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CONCRETE DAMAGE PLASTICITY MATERIAL MODEL PARAMETERS IDENTIFICATION

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Abstract

The procedure for identifying concrete damage plasticity material model parameters is presented in this paper. Concrete damage plasticity material model represents a constitutive model which is based on a combination of theory of plasticity and theory of damage mechanics. This material model is often used in solving geotechnical problems due to its realistic description of mechanical behavior of concrete material. Theoretical basis of concrete damage plasticity material model and material parameters identification procedure are presented in this paper. Proposed identification procedure is applied on experimental data from uniaxial compression and tension load-unload tests taken from literature. By applying experimental data, stress-strain curve is created. Based on stress-strain load-unload curve, stress-plastic strain and stress-degradation dependences are created which are necessary for material parameters identification. Using these dependences material parameters are determined. Verification of estimated parameters is performed in PAK software package using concrete damage plasticity material model. Finite element model is created for numerical simulations of uniaxial compression and tension tests. Numerical simulation results are compared with experimental data. By comparing numerical simulation results and experimental data it can be concluded that this procedure is effective for determining concrete damage plasticity model parameters.

Keywords: Concrete damage plasticity model, PAK software, finite element method, material parameters identification

1. Introduction

Concrete is a very heterogeneous material which shows complex nonlinear mechanical behavior. In addition, it is very difficult to define damage in a concrete structure. In the analysis of concrete structures using the finite element method, material models are used for these purposes. An example of these material models is concrete damage plasticity material model (Lee J. , 1996; Lubliner, Oliver, & Onate, 1989). This material model combines the yield theory of plasticity and theory of damage mechanics in order to effectively analyze the concrete structures behavior. Material parameters identification of concrete damage plasticity material model is performed in this paper. The parameters were identified on the basis of experimental data from uniaxial compression and tension tests from the literature (Tanigawa & Uchida, 1979; Gopalaratnam & Shah, 1985). The parameters determined in this way are verified by numerical simulations of uniaxial compression and tension load-unload tests in PAK software (Kojić, Slavković, Živković, & Grujović, PAK-S: Program for FE Structural Analysis, 2011).

The theoretical basis of this material model, as well as parameters review and their determination methods are presented in the second chapter.

The third chapter presents the concrete damage plasticity material model parameters identification procedure on the basis of experimental data followed by the verification of uniaxial cyclic load-unload compression and tension tests. The numerical simulations results are compared with the experimental data and conclusions about the conducted analyzes are drawn.

2. Theoretical basis

2.1 Concrete damage plasticity material model

Various material models have been developed for nonlinear analysis of concrete structures. These material models are most often based on theory of plasticity, damage mechanics theory or their combination. Concrete damage plasticity material model is a constitutive model used for the analysis of concrete structures subjected to static or dynamic loads and is based on a combination of theory of plasticity and damage mechanics theory (Grassel, Xenos, Nystrom, Rempling, & Gylltoft, 2013).

According to this material model, the concrete behavior is defined by the yield function originally developed by (Lubliner, Oliver, & Onate, 1989), and later improved by (Lee & Fenves, 1998).

Based on the incremental theory of plasticity, the total strain tensor increment can be decomposed into elastic and plastic strain increment (Kojić , Slavković, Živković, & Grujović, Metod konačnih elemenata I, 1998; Kojić & Bathe, Inelastic Analysis of Solids and Structures, 2005):

$$d\mathbf{e} = d\mathbf{e}^E + d\mathbf{e}^P \, . \tag{1}$$

The elastic part is recoverable part of the total strain increment, which for linear elasticity is defined using equation (Lee J. , 1996):

$$d\mathbf{e}^E = \mathbf{C}^{-1} d\boldsymbol{\sigma} \, , \tag{2}$$

where **C** denotes the elastic stiffness tensor.

