„ОТПОРНИ КОНСТРУКЦИИ“ “RESILIENT STRUCTURES”

ЗБОРНИК НА ТРУДОВИ PROCEEDINGS

ДГКМ

ДРУШТВО НА ГРАДЕЖНИ КОНСТРУКТОРИ НА МАКЕДОНИЈА

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MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS

20 МЕЃУНАРОДЕН СИМПОЗИУМ
INTERNATIONAL SYMPOSIUM

СКОПЈЕ, С. МАКЕДОНИЈА
SKOPJE, N. MACEDONIA
28 - 29 септември 2023
September , 28th - 29th , 2023

PROCEEDINGS
OF THE 20th INTERNATIONAL SYMPOSIUM OF MASE

ЗБОРНИК НА ТРУДОВИ
20ТИ МЕЃУНАРОДЕН СИМПОЗИУМ НА ДГКМ

Publisher:
MASE - Macedonian Association of Structural Engineers
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Издавач:
ДГКМ - Друштво на Градежни Конструктори на Македонија
Градежен Факултет, бул. Партизански одреди бр. 24 П.Ф. 560,
1000 Скопје, Република Северна Македонија
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e-book:
електронско издание: ISBN 978-608-66946-3-0

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CONCRETE MODELING IN FINITE ELEMENT PUSH-OUT TEST SIMULATIONS

Isidora JAKOVLJEVIĆ [1], Milan SPREMIĆ[1], Zlatko MARKOVIĆ[1]

ABSTRACT

Push-out tests are commonly used to investigate the shear performance of mechanical connectors applicable in steel-concrete composite beams. These tests can be complemented by numerical finite element simulations to reduce the need for extensive experimental testing. After validation against experimental results, numerical models could be used for additional analysis and parametric studies. The development of finite element models of push-out tests requires special attention to be put on modelling concrete behaviour, especially if concrete failure is the dominant failure mode. The concrete damage plasticity (CDP) models, combining plasticity and damage mechanics to represent the non-linear behaviour of concrete, are commonly applied. This paper summarises and presents four different CDP models that have been successfully used by researchers in finite element simulations of push-out tests. The applicability of different models has been discussed in the specific case of shear connection with headed studs in profiled steel sheeting with a varied angle between profiled sheeting ribs and the beam. Results of comparative analysis are presented, indicating a significant influence of the applied CDP model on the response of push-out specimen. The best match between experimental and numerical results is accomplished by implementing the material model proposed by Pavlović with calibrated input parameters. Nevertheless, the applicability of each CDP model depends on the specific problem that is being analysed and therefore should be carefully approached.

Keywords: Concrete damaged plasticity, Headed stud, Numerical analysis, Concrete failure, Damage factor.

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1. INTRODUCTION

Investigations of the shear performance of mechanical connectors applicable in steel-concrete composite beams are usually based on push-out tests [1]. Although easier to manipulate than large-scale composite beams, push-out specimens still require certain material resources to be made and time, reflected in 28 days necessary for concrete to gain its full strength. Therefore, in order to avoid experimental testing of an extensive number of push-out test specimens, investigations of the shear connector response could be complemented by numerical finite element simulations. After the verification against experimental results, finite element models may be used for parametric studies and the development of a large set of results suitable for formulating conclusions and calculation models.

The development of finite element models of push-out tests requires special attention to be put on modelling concrete behaviour, especially if concrete failure is the governing failure mode. However, accurate simulation of concrete response and damage might be challenging to accomplish due to the complexity of the concrete behaviour and numerous factors which need to be taken into account while analysing it. The non-linear stress-strain relation of the concrete, strain hardening and softening, and time-dependent effects such as creep and shrinkage make the development of a concrete constitutive model more complicated.

The concrete damage plasticity (CDP) model, combining plasticity and damage mechanics to represent the non-linear behaviour of concrete, is commonly applied in finite element simulations of push-out tests. The CDP model is particularly useful in simulating the post-cracking behaviour of concrete elements, accounting for the loss of stiffness and strength due to cracking. The model assumes two primary causes of the failure of concrete material: tensile cracking and compressive crushing [2]. However, there are various formulations and variations of the CDP model available, each with its specific characteristics and parameters [3].

