paper, assumption $b_c = 0.7$ to evaluate the parameter d_c. Fig. 4 illustrates the relationship between compressive damage parameter and inelastic strain with concrete having strength $f_{cm} = 35$ calculated in Eqn. (8).

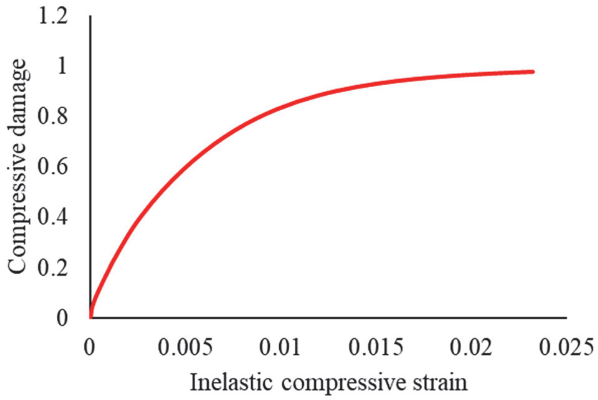

Figure 4: The curve of compressive damage parameter and inelastic strain

Tension damage variable (*dt*)

Similar to the compression damage variable d_c, the damaged parameter in tension d_t depends on ε_t^{pl} and an experimentally determined parameter $b_t = 0.1$. So, unloading is assumed to return almost back to the origin and to leave only a small residual strain.

$$d_t = 1 - \frac{\sigma_c E_c^{-1}}{\varepsilon_c^{pl}\left(1/b_t - 1\right) + \sigma_t E_c^{-1}} \tag{9}$$

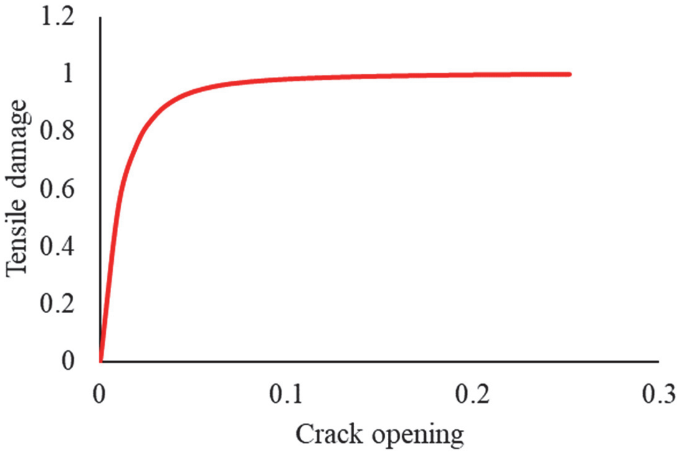

Figure 5: The curve of compressive damage parameter and crack opening.

APPLICATION FOR SIMULATION OF A REINFORCE CONCRETE BEAM

A beam namely C3 is selected as reported by Vecchio và Shim (2004) [8]. The geometry and details of beam C3 are shown in Fig. 6. The beam has a section; 152mm width and 552mm height. The length of the beam is 6400mm. Rebars at the bottom layer arrange (2M30+2M25) and at the top layer is (3M10). Experimental geometry and details of C3 beam are shown in Fig. 6. The material characteristics of the C3 beam are given in Tab. 2.

Numerical simulation was established using ABAQUS software. In detail, the beam uses solid element type C3D8R with 1 point of Gaussian integration, rebar uses T2D3 element which is only under tension and compression conditions, Interaction between rebar and concrete using "Embedded" algorithm. This method allows a node or group nodes of rebar to be constrained to the kinetic boundary conditions with the nodes in the concrete elements. In the simulation C3 beam of Vecchio and Shim (2004) [10], the rebar and the concrete have meshed with the same element size (40mm). The interaction between the rigid steel plate and the concrete uses the "Tie". The progress in the simulation is shown in Fig. 7. A comparison of the displacement which is arranged at the middle beam between the simulation and data obtained from the experiment is given in Fig. 8. The results in Fig. 8 show that the damaged nonlinear model presented satisfies the beam stiffness degradation. Simulation result at the complete failure of the beam registered the loading having 266 kN compared with the test loading having 267 kN.