Consequently, from equations (1) and (2), plastic strain increment can be written as:

$$d\mathbf{e}^P = d\mathbf{e} - \mathbf{C}^{-1} d\boldsymbol{\sigma} \, . \tag{3}$$

Plastic strain in current step can be calculated using solution from previous step, and calculated plastic strain increment as:

$${}^{t+\Delta t}\mathbf{e}^P = {}^{t}\mathbf{e}^P + d\mathbf{e}^P \, , \tag{4}$$

while current stress can be calculated as:

$${}^{t+\Delta t}\boldsymbol{\sigma} = {}^{t}\boldsymbol{\sigma} + d\boldsymbol{\sigma} \, . \tag{5}$$

Damage of a solid body can be defined as degradation phenomenon in material properties such as stiffness, strength and anisotropy. If the damage is defined by stiffness degradation, the elastic stiffness can be written using stiffness degradation parameter as (Lee J. , 1996):

$$\mathbf{C} = (1 - \mathrm{d})\mathbf{C}_0 , \tag{6}$$

where d denotes the degradation, and $\mathbf{C}_0$ represents the initial stiffness matrix. Relation between nominal stress tensor $\boldsymbol{\sigma}$ and effective stress tensor $\bar{\boldsymbol{\sigma}}$ can be written using degradation (1– d):

$$\boldsymbol{\sigma} = (1 - d)\bar{\boldsymbol{\sigma}} , \tag{7}$$

where the effective stress can be expressed using the initial stiffness matrix:

$$\bar{\boldsymbol{\sigma}} = \mathbf{C}_0 : \left(\mathbf{e} - \mathbf{e}^{\mathrm{p}}\right) . \tag{8}$$

Based on equation (6), Young's elasticity modulus current value can be written as:

$$E = (1 - \mathrm{d})E_0 , \tag{9}$$

where E_0 represents the Young’s elasticity modulus initial value.

The yield function of concrete damage plasticity material model is defined by equation (Lee J. , 1996; Rakić, Dunić, Živković, Grujović, & Divac, 2019):

$$F(\bar{\boldsymbol{\sigma}}, \boldsymbol{\kappa}) = \frac{1}{1-\alpha}\left(\alpha \bar{I}_1 + \sqrt{\frac{3}{2}}\left\|\bar{\mathbf{S}}\right\| + \beta(\boldsymbol{\kappa})\langle \bar{\sigma}_{\max} \rangle\right) - c_c(\boldsymbol{\kappa}) \le 0 , \tag{10}$$

where:

- $c_c(\boldsymbol{\kappa}) = \bar{\sigma}_c(\boldsymbol{\kappa})$ - material cohesion,
- $\bar{I}_1 = \mathrm{tr}\bar{\boldsymbol{\sigma}}$ - first stress tensor invariant,
- $\left\|\bar{\mathbf{S}}\right\| = \sqrt{\bar{\mathbf{S}} : \bar{\mathbf{S}}}$ - stress tensor deviator norm,
- $\bar{\mathbf{S}} = \bar{\boldsymbol{\sigma}} - \bar{\sigma}_m \mathbf{I}$ - deviator of effective stress: $\bar{\boldsymbol{\sigma}} = \mathbf{C}_0 : \left(\mathbf{e} - \mathbf{e}^P\right)$,
- $\bar{\sigma}_m = \frac{1}{3}\mathrm{tr}\bar{\boldsymbol{\sigma}}$ - mean effective stress,
- $\bar{\sigma}_{\max}$ - algebraic maximum of eigenvalues of effective stress tensor $\bar{\boldsymbol{\sigma}}$.

The effective stress - total strain dependence for tension and compression is shown in Fig. 1.

