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UNCERTAINTIES IN NONLINEAR MODELLING OF PUNCHING

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Abstract: *Nonlinear finite element analysis (NLFEA) has become a powerful tool for the prediction of the behavior of concrete structural elements. However, uncertainties that accompany the method, limit its practical application in designing of the new structures to prediction e.g. deflection or other displacement related calculation. Prediction of the bearing capacity is sometimes used in the case of the assessment of existing structures. The broadest application of NLFEA can be found in experimental research because from the tests obtained results it is possible to calibrate the FE models. The paper deals with the influence of some key parameters on the results of NLFEA used for prediction punching capacity of flat slab specimen without shear reinforcement. The dimensions of the finite elements are tested as well as input parameters of used material model for concrete using software Atena.*

Keywords: Punching, Nonlinear analysis, Fracture energy, Mesh.

1. Introduction

Punching is one of the most dangerous forms of structural failure in reinforced concrete slabs due to its brittleness. Current design equations for prediction of punching capacity, e.g. in EC2, ACI-318, have empirical nature and were developed on the basis of the test results. A step forward represents the model introduced in Model Code 2010 that is based on the Critical Shear Crack Theory (Muttoni and Ruiz, 2008) and the model can be regarded physical. Thanks to the extensive databases used for their calibration they provide very robust solutions. NLFEA represents another method for the assessment of punching capacity. However, the method suffers from much more uncertainties than design models in the standards and codes, because does not exist one universal procedure for modelling of the structure, where punching can be governing mode of failure.

The modelling in commercial software like Abaqus, Ansys, Atena, Diana or Sofistik for shear and punching requires an application of three dimensional (3-D) finite elements. This raises the question; how many elements need to be meshed through the depth of a slab to get reliable results. Polak and Genikomsou (2015) used 5, 6 and 8 hexahedral (brick) elements for their finite element simulation of the experimental flat slab by the Abaqus software. They obtained similar punching capacities. The differences were in the load-deflection response when the failure of the model with the smallest FEs was corresponding with greater deformation in comparison with the test. Kadlec and Cervenka (2015) carried out a parametric study with a different number of brick elements through the slab depth by the Atena software. The models were calibrated with results obtained from the tests performed in Lausanne (Guandilini and Muttoni, 2004). They found that four, better five elements provide reliable results. Similar results obtained (Augustin et al., 2018) who tested a different number of elements within the slab depth with results on two experimental slabs by the Atena software. He did not found differences in model results when 5 and 10 elements were used. Generally, the maximum number of elements through the slab thickness is limited by their minimum dimension that should not be smaller than maximum aggregate size $d_{g,max}$.

Further uncertainties are connected with used material models, particularly of a concrete. Concrete fracture can be solved by discrete crack modelling or smeared crack modelling (Claus, 2009). The smeared crack

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modelling is the preferred type because does not require change of the finite element topology. Two smeared crack models were developed. Fixed smeared crack model where the crack is fixed upon the initiation and rotating smeared crack model where the crack directions are updated to rotate with the principal strain directions during the loading. Kadlec and Cervenka (2015) recommend use model with fixed cracks for punching analysis.

Material models for concrete have a significant influence on the result accuracy. The fracture-plastic constitutive models are used to for NLFEA modelling, where fracture mechanics describes concrete behaviour in tension and theory of plasticity in compression. Concrete in tension is usually modelled by the uniaxial stress–crack displacement diagram that is defined by concrete tensile strength f_{ct}, fracture energy G_f and crack width w_u, where zero residual tensile strength exists. All parameters are highly variable even for the concrete of the same quality. Fracture energy depends on the concrete strength f_c, maximum aggregate size $d_{g,max}$ and water/cement ratio. According to CEB/FIP Model Code 1990 the value can be calculated by formula (1) and by formula (2) after fib Model Code 2010. However, the difference in value is significant.

$$G_f = G_{f,MC1990} = G_{f0}(f_c/10)^{0.7} = 30 * (33/10)^{0.7} = 69\ \mathrm{N/m} \tag{1}$$

$$G_f = G_{f,MC2010} = 73 * (f_c)^{0.18} = 73 * (33)^{0.18} = 136\ \mathrm{N/m}, \tag{2}$$

where G_{f0} = 30 N/m for $d_{g,max}$ = 16 mm

Concrete tensile strength f_{ct} used to be derived from cylinder compressive strength f_c. Several different formulae exist for this prediction. Eurocode 2 and MC2010 use formula $f_{ct} = 0.30{*}f_c^{2/3}$; software Atena $f_{ct} = 0.267{*}f_c^{2/3}$ and software Abaqus $f_{ct} = 0.33{*}f_c^{1/2}$. Each formula provides a different tensile strength.