To determine the CDP model, a concrete response to uniaxial loading in tension and compression needs to be defined [2]. It is assumed that the stress-strain curve under uniaxial compression is linear elastic until the initial yield stress is reached. Afterwards, the response is characterized by strain hardening until the ultimate compressive stress. Once the ultimate stress is reached, strain softening is present, as shown in Fig. 1.a. Under uniaxial tension, it is considered that the stress-strain response is linear elastic until the ultimate tensile stress is achieved. Beyond the ultimate stress, the stress-strain curve is characterized by strain softening, as illustrated in Fig. 1.b.

The definition of the CDP model in Abaqus FE software [2] allows users to define the strain-softening behaviour of concrete in tension through two different approaches: by defining a stress-cracking strain relation or by applying a fracture energy cracking criterion. Concrete stress-strain behaviour in compression outside the elastic range is defined exclusively through stress-inelastic strain relation. When unloading the material in the strain-softening domain, the concrete response is characterized by decreased elastic stiffness for both uniaxial loading in tension and compression. The decrease in elastic stiffness is described through damage factors for tension (D_t) and compression (D_c), which may have values in the range from 0 to 1.

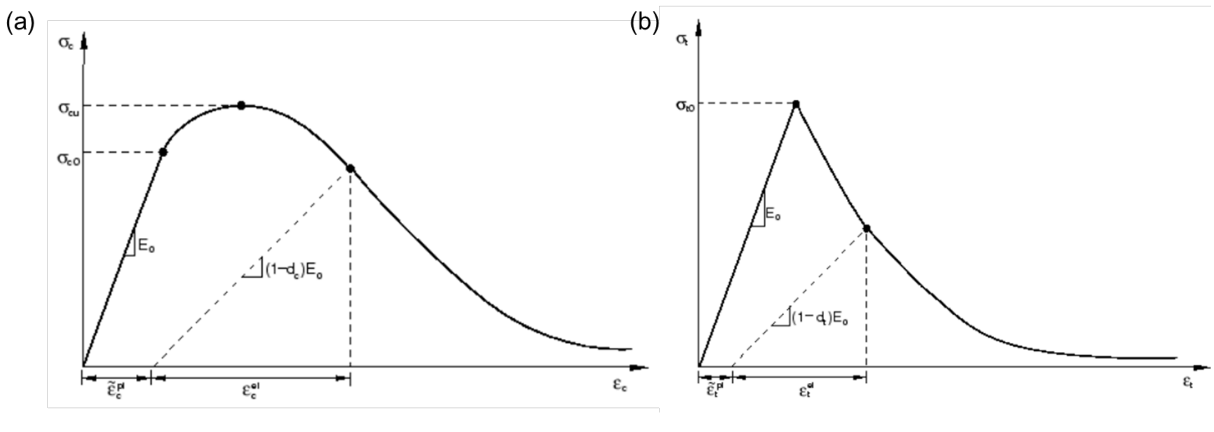

Fig. 1. Concrete stress-strain curves under uniaxial loading: (a) compression, (b) tension [2]

The CDP model requires a definition of plasticity flow parameters, which determine material behaviour to loading conditions beyond its elastic limit. To define a yield condition and flow potential, the input parameters need to be set in Abaqus: dilation angle, flow potential eccentricity, the ratio of equibiaxial-to-uniaxial compressive strength σ_{b0}/σ_{c0}, parameter K which represents the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian, and viscosity parameter. Recommended values for modelling concrete behaviour are: dilation angle in the range 30°–40°, eccentricity 0.1, $\sigma_{b0}/\sigma_{c0} = 1.16$, $K = 2/3$, viscosity parameter 0.

For numerical simulations of push-out tests on shear connectors applicable in steel-concrete composite elements, various CDP models have been used by researchers. This paper summarizes and presents four CDP models based on different stress-strain relations for concrete behaviour in compression and tension, as well as different definitions of concrete damage evolution. The applicability of selected models has been discussed in the specific case of shear connection with headed studs in profiled steel sheeting with a varied angle between profiled sheeting ribs and the beam [4]. Results of comparative analysis are presented and conclusions regarding model predictions are drawn.

2. CONCRETE DAMAGE PLASTICITY MODELS

2.1. The model according to Birtel and Mark

Birtel and Mark [5] developed the CDP model suitable for numerical simulations of the load-bearing behaviour of reinforced concrete beams. They tested the proposed material model by comparing numerical data with the experimental results of two tested beams with the governing shear failure. Their model, in its modified version, also found application in modelling concrete response in push-out tests [6,7].