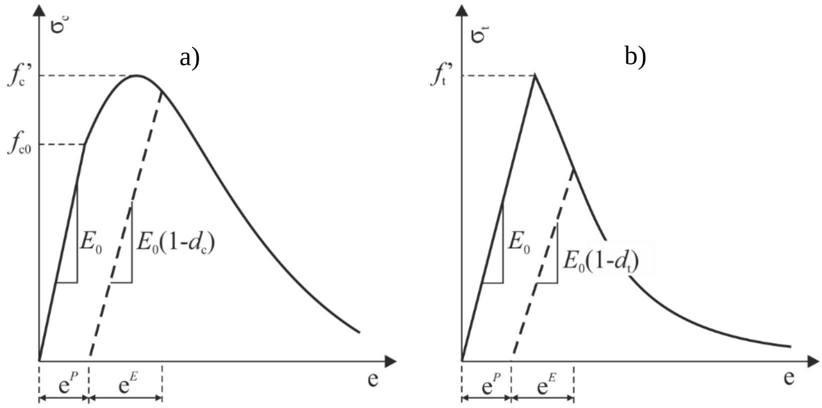

Fig. 1. Dependence of stress on total strain for: a) compression and b) tension.

Maximum stresses (f_c', f_t') and yield stresses (f_{c0}, f_{t0}) for compression and tension are defined with following equations (Lee J. , 1996), respectively:

$$f_c^{'} = f_{cm} = f_{c0} \frac{(1+a_c)^2}{4a_c} \ , \tag{11}$$

$$f_t^{'} = f_{t0} \ , \tag{12}$$

where a_c represents compression curve parameter.

2.2 Concrete damage plasticity material model parameters review and identification procedure

In order to effectively describe the mechanical behavior of concrete using the concrete damage plasticity material model, it is necessary to correctly determine the parameters of this material model. These parameters can be determined on the basis of experimental data. The following is an overview and identification procedure of material model parameters (Rakić, Bodić, Milivojević, Dunić, & Živković, 2021).

Compressive strength $f_c^{'}$ and tensile strength $f_t^{'}$ represent maximum stress values that can be reached in the compression and tension tests. The values of these parameters can be read directly from stress-total strain diagram (Fig. 1).

The relation between compressive strength and yield stress in uniaxial compression test is defined by the pressure curve parameter a_c and is given by equation (11) from which this parameter can be determined.

The parameter D_c represents the degradation value corresponding to the compressive strength. It can be determined from the stress-degradation diagram for the uniaxial compression test, which is given in Fig. 2.

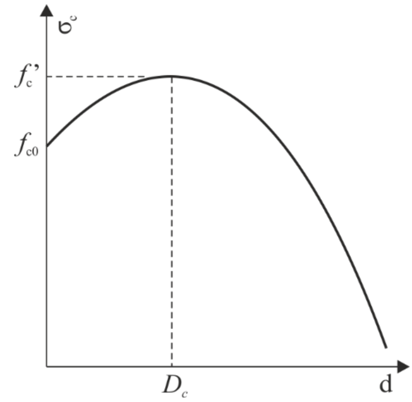

Fig. 2. Determination of the D_c parameter.

The parameter D_t is defined as the degradation value corresponding to the stress value f_t'/2. It can be determined from the stress-degradation diagram for the uniaxial tension test, which is given in Fig. 3

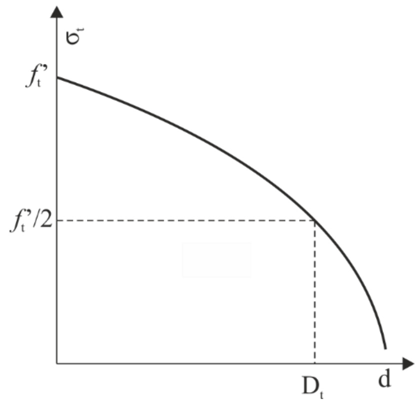

Fig. 3. Determination of the D_t parameter.

The compressive fracture energy G_c and the tensile fracture energy G_t represent the areas below the stress-plastic strain curve for uniaxial compression and tension tests, respectively. Fig. 4 shows a graphical interpretation of these parameters.