When the fixed crack model is used the shear stiffness of cracked concrete has to be known. The shear stiffness of a cracked concrete can be expressed by normal stiffness and shear factor. Shear factor expresses how many times is normal stiffness higher than shear stiffness. According to Červenka et al. (2018) recommended value is 20 for punching failure analyses.

In order to quantify an effect of a different meshing and as well as input parameters for concrete material model, the following parametric study was carried out in software Atena.

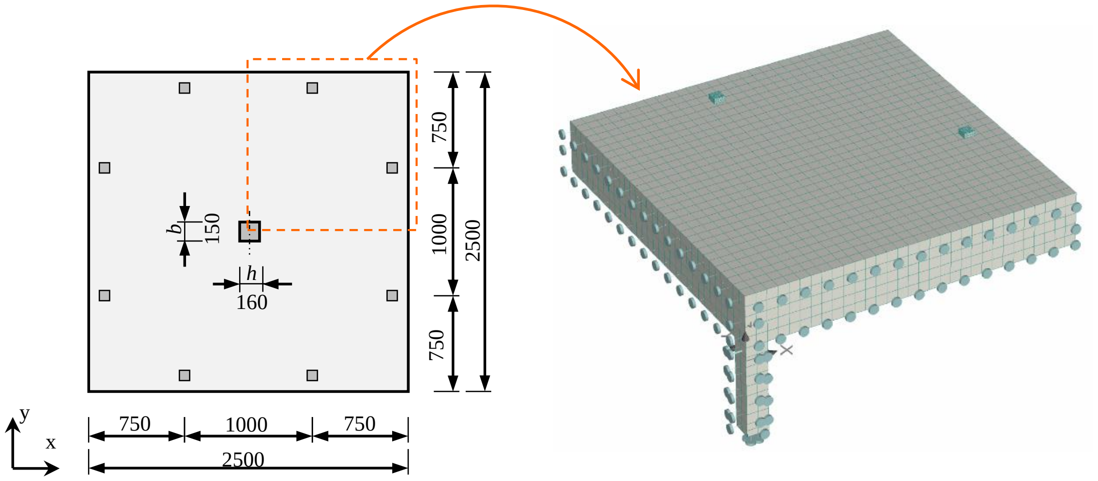

Fig. 1: Analysed slab specimen; on the left scheme, on the right model analysed by Atena.

2. Description of the specimen analyzed

The parametric study was carried out on the fragment of flat slab with a thickness of 200 mm and an effective depth of 159 mm, see Fig. 1. The specimen was supported by rectangular column with a dimension of the cross-section 160 × 150 mm. Cylinder concrete strength f_{cm} was assumed 33 MPa and reinforcing steel with yield strength of f_{ym} = 580 MPa. Reinforcement ratio ρ was 1.26 % (bars with diameter of ϕ16 mm by 100 mm). Specimen analyzed is without transverse reinforcement. The maximum aggregate size $d_{g,max}$ was taken 16 mm.

The punching capacity of the specimen was calculated by the EC2 (2004) model with a resistance of 550 kN and the CSCT model (Muttoni and Ruiz, 2008) with a resistance of 545 kN. Calculation was performed with partial safety factor γ_C equal unity and mean value of the concrete strength 33 MPa.

3. Nonlinear analysis

The effect of the mesh size was investigated with recommended input parameters for material model according to Kadlec and Cervenka (2015). Fracture energy was determined with formula (1) G_f = 69 N/m and concrete tensile strength f_{ct} = 2.76 MPa. The shear factor was assumed 20 and Poisson's ratio $\nu = 0.2$. Fixed smeared crack model was applied. Comparison of results obtained is shown in Fig. 2. Load was iterated step by step using the Newton-Raphson method and iteration limit for one analysis step was 80 iterations. Two ways of specimen loading were used: the first one with increments of force, for results, see Fig. 2a and the second one with increments of deformation applied on the column stub, see Fig. 2b.