For describing concrete stress-strain relation in compression, Birtel and Mark used three equations [5]:

$$\sigma_c(\varepsilon_c) = E_{cm}\varepsilon_c, \;\; \sigma_c \le 0.4 f_{cm} \tag{1}$$

$$\sigma_c(\varepsilon_c) = f_{cm} \frac{E_{ci}\,\varepsilon_c/f_{cm} - (\varepsilon_c/\varepsilon_{c1})^2}{1 + (E_{ci}\,\varepsilon_{c1}/f_{cm} - 2)\,\varepsilon_c/\varepsilon_{c1}}, \; \varepsilon_c \le \varepsilon_{c1} \tag{2}$$

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

where:

E_{cm} is the secant modulus of elasticity of concrete;
E_{ci} is the initial modulus of elasticity of concrete, defined in Ref. [8];
f_{cm} is the mean value of the cylinder compressive strength of concrete;
ε_{c1} is the compressive strain in the concrete at f_{cm};
γ_c is the parameter that defines the area under the stress-strain curve.

Eq. (1) describes concrete response in the elastic domain, up to the stress of $0.4f_{cm}$. For stresses between $0.4f_{cm}$ and f_{cm}, at the ascending branch of the concrete stress-strain curve, Eq. (2) should be applied, whereas Eq. (3) is applicable for the descending branch of the stress-strain curve, for strains higher than ε_{c1}. The first two equations are similar to the relations described in EN 1992-1-1 [9]. The third equation has been previously elaborated by Krätzig and Pölling [8], who also provided an expression for calculating the parameter γ_c as the function of crushing energy and length of finite element. Xu et al. [6] and Bonilla et al. [7] adopted the value of the parameter γ_c as 1.7 for modelling concrete crushing in shear connections with headed studs during push-out tests.

Furthermore, Birtel and Mark proposed the expression for obtaining the compressive damage variable D_c:

$$D_c = 1 - \frac{\sigma_c/E_{cm}}{\varepsilon_c^{pl}(1/b_c - 1) + \sigma_c/E_{cm}} \tag{4}$$

where:

ε_c^{pl} is the plastic strain defined as inelastic strain multiplied by the factor b_c, $0 < b_c \leq 1$,

$$\varepsilon_c^{pl} = b_c(\varepsilon_c - \sigma_c/E_{cm}) \tag{5}$$

The proposed value of the factor b_c is 0.7.

Instead of applying the stress-strain curve to define the tensile behaviour of concrete, Birtel and Mark used the following relation between the stress and crack opening:

$$\sigma_t(w) = f_{ctm}\left[g(w) - \left(\frac{w}{w_c}\right)g(w_c)\right] \tag{6}$$

where:

f_{ctm} is the mean value of the concrete tensile strength;

$$g(w) = \left[1 + \left(\frac{3w}{w_c}\right)^3\right]e^{\left(-\frac{6.93w}{w_c}\right)} \tag{7}$$

w is the crack opening,

$$w = 5.14\frac{G_F}{f_{ctm}} \tag{8}$$

w_c is the critical value of the crack opening at which tensile stress cannot be transferred;

G_F is the fracture energy, which is the function of the concrete compressive strength according to Model Code 2010 [10].

Similarly to compressive damage, Birtel and Mark defined the tensile damage variable D_t:

$$D_t = 1 - \frac{\sigma_t/E_{cm}}{\varepsilon_t^{pl}(1/b_t - 1) + \sigma_t/E_{cm}} \tag{9}$$

where ε_t^{pl} is the plastic strain defined as inelastic strain multiplied by the factor b_t, $0 < b_t \leq 1$,

$$\varepsilon_t^{pl} = b_t(\varepsilon_t - \sigma_t/E_{cm}) \tag{10}$$

The proposed value of the factor b_t is 0.1.

2.2. The model according to Pavlović

Pavlović [11,12] analysed the behaviour of bolted connectors with embedded nuts in steel-concrete composite beams. To simulate an accurate concrete response during push-out tests corresponding to the experimental findings, he proposed a CDP model, which has been proven beneficial and effectively implemented in numerical studies by several other researchers [13,14].