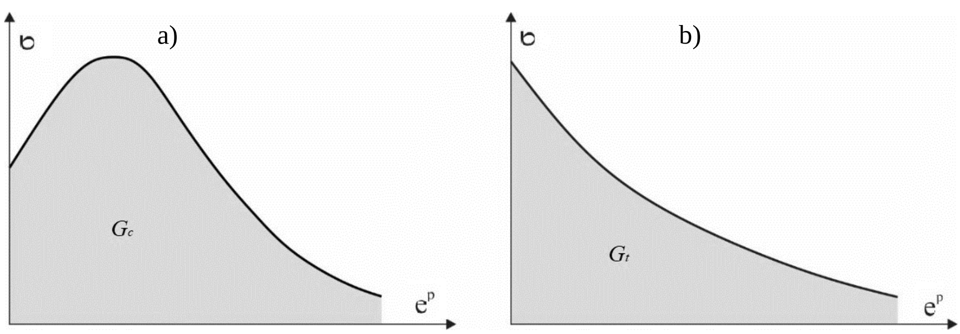

Fig. 4. Determination of a) compressive fracture energy G_c and b) tensile fracture energy G_t.

The parameter D_{cr} represents the degradation critical value, i.e., the maximum value of degradation that can be reached during uniaxial compression and tension tests.

The parameter α defines the ration of the uniaxial and biaxial initial yield stresses values and can be calculated using the following relation (Lubliner, Oliver, & Onate, 1989):

$$\alpha = \frac{\frac{f_{b0}}{f_{c0}} - 1}{2\frac{f_{b0}}{f_{c0}} - 1} , \tag{13}$$

where f_{c0} and f_{b0} represent initial yield stresses for uniaxial and biaxial compression, respectively.

Graphical interpretation of these stresses is shown in Fig. 5.

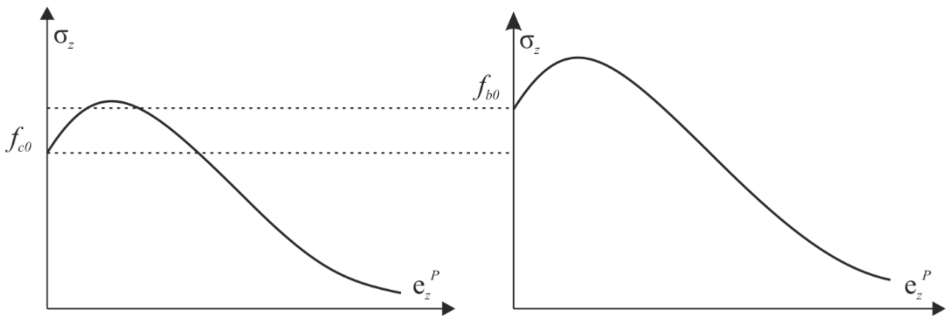

Fig. 5. Graphical interpretation of f_{c0} and f_{b0} stresses.

The parameter γ defines the ratio of the second invariant of deviatoric stress in the tension and compression meridians, which correspond to the same value of the first stress invariant I_1 (Lubliner, Oliver, & Onate, 1989). Graphical interpretation of the quantities necessary to determine the parameter γ is given in the Fig. 6.

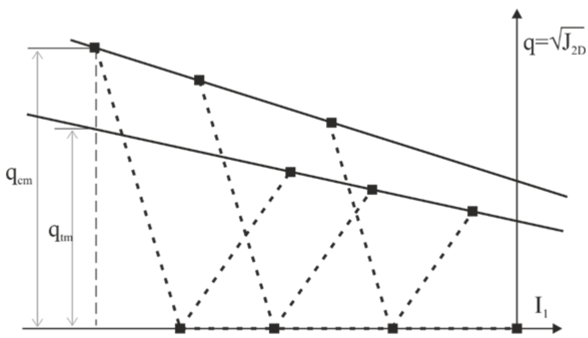

Fig. 6. Compression and tension meridians.