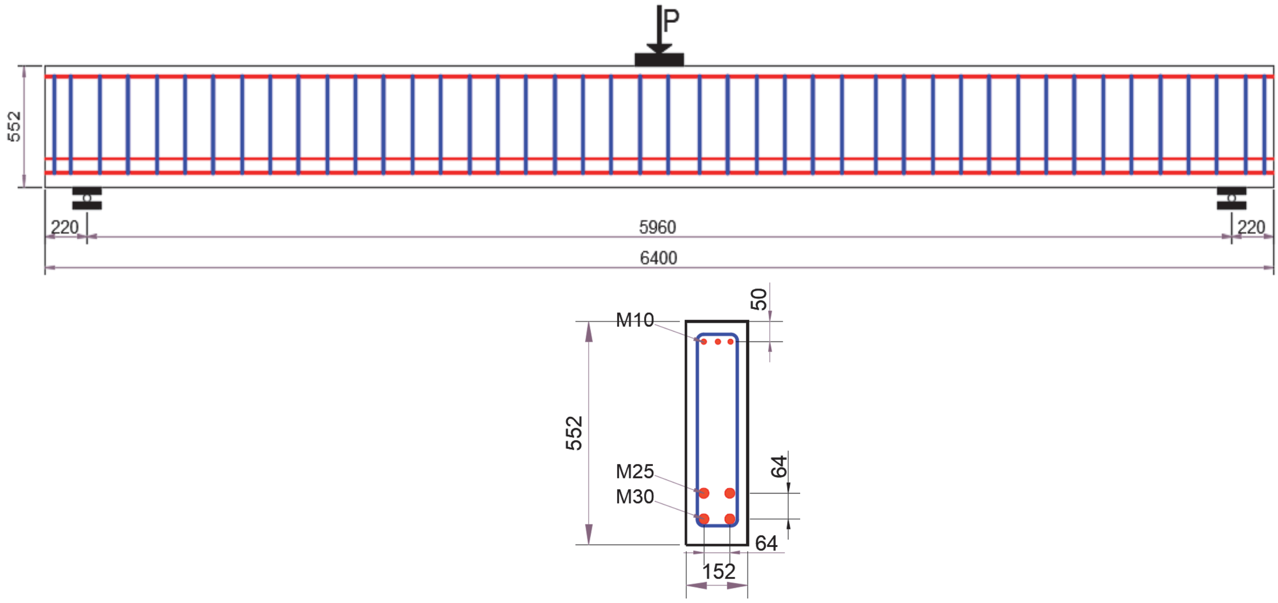

Figure 6: Elevations and cross-sections of C3 beam.

Concrete			
Avarage compressive strength	f_{cm}	43.5	N/mm^2
Modulus of elasticity	E_{ci}	34300	N/mm^2
Tensile strength	F_{tm}	3.13	N/mm^2
Rebar-M10			
Diameter	ϕ	11.3	mm
Modulus of elasticity	E	200000	N/mm^2
Yield strength	f_y	315	N/mm^2
Ultimate tensile strength	f_u	460	N/mm^2
Rebar- M25			
Diameter	ϕ	25.2	mm
Modulus of elasticity	E	200000	N/mm^2
Yield strength	f_y	445	N/mm^2
Ultimate tensile strength	f_u	680	N/mm^2
Rebar- M30			
Diameter	ϕ	29.9	mm
Modulus of elasticity	E	200000	N/mm^2
Yield strength	f_y	436	N/mm^2
Ultimate tensile strength	f_u	700	N/mm^2
Rebar- D4			
Diameter	ϕ	3.7	mm
Modulus of elasticity	E	200000	N/mm^2
Yield strength	f_y	600	N/mm^2
Ultimate tensile strength	f_u	651	N/mm^2

Table 2: Material characteristics of the C3 beam.