Pavlović defined the concrete stress-strain relation in compression by combining the curve given in EN 1992-1-1 [9] and appropriate sinusoidal and linear function extensions. EN 1992-1-1 [9] provides the following equation for describing the concrete stress-strain relation:

$$\sigma_c(\varepsilon_c) = f_{cm}\frac{k\cdot\eta - \eta^2}{1 + (k-2)\eta},\ \varepsilon_c \leq \varepsilon_{cu1} \tag{11}$$

where:

$$\eta = \frac{\varepsilon_c}{\varepsilon_{c1}} \tag{12}$$

$$k = 1.05\,\varepsilon_{c1}\frac{E_{cm}}{f_{cm}} \tag{13}$$

Eq. (11) is limited to strains smaller than $\varepsilon_{cu1} = \varepsilon_{cuD}$, which is defined as the ultimate compressive strain of concrete. According to EN 1992-1-1 [9], ε_{cu1} equals 3.5‰ for concrete classes up to C50/60. For higher strains beyond ε_{cu1}, Pavlović [11] proposed the following equation, including the sinusoidal part (for strains between ε_{cuD} and ε_{cuE}) and linear part (for strains higher than ε_{cuE}):

$$\sigma_c(\varepsilon_c) = \begin{cases} f_{cm}\left[\frac{1}{\beta} - \frac{\sin(\mu^{\alpha_{tD}}\cdot\alpha_{tE}\,\pi/2)}{\beta\cdot\sin(\alpha_{tE}\,\pi/2)} + \frac{\mu}{\alpha}\right], \varepsilon_{cuD} < \varepsilon_c \le \varepsilon_{cuE} \\ \left[f_{cuE}(\varepsilon_{cuF} - \varepsilon_c) + f_{cuF}(\varepsilon_c - \varepsilon_{cuE})\right]/(\varepsilon_{cuF} - \varepsilon_{cuE}), \varepsilon_c > \varepsilon_{cuE} \end{cases} \tag{14}$$

where:

$$\mu = \frac{\varepsilon_c - \varepsilon_{cuD}}{\varepsilon_{cuE} - \varepsilon_{cuD}} \tag{15}$$

$$\beta = \frac{f_{cm}}{f_{cuD}} \tag{16}$$

$$\alpha = \frac{f_{cm}}{f_{cuE}} \tag{17}$$

α_{tD} and α_{tE} are factors that influence the shape of the sinusoidal function;
f_{cuE} and f_{cuF} are compressive stresses at the points E and F, according to Fig. 2;
ε_{cuD}, ε_{cuE} and ε_{cuF} are compressive strains at points D, E and F, according to Fig. 2.

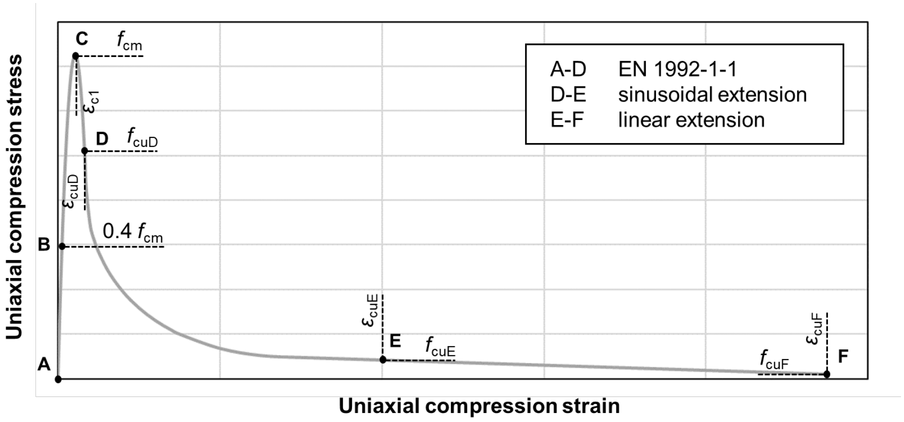

Fig. 2. Stress-strain curve for concrete behaviour in compression according to Pavlović [11]

The proposed curve extensions are flexible in terms of adopting the exact shape of the sinusoidal function and stress and strain values at points E and F. Pavlović used the following values of parameters, suitable for numerical analyses that he performed: $\alpha = 15$, $\alpha_{tD} = 0.50$, $\alpha_{tE} = 0.90$, $\varepsilon_{cuE} = 0.03$, $\varepsilon_{cuF} = 0.10$, and $f_{cuF} = 0.40$ MPa. However, all parameters could be set to other values based on calibrations with experimental results in each case.