Parameter γ can be determined using equation (Voyiadjis , Taqieddin, & Kattan, 2008):

$$\gamma = \frac{3(1-\rho)}{2\rho - 1} , \tag{14}$$

where ρ represents ratio of the second deviatoric stress invariant in the tension meridian q_{tm} and second deviatoric stress invariant in the compression meridian q_{cm}:

$$\rho = \frac{q_{tm}}{q_{cm}} = \frac{\sqrt{3J_{2D}}_{\;tm}}{\sqrt{3J_{2D}}_{\;cm}} . \tag{15}$$

The values of q_{cm} and q_{tm} can be determined in accordance with Fig. 6, and on the basis of a triaxial compression test.

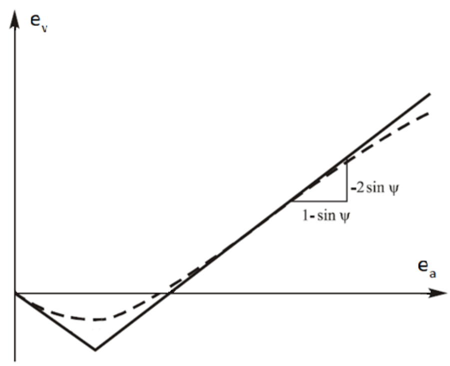

Fig. 7. Diagram of volume deformation depending on axial deformation.

The dilatation parameter α_p represents the tangent of the dilatation angle (Lee & Fenves, 1998):

$$\alpha_p = \tan(\psi) . \tag{16}$$

The dilatation angle can be determined based on the ratio of the change in volume and axial strain, using the following expression:

$$\psi = \arcsin\left(\frac{\frac{de_v}{de_a}}{\frac{de_v}{de_a} - 2} \right) . \tag{17}$$

Graphical interpretation of the procedure for determining the dilatation angle is shown in Fig. 7 (Maranha & Maranha das Neves, 2011) and can be determined based on the results of the triaxial test.

3. Material model parameter identification

The concrete damage plasticity material model parameters can be determined based on experimental data obtained from uniaxial, biaxial and triaxial tests. The parameters identification procedure based on experimental data from uniaxial compression and tension tests taken from the literature (Tanigawa & Uchida, 1979; Gopalaratnam & Shah, 1985) is presented below. Values of the parameters determined from the biaxial and triaxial tests (i.e. parameters α, α_p and γ) are adopted as predefined values from the literature, because they do not affect the solutions of uniaxial tests.

Stress-total strain dependences can be created based on experimental data from uniaxial compression and tension load-unload tests (Fig. 8).

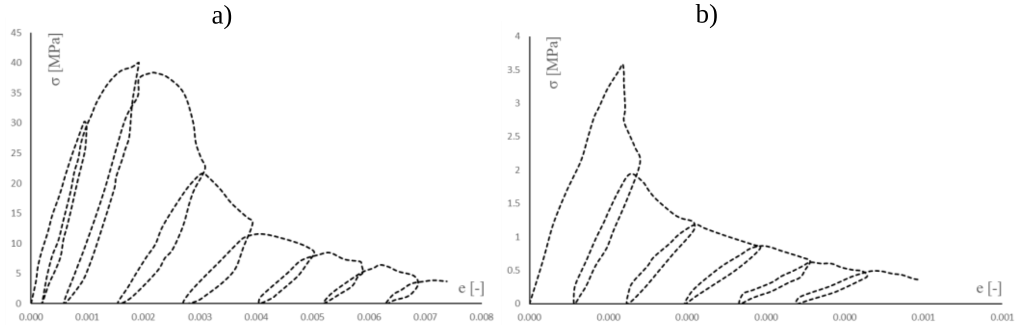

Fig. 8 Stress-total strain dependences for a) uniaxial compression and b) uniaxial tension load-unload test.

