Experimentální Analýza Napětí 2011
Experimental Stress Analysis

Numerical Analysis of Shallow Cast-in-Place Headed Studs Behaviour in Tension

Jindřich Fornůsek[1], Petr Konvalinka[2] & John J. Cairns[3]

Abstract: Numerical analysis of behaviour of shallow cast-in-place headed stud is presented in this paper. The research is mainly focused on behaviour of cast-in-place headed studs for concrete structures in tension. Numerical analysis was realized in ATENA (**A**dvanced **T**ool for **E**ngineering **N**onlinear **A**nalysis) finite element analysis software, which is very suitable for concrete structures and members. The numerical 2D axi-symmetric model of concrete member with rigid headed anchor was carried out in GiD software. Fracture-Plastic constitutive model CC3DNonLinCementitious2 numerical model for concrete was set. Main variable was effective depth of anchor which was set between 90 and 190 mm. The results of analysis were quite satisfying and very well correspond to analytical CCD solution used in Eurocodes.

Keywords: Numerical analysis, Anchor, Headed studs, Concrete

1. Introduction

Using of headed stud anchors is well known especially in composite beams (usually steel-concrete) where they are used for transfer of shear load between steel and concrete. As new technologies of composite structures came to be more common, tension and combination of tension and shear became more important. This paper is focused on tension above all.

There are two possible ways of fracture caused by tension load – brittle fracture of concrete and failure of steel anchor. It has to be mentioned that there is endeavour to avoid brittle fracture of concrete in the ultimate limit state of resistance because of its dangerous suddenness. It is requested to design these types of joints to failure of steel members because yielding of steel can ensure attention and plenty of time to escape the endangered structure.

This paper is focused on presentation of numerical analysis of behaviour of shallow embedded anchors in concrete, breakout fracture of anchor from concrete to be specific. The main objective of research is aimed at cast-in-place headed studs which consist of head and shank. The head is the main bearer of load to concrete. The bond between the shank and concrete is neglected (Fig. 2) in this research. This presumption fully corresponds to the CCD (concrete capacity design) theory which is used in European and American standards [1, 6].

The anchor capacity depends on three different ways of failure – steel failure, concrete pull-out failure and concrete break-out failure .The steel failure depends on yielding strength of steel and diameter of shank and can be easily calculated by Eq. 1:

$$N_{Rk,s} = A_s \cdot f_{yk}; \qquad (1)$$

[1] *Ing. Jindřich Fornůsek, Experimental Center, Faculty of Civil Engineering, CTU in Prague, Thákurova 7, Prague 6, 166 29, Czech Republic, jindrich.fornusek@fsv.cvut.cz*
[2] *prof. Ing. Petr Konvalnka, CSc., Experimental Center, Faculty of Civil Engineering, CTU in Prague, Thákurova 7, Prague 6, 166 29, Czech Republic, petr.konvalinka@fsv.cvut.cz*
[3] *Dr. John J. Cairns, School of the Built Environment, Heriot-Watt University, Edinburgh, Scotland, UK EH14 4AS; j.j.cairns@sbe.hw.ac.uk*

with

$N_{rk,s}$ characteristic resistance of anchor during steel failure [N]

A_s minimum cross-section area along the stressed anchor [mm^2]

f_{yk} characteristic steel yield strength ($f_{yk} = 0.8 \,.\, f_{uk}$; f_{uk} is ultimate tensile strength) [MPa]

The pull-out failure depends on head size. The pull-out capacity of anchor is very high in comparison to steel capacity and breakout capacity if the recommendation for head diameter d_d to shank diameter d_b ratio is met. According to the ACI-318 [1] and [9] this ratio should exceed the value 1.71. Both mentioned failures can be easily calculated or avoided by meeting the recommendations. This paper deals with the third way of failure and that means break-out failure. Thus the next chapter is focused on this problem in detail.

2. Concrete capacity design (CCD) approach

Concrete capacity design is one of two approaches how to calculate break-out capacity of an anchor for concrete. The second was is so called stress cone method (SCM) or 45 degree method [3, 7]. This method is still used for design of anchorage for structures in nuclear power stations in the US according to the ACI-349 [2]. Nevertheless the new trend for national standards around the world is to involve the first approach – the CCD theory. This approach is involved in the European standards [6] and American ACI-318 [1]. Hence this approach is used in this study.