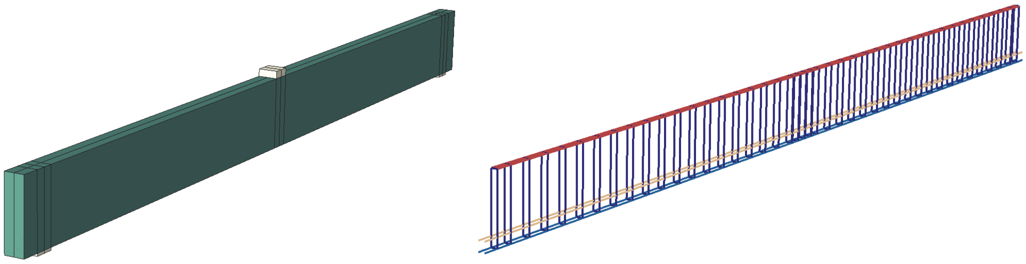

Figure 7: Simulation C3 beam using ABAQUS.

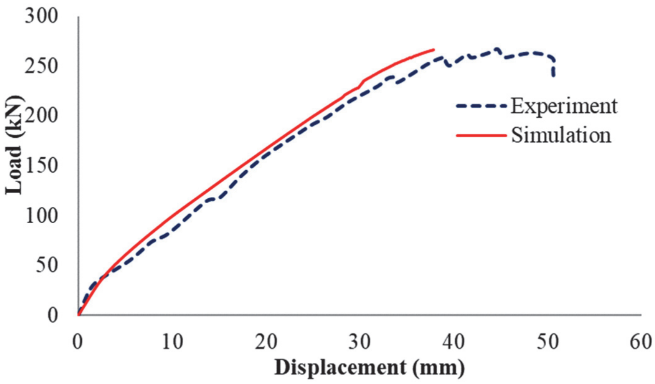

Figure 8: Comparison of the displacement between simulation and experiment.

Figure 9: Cracking pattern in simulation.

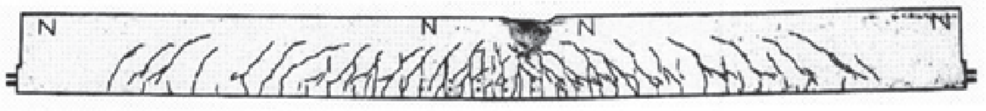

Figure 10: Damaged C3 beam in an experiment.

Figure 11: Crushing pattern in simulation.

The patterns of cracking and crushing in the simulation are given in Fig. 9 and Fig. 11. In comparison with the complete failure of the beam in Fig. 10. Based on the results, we can recognize that the cracking/crushing pattern using simulation is consistent with the experimental results. The damaged model used in this paper can show cracked/crushed elements that having the damaged parameters d_t / d_c in range value $\left[0,1\right]$.

APPLICATION FOR SIMULATION OF A REINFORCE CONCRETE SLAB

This example presents finite element simulations of punching shear in a concrete slab implemented by Adetifa and Polak [9]. This example is employed to evaluate the reliability of the proposed damaged model for predecting the behavior of a complex structure concrete. The geometry and details of the specimen concrete slab had the dimensions 1800 × 1800 × 120mm. For bending reinforcement, 10M bar were used to embed in the slab. The arrangement of bars in top layer and bottom layer is illustrated in Fig. 12. The section A-A is shown in Fig. 13 and the material characteristics are given in Tab. 3.

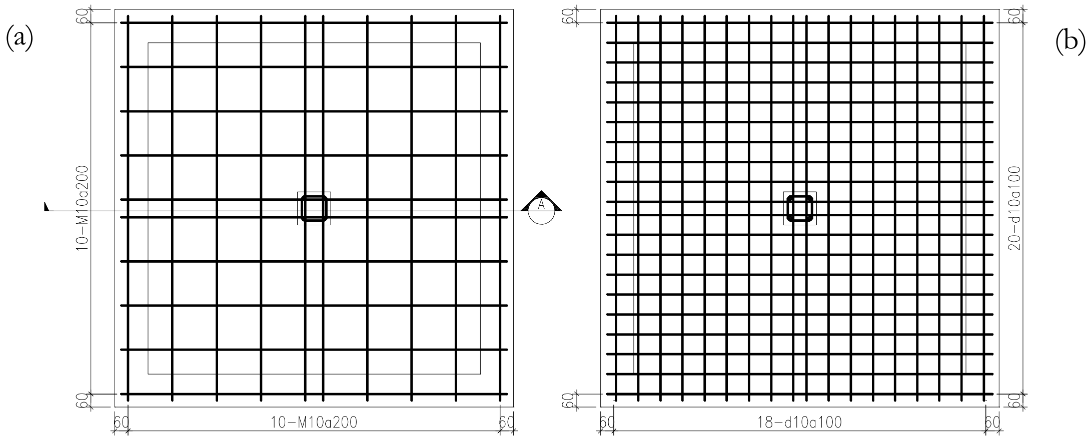

Figure 12: The arrangement of bars: (a) in the top layer, (b) in the bottom layer.