Based on the incremental theory of plasticity, using relation (1), the total strain can be decomposed into elastic and plastic strain. The stress-strain dependence in the elasticity region can be defined by Young's elasticity modulus, which according to Hooke's generalized law is given as:

$$d\boldsymbol{\sigma} = \mathbf{C}^E d\mathbf{e}^E \ , \tag{18}$$

from which the value of the Young's elasticity modulus can be determined by applying an equivalent expression for the axial load:

$$d\sigma_z = E de_z^E \ . \tag{19}$$

The initial value of Young's elasticity modulus represents the initial slope of the stress-total strain curve (linear behavior), so it can be easily determined from stress-total strain diagram. Based on that, by applying relation (9), the degradation value can be determined at each specimen unloading cycle. Thus, with known values of plastic strain and degradation at each specimen unloading cycle, it is possible to create stress-plastic strain and stress-degradation diagrams.

Stress-plastic strain and stress-degradation diagrams for uniaxial compression are given in Fig. 9.

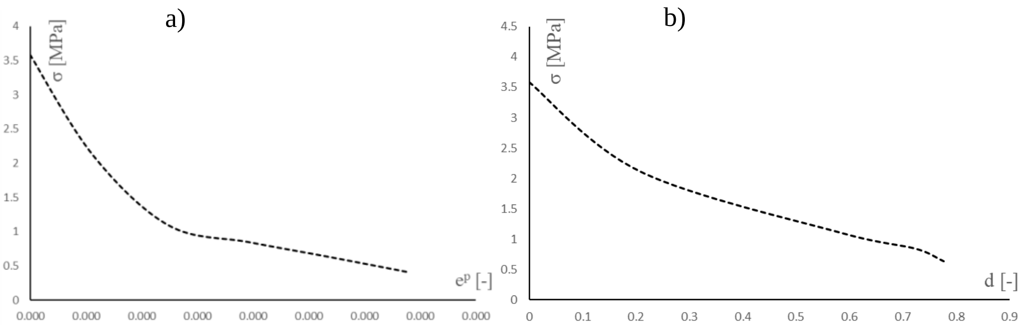

Fig. 9. Diagrams a) stress-plastic strain and b) stress-degradation for uniaxial compression.

Stress-plastic strain and stress-degradation diagrams for uniaxial tension are given in Fig. 10.

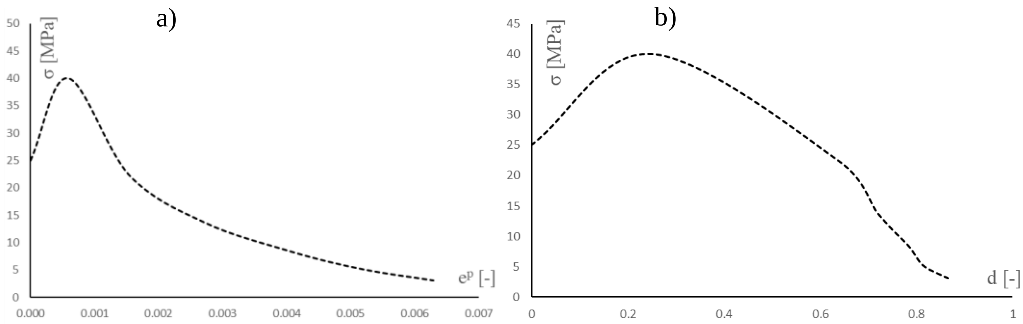

Fig. 10. Diagrams a) stress-plastic strain and b) stress-degradation for uniaxial compression.

Based on the stress-plastic strain and stress-degradation diagrams of the uniaxial compression and tension tests, and by applying the procedure from the previous chapter, the concrete damage plasticity material model parameters can be determined. The parameters α, α_p and γ do not affect the mechanical behavior of the specimen in uniaxial compression and tension tests, so they are taken as predefined values from the literature. However, these parameters can be determined based on biaxial and triaxial tests, and the procedure is given in the previous chapter.