The CCD theory calculates anchor break-out capacity by using the pyramid shape with height h_{eff} and side $3h_{eff}$ (Fig. 1). It was experimentally approved that the pyramid shape can be used for breakout capacity of anchor [9]. The concrete pyramid failure load N_{n0} of single anchor in non-cracked concrete unaffected by edge influences or overlapping pyramids of neighbouring anchors loaded in tension is given by Eq. 2 [7]:

$$N_{n0} = k_1 \cdot \sqrt{f_{cc}{}'} \cdot k_2 \cdot h_{ef}^2 \cdot k_3 \cdot h_{ef}^{-0.5}; \qquad (2)$$

with

k_1, k_2, k_3 are calibration factors

$$k_{nc} = k_1 \cdot k_2 \cdot k_3$$

hence

$$N_{n0} = k_{nc} \cdot \sqrt{f_{cc}{}'} \cdot h_{ef}^{1.5}\ ; \qquad (3)$$

with

k_{nc} = 13.5, for post-installed anchors

= 15.5, for cast-in-place headed studs and headed anchor bolts

$f_{cc}{}'$ concrete compression strength measured cubes with side length 200 mm [MPa]

h_{ef} effective embedment depth [mm] (Fig. 1)

The parameters k_1, k_2 and k_3 in the Eq. 2 represent three different factors. The factor $k_1 \cdot \sqrt{f_c{}'}$ represents the nominal concrete tensile strength at failure over the failure area, given by $k_2 \cdot h_{ef}^2$. The factor $k_3/\sqrt{h_{ef}}$ involves the size effect in the Eq. 2 [7]. The different values of k_{nc} are introduced in CEB – fib Design manual [4], k_{nc} is noted as k_1 in [4] and the values are lower: k_1 = 7.5; for headed studs and undercut studs can be increased up to 9.0. In British standards [6] the value of k_{nc} is 8.5 for cracked and 11.9 for non-cracked concrete.

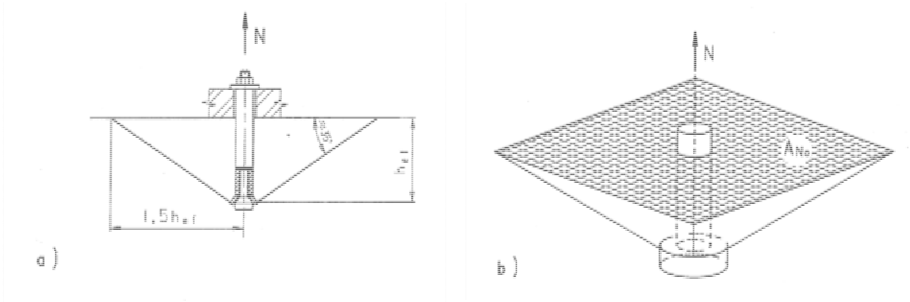

Fig. 1. Idealized concrete breakout cone for individual anchor according to CCD theory [6]

3. 2D axi-symetric numerical model

The numerical analysis was carried out in ATENA Science (**A**dvanced **T**ool for **E**ngineering **N**onlinear **A**nalysis) finite element software. This software is specialized on analysing of concrete members or structures. The 2D axi-symetric numerical model was carried out in GiD-2D and 3D Interface.

3.1. Geometry of numerical model

The model was created as axi-symetric because of time saving (Fig. 2). The effective depth h_{eff} varies from 90 to 190 mm. The model simulates cylinder of concrete with dimensions a = 425 mm for h_{eff} = 90 to 140 mm or a = 600 mm for h_{eff} = 160 and 200 mm, respectively. Height of model b = 500 mm was set to ensure the breakout of anchor instead of cracking because of bending. The breakout simulation was displacement controlled. The maximum displacement u varied from 3 to 8 mm, in dependence of h_{eff}. The displacement was applied in 50 to 80 steps. The two different materials were set for the model. Green means concrete and blue rigid material in the Fig. 2. Head of anchor was simulated by rigid material (blue) in rectangular shape. There were no bond between concrete and head of anchor in the bottom and on the side of the head (Fig. 3). Rigid connection with concrete was set on the top of the head. Head size varies in dependence on effective depth h_{eff} and supposed load to ensure theoretical concrete breakout instead of theoretical steel failure (Eq. 4):

$$N_{Rk,s}/N_{n0} \cong 1{,}1 \qquad (4)$$

The ratio between $d_b/d_d = 2$ (fig).