Pavlović defined concrete compression damage using the compressive damage variable D_c, derived from the uniaxial stress-strain curve:

$$D_c = 1 - \frac{f_{cm}}{\sigma_c} \tag{18}$$

Pavlović described concrete behaviour in tension through stress-strain relation: linear elastic at ascending branch up to concrete tensile strength f_{ctm}, and sinusoidal tension softening at descending branch until stress $f_{ctm}/20$. Concrete tensile damage was defined similarly as concrete compression damage, using the tensile damage variable D_t:

$$D_t = 1 - \frac{f_{ctm}}{\sigma_t} \tag{19}$$

2.3. The model according to Katwal

Katwal et al. [15,16] investigated the behaviour of headed studs in profiled steel sheeting. They developed a CDP model for numerical simulations of push-out and large-scale beam tests, based on the stress-strain relation for uniaxial compression proposed by Carreira and Chu [17], and the stress-strain curve for uniaxial tension suggested by Hassan [18].

Carreira and Chu [17] intended to provide one equation for describing concrete behaviour in compression that would cover the stress-strain relationship before and after reaching the ultimate stress, i.e. including both ascending and descending branches of the stress-strain curve. After fitting the proposed equation to the set of experimental results, they provided its final form:

$$\sigma_c(\varepsilon_c) = f_{cm} \frac{\beta\,(\varepsilon_c/\varepsilon_{c1})}{\beta - 1 + (\varepsilon_c/\varepsilon_{c1})^{\beta}} \tag{20}$$

where:

$$\beta = \left(\frac{f_{cm}}{32.4\ \text{MPa}}\right)^3 + 1.55 \tag{21}$$

f_{cm} is the mean value of the cylinder compressive strength of concrete in MPa;
ε_{c1} is the compressive strain in the concrete at f_{cm}.

Unlike the stress-strain relation for concrete in compression given in EN 1992-1-1 [9], which is limited to strains up to the nominal ultimate strain ε_{cu1}, the relation proposed by Carreira and Chu has no upper limit. Therefore, unlike the previously described models according to Birtel and Mark [5] and Pavlović [12], Katwal et al. managed to simulate concrete compressive response by only one equation, covering both low and high strain domains.

Katwal et al. specified concrete damage evolution according to Eq. (18), as suggested by Pavlović.

Concrete response to uniaxial tension was defined as linear elastic up to concrete tensile strength f_{ctm}, followed by tension softening until the strain $30\varepsilon_{cr}$, according to the equation proposed by Hassan [18]:

$$\sigma_t(\varepsilon_t) = f_{ctm}\ \mathrm{e}^{-((\varepsilon_t - \varepsilon_{cr})/0.00035)^{0.85}} \tag{22}$$

where:

f_{ctm} is the mean value of the concrete tensile strength;
ε_{cr} is the tensile strain in the concrete at f_{ctm}.

In the same manner as concrete compression damage, tensile damage was defined according to Eq. (19).

2.4. The model according to Vigneri

Vigneri [19,20] performed a set of experimental push-out tests on welded headed studs in profiled steel sheeting, which was followed by numerical simulations. For modelling concrete behaviour, Vigneri combined the stress-strain relation for uniaxial compression proposed by Popovics [21] and Thorenfeldt [22], and the fracture energy cracking criterion for uniaxial tension suggested by Birtel and Mark [5].

Vigneri used the following relation to simulate concrete compressive response, referring to Popovics [21] and Thorenfeldt [22]:

$$\sigma_c(\varepsilon_c) = f_{cm} \frac{n\left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)}{(n-1) + \left(\frac{\varepsilon_c}{\varepsilon_{c1}}\right)^n} \tag{23}$$

where:

$$n = 1.25\left(0.058 f_{cm} + 1\text{ MPa}\right) \tag{24}$$

f_{cm} is the mean value of the cylinder compressive strength of concrete in MPa;
ε_{c1} is the compressive strain in the concrete at f_{cm}.

Similar to the stress-strain relation proposed by Chareira and Chu, Eq. (23) also covers the whole stress-strain domain of concrete response including the region of high strains.