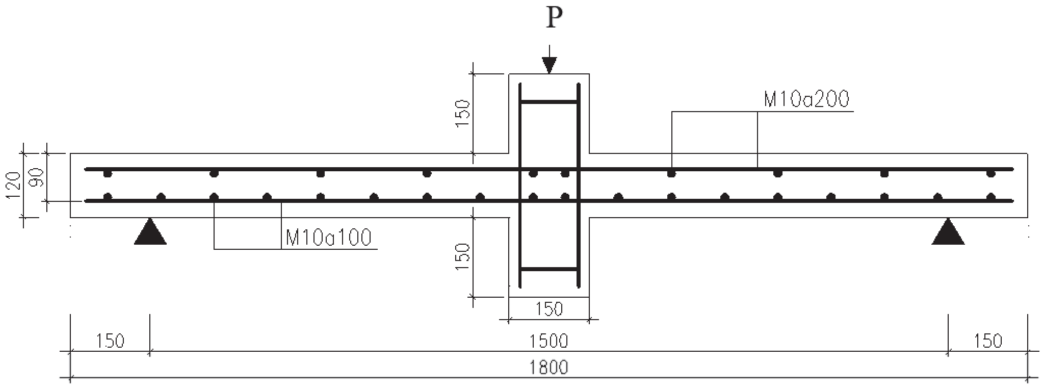

Figure 13: The section A-A of specimen.

Concrete			
Avarage compressive strength	f_{cm}	44	N/mm^2
Modulus of elasticity	E_{ci}	36483	N/mm^2
Rebar-d10			
Diameter	ϕ	10	mm
Modulus of elasticity	E	200000	N/mm^2
Yield strength	f_y	455	N/mm^2
Ultimate tensile strength	f_u	620	N/mm^2

Table 3: Material characteristics of the concrete slab.

The process of numerical simulation using ABAQUS is carried out similar to the previous example. This process includes defining geometrical dimensions, defining the nonlinear behavior of steel and concrete materials, establishing the boundary conditions, and setting the loading process until the structure is completely damaged. The geometrical dimensions in the simulation are given in Fig. 14.

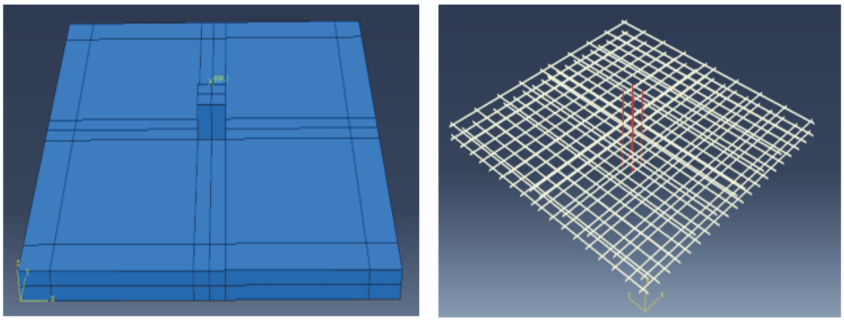

Figure 14: Simulation reinforce concrete slab using ABAQUS.

The simulation result show that the maximum punching shear force value is 243 kN compared to the of 241 kN obtained from experimental result. The difference between numerical simulation results and experimental results is only 0.82%. The relationship between punching shear force – Displacement at the middle of slab using simulation is also very good agreement compared to experimental results as shown in Fig. 15.