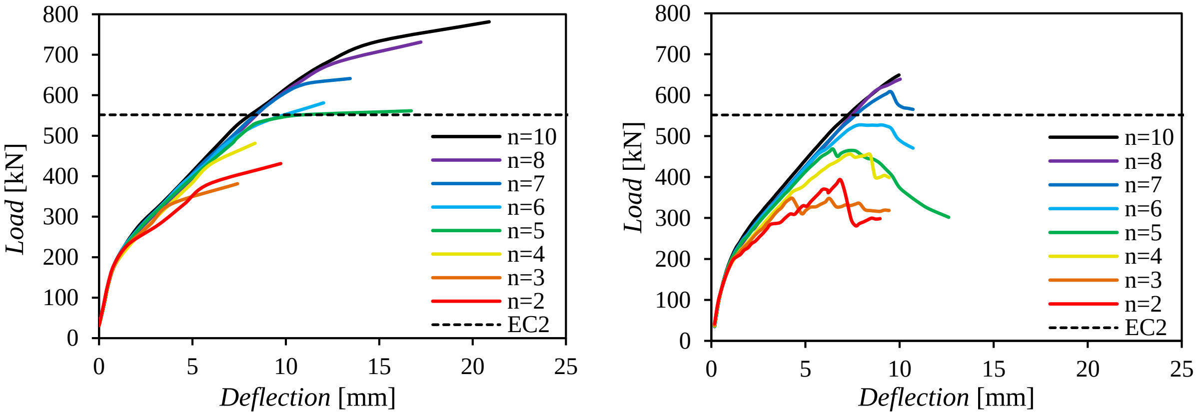

Fig. 2: Effect of the mesh size; on the left loading by force, on the right loading by deformation.

The analyses show, that with increase of elements through the slab thickness punching capacity increases for both ways of loading. The best prediction in punching capacity were obtained for 5 elements in the case of force loading. The model with the smallest elements (20 mm) significantly overestimated expected punching capacity by 42 %. In the case of loading by deformation, different force-deflection diagrams were obtained with descending branch. The best results provided model with 6 FEs and capacity of 527 kN.

Differences in results, if the model with fixed cracks and rotated cracks is used, are shown in Fig. 3. The predicted punching capacities are similar; 561 kN vs. 521 kN in the case of force loading. Much bigger differences were obtained in the case of loading by deformation. Model with rotated cracks significantly underestimates punching capacity. Obtained value 344 kN represents 62.5 % of expected value. The fixed crack model also underestimated punching resistance with a value of 527 kN, 95.8 % of expected value.

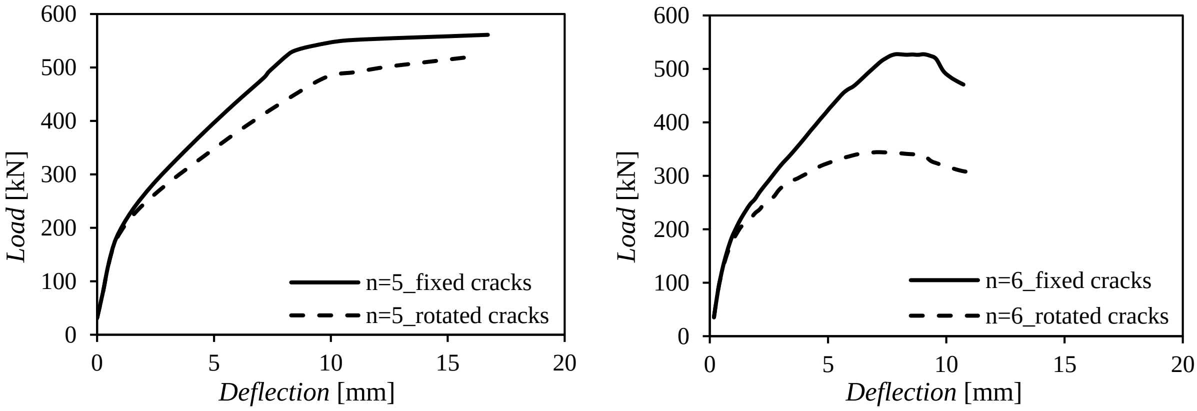

Fig. 3: Modelling of the smeared cracks; on the left loading by force, on the right loading by deformation.

Fracture energy G_f has a significant effect on the assessed punching resistance; see Fig. 4a. With increase G_f, increases punching capacity 681 kN vs. 561 kN. An application of the G_f determined according to MC2010 leads to the overestimation of punching resistance, e.g. in the case of the analysed slab by 23.8 %.