3.2. Material model of concrete

The numerical model for concrete was set CC3DNonLinCementitious2 (Cementitious2). This model represent fracture-plastic constitutive numerical model for concrete. The model can be used to simulate concrete cracking, crushing under high confinement and crack closure due to crushing in other material direction. This numerical model is not discussed in this paper in detail; thus more about this numerical model can be explained in ATENA Theory manual [5].

3.3. Mesh

The unstructured mesh was carried out because of hard shape conditions in the vicinity of contact between head and concrete (Fig. 4). Plane linear triangular elements were set to crate the mesh. Very high density mesh was created in the area close to the head of the anchor where *c* (Fig. 2) was set larger than 1,5h_{eff} to cover the expected concrete cracking area according to CCD theory. The size of the elements in this part was about 5 mm. The mesh of the anchor head was generated also with high density because of right connection to concrete.

In the other parts of concrete and of rigid reaction plate was generated thinner mesh to save computational time.

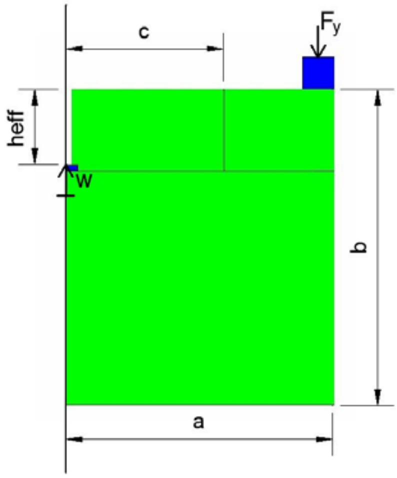

Fig. 2. Geometry of the sample (green – concrete, blue – rigid material)

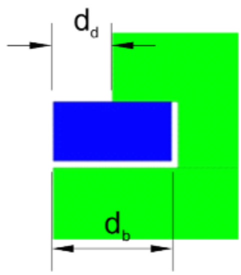

Fig. 3. Anchor head geometry detail (green – concrete, blue – rigid material)

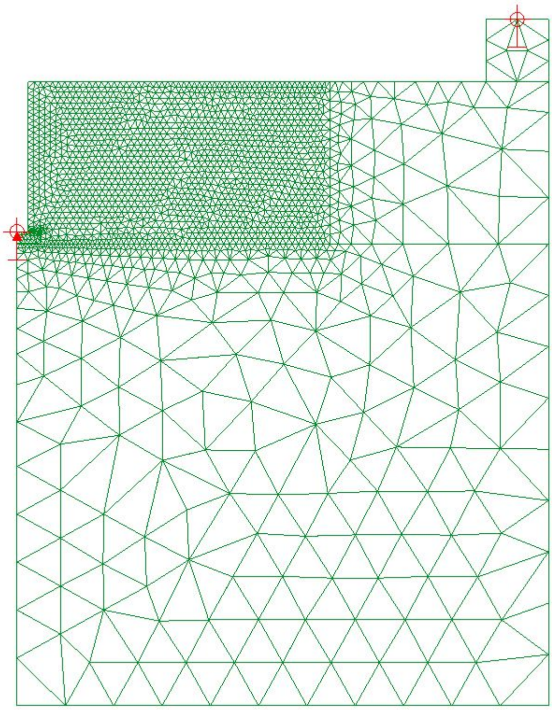

Fig. 4. Mesh of the sample. Denser mesh is in the vicinity of the anchor in the area where presumed cracks are expected to appear

4. Numerical analysis outcomes

The numerical analysis outcomes are presented in the next diagram (Fig. 5). The blue curve represents the anchor capacity according to CCD theory, red SCM theory and the green dots represent numerical models results. Good correlation of calculated data and theoretical CCD prediction (correlation coefficient 0,998) can be observed. So the numerical Cementitious2 model for concrete is appropriate to use for modelling of this problem type. In the most of similar researches the micro-plane M4 model is used [8], thus it was approved by this research that the Cementitious2 material model is able to carry out more than satisfying results.