Parameter	**Value**
E [Pa]	$40/32\cdot10^6$ (c/t)
v [-]	0.2
f_c' [Pa]	$39\cdot10^3$
f_t' [Pa]	$3.6\cdot10^3$
a_c [-]	4.150
D_c [-]	0.27
a_t [-]	0.02
D_t [-]	0.3
G_c [-]	120
G_t [-]	0.645
α_p [-]	0.065
α [-]	0.120
γ [-]	3
D_{cr} [-]	0.95

Table 1. Identified values of concrete damage plasticity material model parameters.

The identified values of concrete damage plasticity material model parameters for experiments from the literature are given in Table .

4. Verification

Numerical simulations of load-unload uniaxial compression and tension tests are performed using PAK software package. For the purpose of numerical simulations, concrete damage plasticity material model is used, and parameter values were taken from Table . The numerical simulations results are compared with the experimental data.

A schematic representation of the specimen model used in uniaxial tests simulations with defined boundary conditions and load is given in Fig. 11. Model dimensions are 1 m x 1 m x 1

m. The FEM model consists of one three-dimensional hexahedral finite element without midside nodes.

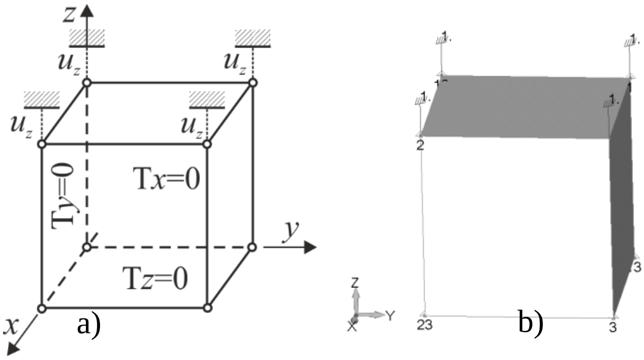

Fig. 11. Specimen model for uniaxial tests a) schematic representation, b) finite element model.

Boundary conditions are set to correspond to the specimen experimental uniaxial test conditions: nodes located in symmetry planes have symmetry boundary conditions in that plane. The load is applied using prescribed displacement in the direction of the z-axis at the nodes on the upper face of the model. In both, uniaxial compression and tension tests, the prescribed displacement is multiplied by the load function that corresponds to the experiment.

4.1 Results of numerical simulation

The results of uniaxial tests numerical simulations are compared with experimental data and presented in Fig. 12 in the form of stress-total strain dependence.

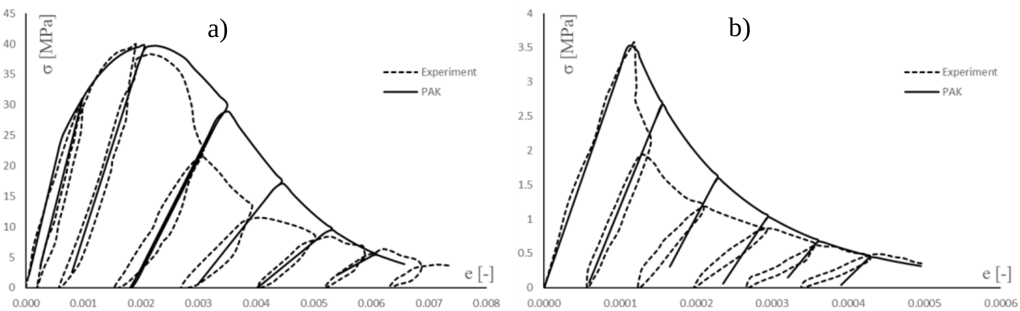

Fig. 12. Stress-total strain diagrams for a) compression b) tension.