Vigneri applied concrete compressive damage according to Eq. (4).

To model concrete tensile behaviour, Vigneri implemented the same procedure as proposed by Birtel and Mark [5] through Eq. (6). However, Vigneri did not use Eq. (9) to define tensile damage variable; instead, Eq. (19) was applied.

3. COMPARISONS BETWEEN CDP MODELS

Stress-strain curves for concrete uniaxial compression and corresponding damage evolution lows according to CDP models presented in the previous section are compared in Fig. 3. Stress-strain curve for the model proposed by Pavlović is given in two forms: with original input parameters ($\alpha = 15$, $\alpha_{tD} = 0.50$, $\alpha_{tE} = 0.90$, $\varepsilon_{cuE} = 0.03$, $\varepsilon_{cuF} = 0.10$, and $f_{cuF} = 0.40$ MPa) and with modified parameters ($\alpha = 8$, $\alpha_{tD} = 0.50$, $\alpha_{tE} = 0.60$, $\varepsilon_{cuE} = 0.05$, $\varepsilon_{cuF} = 0.20$, and $f_{cuF} = 0.40$ MPa).

Furthermore, the concrete responses to uniaxial tension as described within the presented CDP models are summarized in Fig. 4. Tensile stress and damage variable are shown as functions of cracking strain and cracking displacement, depending on how a CDP model is defined. Damage-cracking strain curve according to Birtel and Mark described through Eq. (9) is not presented, as it would require the calculation of cracking strain as a quotient of crack opening w and finite element characteristic length l_{eq}. Therefore, in further application of this CDP model in FE simulations of push-out tests presented in this paper, Birtel and Mark's model is applied with concrete tensile damage variable calculated according to Eq. (19), meaning that concrete tensile behaviour is defined as done by Vigneri.

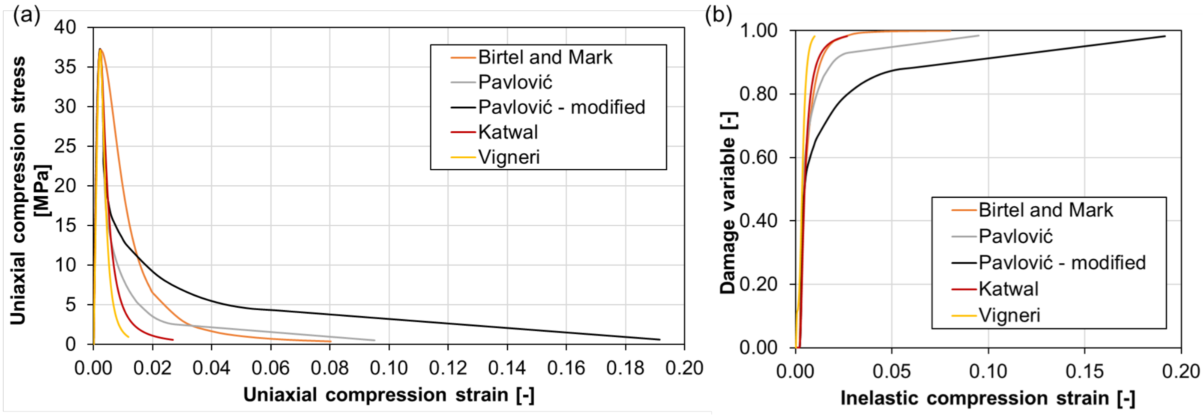

Fig. 3. Concrete behaviour in compression ($f_{cm} = 37.3$ MPa): (a) stress-strain curves, (b) compression damage

The presented diagrams illustrate certain differences between CDP models. Stress-strain curves for uniaxial compression according to all models except Birtel and Mark's mostly match for strains smaller than ε_{cu1}, following the stress-strain relation provided in EN 1992-1-1 [9]. For strains higher than ε_{cu1}, descending parts of curves differ, with the largest stress decrease in Vigneri's model and the smallest decrease in Pavlović's model with modified input parameters. On the opposite, the stress-strain curve according to Birtel and Mark has a slower decline just after reaching the peak stress than all the other models. Nevertheless, the exact shape of this curve in the post-ultimate domain is dependent on the parameter γ_c, which value is adopted as 1.7 in this case, according to Ref. [6,7]. However, compression damage evolution according to Birtel and Mark is distinguished by a relatively sharp increase.