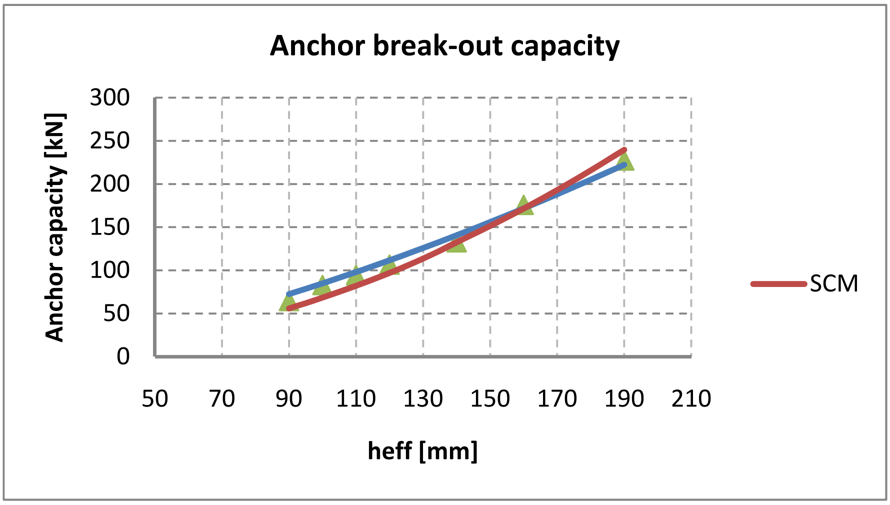

Fig. 5. Anchor pullout capacity – numerical analysis in comparison to CCD theory

The typical diagram (imported from ATENA) of reaction against displacement is in the Fig. 6. The diagram does not start from zero values because it starts with the first displacement application step. There can be seen steep reaction increase in the beginning of the loading and after the reaching of the maximum reaction slow decreasing. That is fully corresponding with the fracture mechanics of concrete. The shaking of the curve in the decreasing part can be caused by not fully satisfied convergent criteria because of problem nonlinearity. This irregularity will be investigated in the next part of the research.

The typical cracking of break out concrete is shown in the Fig. 7. The angle of cracking concrete very well corresponds to the CCD theory, but it is necessary to note that the axi-symetric model cannot simulate the pyramid shape of breaking concrete. The colour scale in the figure represents displacement of concrete and anchor and the black lines represent the concrete cracking.

5. Conclusion

The Cementitous2 numerical model appeared to be fully applicable for calculation of concrete breakout capacity of anchor. The simplified numerical 2D axi-symetric model is fully capable to predict the anchor breakout capacity behaviour. It was verified that the numerical model calculation outcomes fully corresponds to the CCD theory which is used for the anchor capacity prediction in the Eurocodes.

The main objective of this research was verification of use of Cementitious2 material model and its ability to calculate this problem. The ability was fully approved and this material model can be used in the next phases of research. The next research of this problem will be focused on 3D modelling and calculation of anchor capacity in dependence of head size and shape. The capacity in dependence of concrete strength will be also investigated.

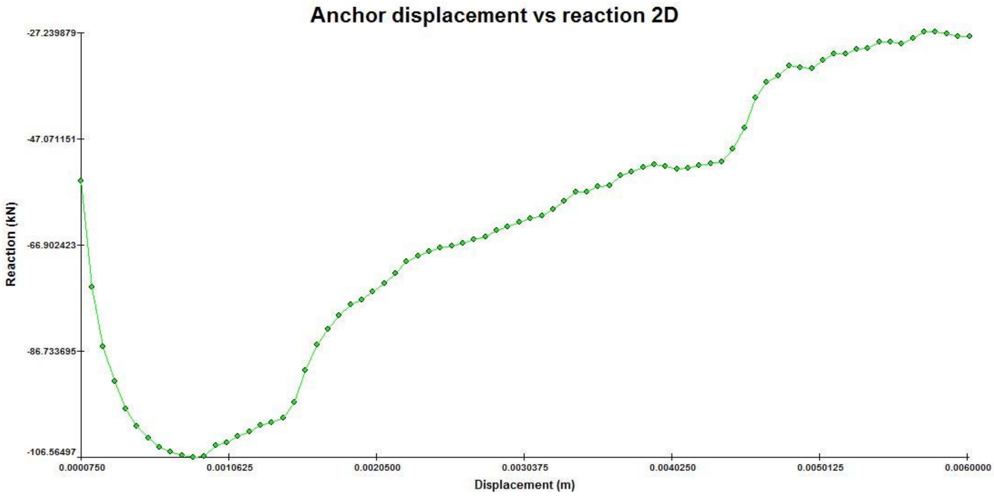

Fig. 6. Typical diagram of displacement versus reaction (this concrete diagram is for h_{eff} = 120 mm)