In addition to the stress-total strain dependence, comparison of the stress-plastic strain and stress-degradation diagrams between numerical simulation in PAK software and experimental data is given.

Fig. 13 shows stress-plastic strain diagram for uniaxial compression and tension.

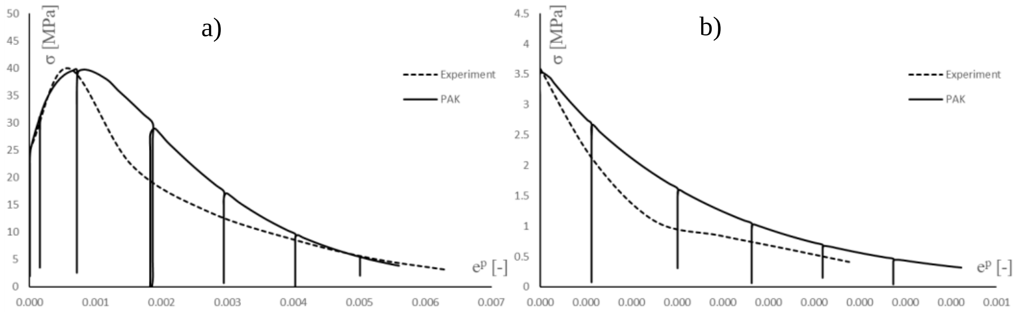

Fig. 13. Stress-plastic strain diagram for a) compression and b) tension.

Fig. 14 shows stress-degradation diagram for uniaxial compression and tension.

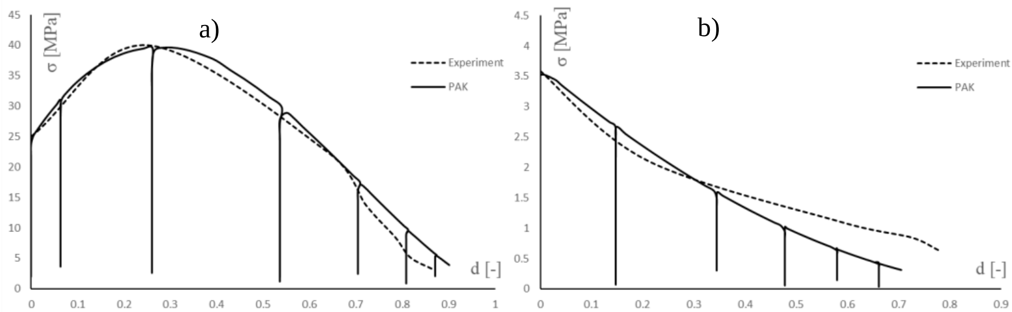

Fig. 14. Stress-degradation diagram for a) compression and b) tension.

By comparing the previous diagrams, it can be concluded that the numerical simulation results by character correspond to the experimental data. Minor deviations in values can be observed, but they are not significant, so it can be concluded that the match of previously compared diagrams is satisfactory.

Based on the above, it can be concluded that the described procedure can be used for effective identification the concrete damage plasticity material model parameters except for the three mentioned parameters that do not affect the results of uniaxial tests, and whose values are adopted from the literature.

5. Conclusions

The concrete damage plasticity material model parameters identification procedure is presented in this paper. Parameter identification is performed on the basis of experimental data from uniaxial compression and tension load-unload tests. By applying experimental data, stress-total strain dependences for uniaxial compression and tension were created. Based on the stress- total strain dependence, stress-plastic strain and stress-degradation diagrams were created. By applying these diagrams, the concrete damage plasticity material model parameters were determined, while predefined values were adopted for the parameters for which biaxial and triaxial tests are required and whose values do not affect the solutions of uniaxial tests. The estimated parameters were verified by numerical simulations of uniaxial compression and tension load-unload tests. By comparing the numerical simulations results and experimental data, it can be concluded that the proposed identification procedure can be used for effective determination of the concrete damage plasticity material model parameters.

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