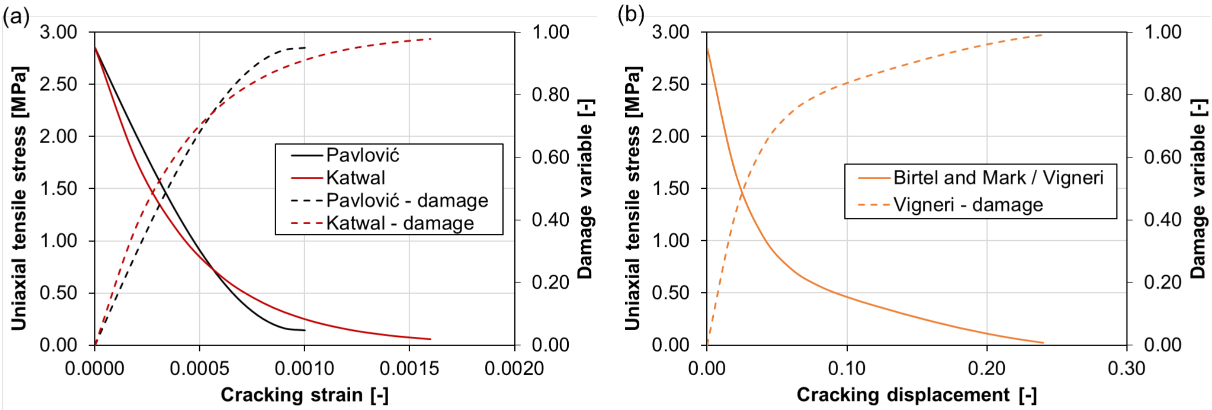

Fig. 4. Concrete behaviour in tension (f_{cm} = 37.3 MPa, f_{ctm} = 2.85 MPa):
(a) defined as a function of cracking strain, (b) defined as a function of cracking displacement

A concrete response to uniaxial tension according to different models could not be easily compared due to different presentations of tensile stress and damage evolution as functions of cracking strain and cracking displacement. However, it could be observed that there are only minor differences in the uniaxial tension model according to Pavlović and Katwal.

4. CDP MODELS IN PUSH-OUT TEST SIMULATIONS

The application of presented CDP models is tested on two different finite element models of push-out tests conducted on headed studs embedded in concrete slab with profiled steel sheeting. The difference between the two models is mainly reflected in the orientation of profiled steel sheeting: sheeting ribs are transverse to the beam at model DLU, whereas the angle between ribs and the beam in model S45 is 45°. Model DLU represents a demountable connection with headed studs welded to the angle, that is connected to the profile flange by bolts. Model S45 is a non-demountable with headed studs welded to the steel profile flange. Detailed explanations regarding the development of numerical models could be found in the authors' previous publications [4,23,24].

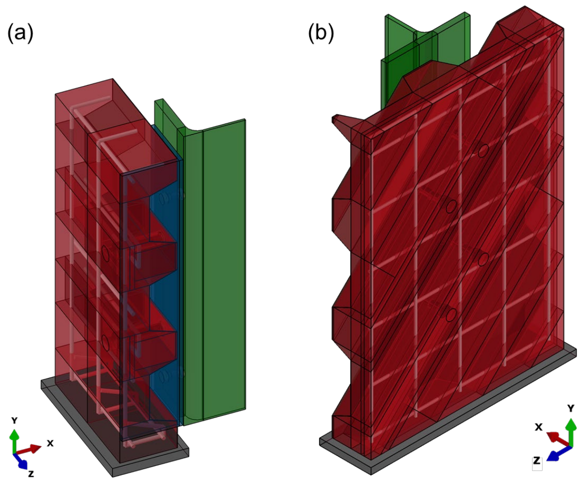

Fig. 5. Finite element models of push-out tests: (a) model DLU, (b) model S45

Finite element models are developed in Abaqus software [2], simulating concrete behaviour through CDP models presented in this paper. In all analysed cases, concrete elastic behaviour is described through the modulus of elasticity and Poisson's ratio. The dilation angle is set to 38° as done in some other studies [13,19], whereas the other values of plasticity parameters are adopted according to Abaqus user manual recommendations. The obtained load-slip curves for both analysed models, DLU and S45, are compared to the experimental ones in Fig. 6.