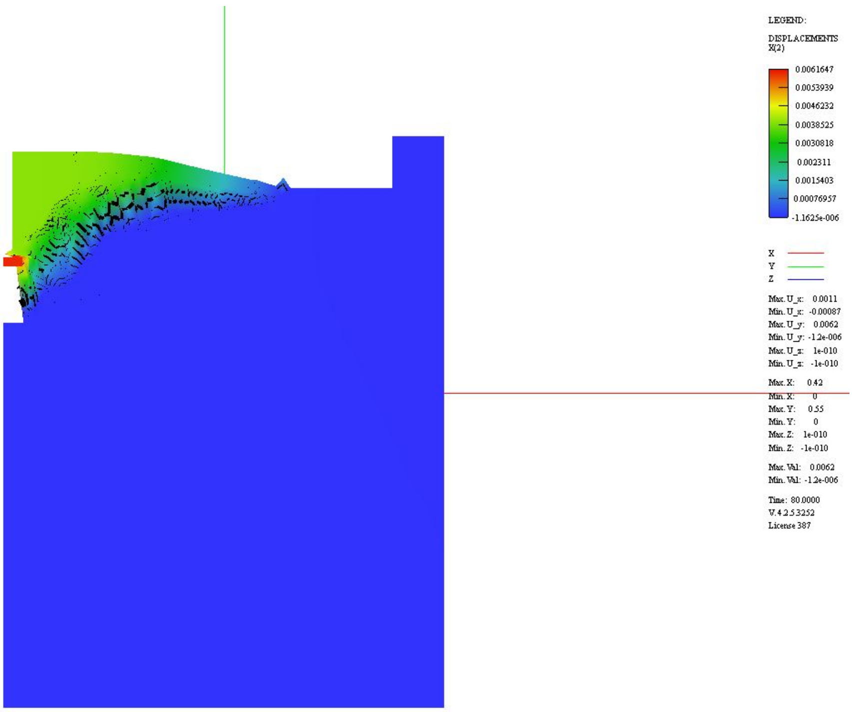

Fig. 7. Displacement of the concrete cone (green and warmer colours) and cracking of concrete on the edge of the breakout cone (black)

Acknowledgement

This research has been supported by the Ministry of Education of the Czech Republic under the project №: MSM6840770031. Many thanks to firm Červenka Consulting for providing of ATENA Science student vision.

References

[1] ACI Comittee 318, "Appendix D – Anchoring to Concrete", Building Code Requirements for Structural Concrete and Commentary, ISBN-10: 9780870312649.

[2] ACI 349 "Code Requirements for Nuclear Safety Related Concrete Structures," American Concrete Institute, Detroit (1985).

[3] Cannon R., "Straight Talk About Anchorage to Concrete – Part I," ACI Structural Journal, 92-S56, pp. 580-586 (1996).

[4] CEB-fib, "Design of Fastening in Concrete: Design Guide", Thomas Telford, London, UK (1997).

[5] Červenka V., Jendele L. and Červenka J., "ATENA Program Documentation Part 1 - Theory," Červenka Consulting, Praha (2009).

[6] DD CEN/TS 1992-4-2:2009, "Part 4-2: Headed Fasteners", Design of fastening for use in concrete, BSi British Standards, London, UK.

[7] Fuchs W., Eligehausen R. and Breen J.E., "Concrete Capacity Design (CCD) Approach for Fastening to Concrete," ACI Structural Journal, 92-S9, pp. 73-94 (1995).

[8] Ožbolt J., Eligehausen R., Periškić G and Mayer U., "3D FE analysis of anchor bolts with large embedment depth," Engineering Fracture Mechanics, 74, pp. 168-178 (2007).

[9] Pallarés L. and Hajjar N.F., "Headed steel stud anchors in composite structures, Part II: tension and interaction," Journal of Constructional Steel Research, 66, pp. 213-228 (2010).

[10] Pivonka P., Lackner R and Mang H.A., "Concrete Subjected to Triaxila Stress States: Application to Pull-Out Analysis," Journal of Engineering Mechanics, pp. 1486-1498 (December 2004).