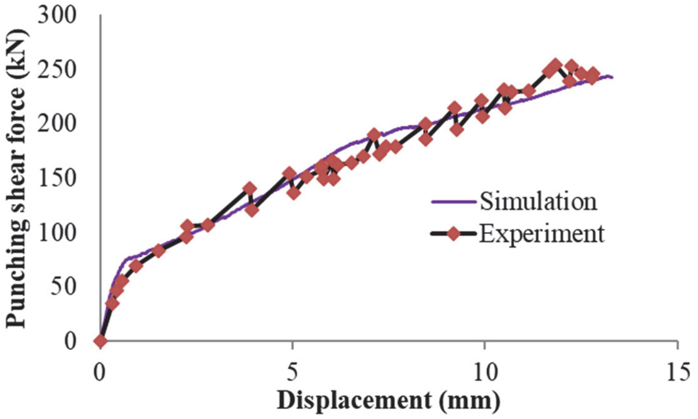

Figure 15: Comparison of displacement between simulation and experiment.

The damaged model of concrete materials using in this paper also allows to predict the crack pattern, which is defined by the elements having plastic deformation, the crack shapes in Fig. 16 and in Fig. 17 show that the position around the column with 1.5m distance from the edge of the column is the crack appearing with the largest density and width.

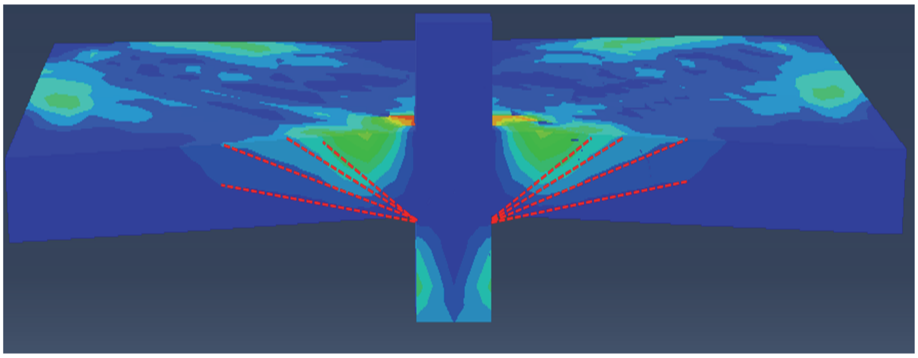

Figure 16: The damaged shape of punching shear in section view.

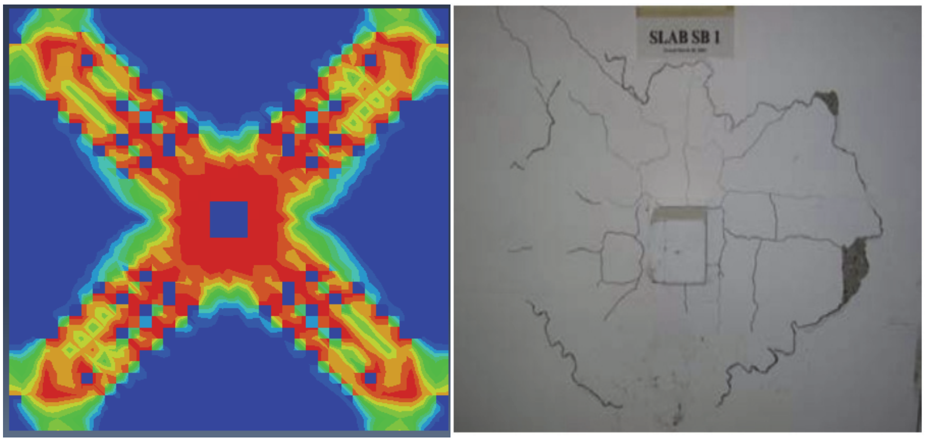

Figure 17: Comparison the crack pattern on the top of slab between simulation and experiment.

CONCLUSION

The paper presents a damaged model of concrete in numerical simulation. This model is developed lied on the CDP (available in ABAQUS) associating with the proposed damaged parameters $b_c = 0.7$ in compression and $b_t = 0.1$ tension. This damaged model is employed to simulate the real-test beam namely C3 in Vecchio và Shim (2004) [8] under static loading and a flat concrete slab in the test of Adetifa and Polak [9]. The numerical simulation results show that the model satisfies well with the data obtained from testing. The complete failures of the C3 beam the cracking in the top face of slab using numerical simulation illustrated that two damaged parameters responded well to the experiment's results. The model presenting in this paper can be considered as a reference model with high reliability in simulation structural reinforced concrete.

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