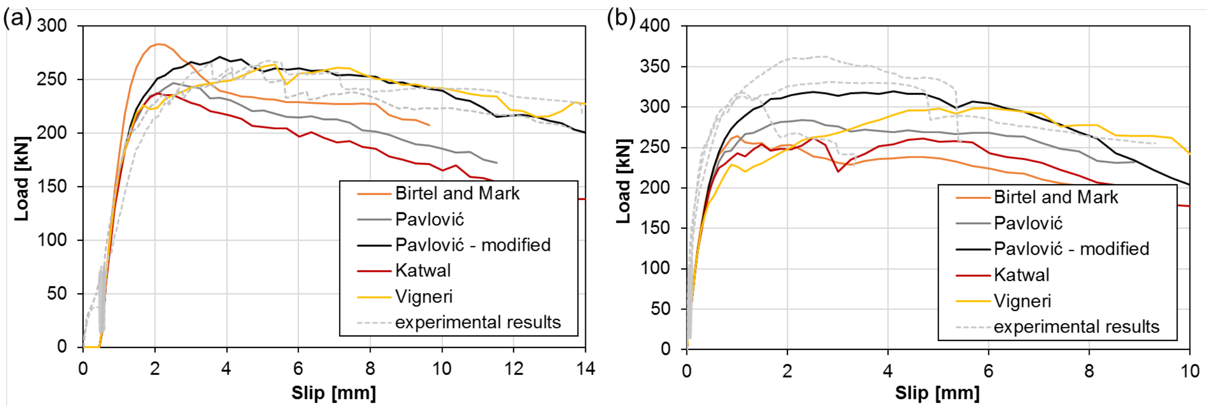

Fig. 6. Load-slip curves for different CDP models: (a) model DLU, (b) model S45

The presented results indicate a significant influence of the applied CDP model on the response of a push-out specimen, which is expected as both tested shear connections failed due to the development of a concrete cone around headed studs and its separation from the rest of the concrete slab.

The model given by Birtel and Mark overestimates the connection resistance and the load-slip curve does not follow the experimental results for the specimen DLU. The model according to Katwal predicts lower shear resistance and slip capacity than experimentally obtained. Similar results are observed applying the model proposed by Pavlović with the originally selected input parameters. Best matches between experimental and numerical results for model DLU are present for the concrete damage model according to Vigneri and according to Pavlović with the modified input parameters. Good predictions obtained through Vigneri's model are not surprising knowing that he used the CDP model for numerical simulations of headed studs in profiled steel sheeting with ribs transverse to the beam.

However, the model used by Vigneri does not provide accurate predictions for push-out specimen S45 with the angle between profiled sheeting ribs and the beam of 45°, predicting a considerable decrease in the connection stiffness for loads above 200 kN. On the contrary, the model proposed by Pavlović with the modified input parameters well simulates the connection response. The other three CDP models according to Birtel and Mark, Pavlović and Katwal considerably underestimate the ultimate load obtained during experimental testing.

5. CONCLUSIONS

This paper summarizes and discusses four different CDP models which have been used in numerical simulations of push-out tests by different researchers. The applicability of these models is tested on the specific case of push-out tests conducted on headed studs in profiled steel sheeting with two different rib-to-beam angles of 90° and 45°.

Results closest to experimentally obtained load-slip curves are accomplished by applying the CDP model suggested by Pavlović and modifying its input parameters for concrete uniaxial compression in order to develop a curve with slower descending at strains higher than ε_{cu1} than the original stress-strain curve. Pavlović's model was originally designed for modelling push-out tests with solid concrete slabs where local concrete damage occurs in the area near shear connectors. However, different failure mechanisms present in the case of connections with headed studs in profiled steel sheeting, failure of concrete cone and propagation of cracks throughout the larger area of the slab, request the adoption of the curve with higher stresses and strains in the post-ultimate domain. The advantage of Pavlović's model is reflected in its flexibility to calibrate input parameters which define curve extension beyond ε_{cu1} according to the experimental results.

Nevertheless, this paper does not neglect the benefits and applicability of all the presented models. Instead, it emphasizes the importance of adequate modelling of concrete behaviour and consideration of different material models depending on the exact problem that is being analysed. The presented results once more underline the necessity of the numerical model validation by comparison with experimental data before performing any further analysis.

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