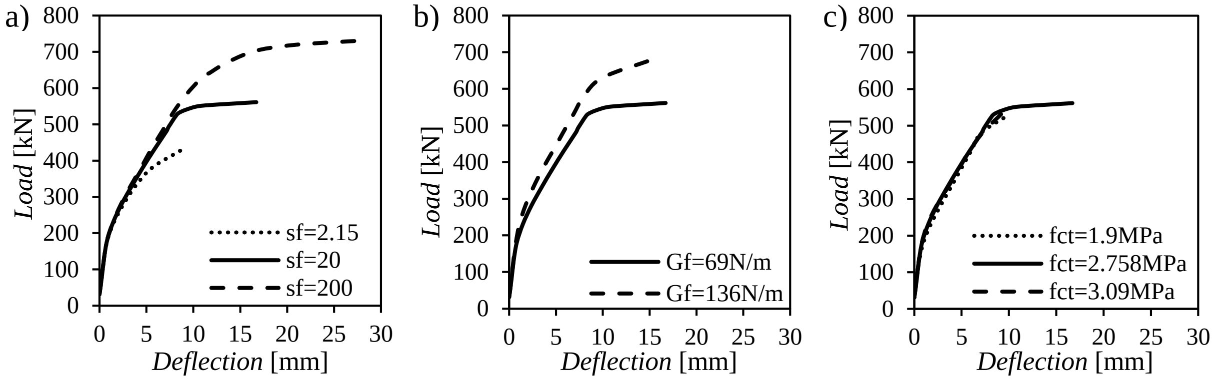

Fig. 4: Effect of material model inputs: a) fracture energy; b) concrete tensile strength (loading by force, G_f = 69 N/m); c) shear factor.

The effect of concrete uniaxial tensile strength is shown in Fig. 4b. Tensile strength of 1.9 MPa was calculated according to Abaqus software recommendation, 2.76 MPa according to Atena and 3.09 MPa according to EC2 and MC2010. The analyses show a very small sensitivity of nonlinear models on the concrete tensile strength. The assessed punching resistance was within a tight interval of 561 - 581 kN. The last parameter investigated was a shear factor. Three values were tested. A value of 2.15 represents elastic material, 20 by Atena recommended value and 200 as a maximum value. Shear factor affected both, punching capacity and deformation at failure. Value of both increases with increasing value of the shear factor.

4. Conclusions

Parametric study confirmed great uncertainties concerning of nonlinear analysis in punching phenomenon. Nonlinear models suffer from great differences in results obtained depending on meshing, way of loading and input parameters for the material model of concrete, except for tensile strength. Therefore, nonlinear models should be always calibrated with results of tests or experiments. The application of nonlinear modelling for shear and punching requires very skill users and knowledge beyond what is contained in manual for software application.

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References

Augustin et al. (2018) Punching Resistance of Flat Slabs with Openings - Experimental Investigation. In Solid State Phenomena: 24th Concrete Days 2017. Nov. 22 - 23, 2017, Litomyšl, CZ. vol. 272, pp. 41-46.

Cervenka, V., Jendele, L., Cervenka, J. (2018) Atena Program Documentation, Part 1: Theory. 2018, Prague.

Comité Euro-Internationale du Béton, CEB-FIP Model Code 1990, EPF Lausanne, Switzerland, 1993.

EN 1992-1-1 (2004) Eurocode 2 - Design of Concrete Structures, Part 1-1 General Rules and Rules for Buildings

fib Model Code 2010 – final draft (2013). fib Bulletin 65, vols. 1 and 2, 350 p., fib Bulletin 66, 370 p.

Genikomsou, A. and Polak A.M. (2015) Finite element analysis of punching shear of concrete slabs using damaged plasticity model in ABAQUS. Engineering Structures 98, pp. 38-48.

Kadlec, L. and Cervenka, V. (2015) Uncertainty of Numerical Models for Punching. In proceedings of *fib* Symposium Copenhagen, Denmark, May 18-20.

Muttoni A., Fernández Ruiz M. (2008) Shear strength of members without transverse reinforcement as function of critical shear crack width, ACI Structural Journal, vol. 105, no. 2, pp. 163-172.

Guandilini, S. & Muttoni, A. (2004) Punching tests on symmetrical reinforced concrete slabs without shear reinforcement. EPFL Institut de Structures, Rapport déssai IS-BETON, Lausanne.

Sucharda et al. (2018) Punching Shear Failure of Concrete Ground Supported Slab. International Journal of Concrete Structures and Materials. vol. 12, iss. 1, Article no. 36.

Thijs Claus (2009) Non-Linear Finite Element Analysis of Shear Critical Reinforced Concrete Beams, Delft University of Technology. Master Thesis Report.