12th International Conference on
Steel, Space and Composite Structures
28-30 May 2014, Prague, Czech Republic

INFLUENCE OF SELECTED PARAMETERS ON DESIGN OPTIMISATION OF ANCHOR JOINT

Miroslav Bajer*, Martin Vild*, Jan Barnat* and Josef Holomek*

*Brno University of Technology, Faculty of Civil Engineering, Institute of Metal and Timber Structures
Veveří 95, 602 00 Brno
e-mail: <vild.m@fce.vutbr.cz> webpage: http://www.fce.vutbr.cz

Keywords: Cast-in anchors, concrete pad, rigid joint, experiment

Abstract. *Main topic of this article is description of real behaviour of selected statically loaded anchor joints — design of individual anchor joint components in context of determination of selected parameters used during the anchor joint optimisation process.*

The standard design approach is Component method used in codes which is not able to solve more complex and atypical anchoring joints especially when the character of load is complicated. First the parameters which should be used in design process are determined and described. Then the parameters are surveyed in detail. These parameters should be used not only in further development of component method but also as inputs for other methods such as Finite Element Method (FEM). Models of the anchor joint based on FEM usually demand solid modelling approach, which is very complicated, time consuming and very difficultly applied in practice. Thus the aim is to simplify the model as much as possible with similar accuracy.

This paper is mainly focused on description of experiments which were prepared and realised in laboratories of Brno University of Technology. Joints of columns and concrete using base plate were realized to monitor the real behaviour of individual parts of anchor joint (concrete, anchor bolts, base plate, welds etc.) Results are presented and compared to models. Data obtained from these tests could be further used in design of anchor joints.

1 INTRODUCTION

The article presents a research which is focused on developing a simplified engineering model of a steel or steel-concrete joint of a structure. Both creation and solution of this simplified model should require only the most necessary material parameters, geometry and short duration of solution. Therefore, the aim is to use simple beam or shell elements instead of solid elements, complex contact parameters and areas with detail modelling with keeping the same quality and accuracy of results.

For example, to model an anchor bolt it is possible to use a beam element and to replace a complex behaviour of a mechanical (e.g. expansion anchor) or glued (bonded anchor) contact between the bolt and concrete by an appropriate setting of the beam element, e.g. see [1]. In addition, the whole concrete pad including a grout can be simplified to Winkler foundation model. Then, with the correct setting of stiffness, the model will provide forces and stresses, which can be evaluated according to analytical solutions. Steel structures mostly comprise of plates which can also be modelled using shell elements.

In current praxis it is very difficult or impossible and always expensive to determine all necessary parameters which are required in complex nonlinear material models and contact settings. General effort is to find the parameters that mostly influence the accuracy of results and the ones that can be neglected. In the design phase an engineer does not know some values of the most important parameters and thus a default values should be recommended at least for common types of joints. Ideally, the sensitivity analysis is performed, e.g. see [2].

The values of these parameters have to be based on experimental research. The execution of experiments can lead to another problems concerning methods of measuring of forces or deformations. For example, there are two most widespread methods to measure the tensile force in an anchor bolt: strain gauges glued to bolt surface and force washers.

At Brno University of Technology a basic type of steel-concrete joint was selected for an experiment. The joint is simple enough so its resistance can be calculated by Component Method used in Eurocode and to be modelled by FEM. The experiments described below were performed to acquire data used in software for creation of simple engineering models, for example IdeaCON. Another useful result was verification of measuring methods.

2 METHODS

The intention was to subject a steel-concrete joint to a constant compressive force and an increasing bending moment. Hence, four specimens consisting of reinforced concrete pad, cast-in anchors and steel column were prepared. The cast-in anchors were made of threaded rods M20, steel grade 8.8, corresponding nuts and a steel plates with dimensions 60 x 60 x 20 mm and a hole in the middle, which served as a head of the bolt and big washers to cover the holes in base plate. The head of the bolt, which resisted the pull-out failure mode, was created by pulling the threaded rod through the small hole in the steel plate, which was fixed in place with a nut from each side. A small part of a thread adjacent to the upper concrete surface was milled off and a strain gauge was applied on each anchor which was to be subjected to tension.

First the formwork of OSB was prepared, then reinforcement cage and anchors were fixed in place using wooden frame. The reinforcement was standard for concrete pad: rods of steel grade B 490 with 12 mm diameter with spacing 150 mm at the bottom and 300 mm at the top. The cover to reinforcement was 40 mm. Four reinforcing bars for crane hooks were added for manipulation. Polystyrene was attached to the wooden frame to keep the place for shear lug. Three strain gauges were fixed to the wooden frame in a position where an area of concrete in compression was expected. Hereby the pad was ready for pouring of concrete. The formwork with all the above described elements can be seen in Fig. 1.

Figure 1: On the left: formwork, reinforcement, anchors and strain gauges ready for casting; on the right: column, base plate and shear lug

The grade of concrete was C16/20 and 4 concrete pads (1500 mm length, 1000 mm width and 400 mm height) and 9 testing specimens (5 cubes and 4 prisms) were cast from one batch. The concrete was sufficiently vibrated and cured for 2 days against shrinkage.

A base plate with holes for anchors and a spreading plate, both with 20 mm thickness, were welded to bottom and top of column HEB 240, respectively. A shear lug was welded to the bottom of the base plate. The shear lug was IPE 100 with length 100 mm. All these components were from steel grade S 235. The base plate with the shear lug and the bottom part of the column is shown in Fig. 1.

One month after the casting of the concrete the columns welded with plates and shear lugs were attached to the concrete pads using grout Groutex 603 and cast-in anchors.

Strain gauge was applied in the height of 150 mm to each side of a column flange which was in tension when the sufficient bending moment was applied. Another gauges were glued to the base plate: one near the flange where maximum deformation of the base plate was expected and a rosette between two anchors in tension. Additionally the lifting of a base plate above the concrete pad and the horizontal and vertical displacement on loading cylinders was measured.

Two independent forces were applied by the loading cylinders on the top of the column: the axial force, which was applied first and then held constant at 400 kN, and the horizontal force, which varied and caused a bending moment in the joint. The axial force was applied using a special set-up of rigid steel beams not to interfere greatly with the horizontal force and not to cause any unwanted stresses in the concrete pad. The loading cylinder was held by two rods attached by pins to a short beam which was bolted to two larger beams fastened to the ground in the laboratory, which is specially designed to withstand great loads. The beams also stabilized the specimen in place. Ideally the pins should be in the point around which the column would turn. In our case the pins were 485 mm above this point and therefore the axial force slightly stabilized the column when horizontal deflection raised. The horizontal force was applied by loading cylinder pinned in the height of 1.83 m above the base plate, thus causing bending moment and shear force in the joint. Specimens 1 and 2 were subjected to in-plane axial force along the stronger axis of the column. Specimens 3 and 4 were rotated by 26.56˚ along the vertical axis, thus bended in out-of-plane direction. The scheme and the photograph of the set-up with in-plane bending is shown in Fig. 2 and Fig. 3, respectively.

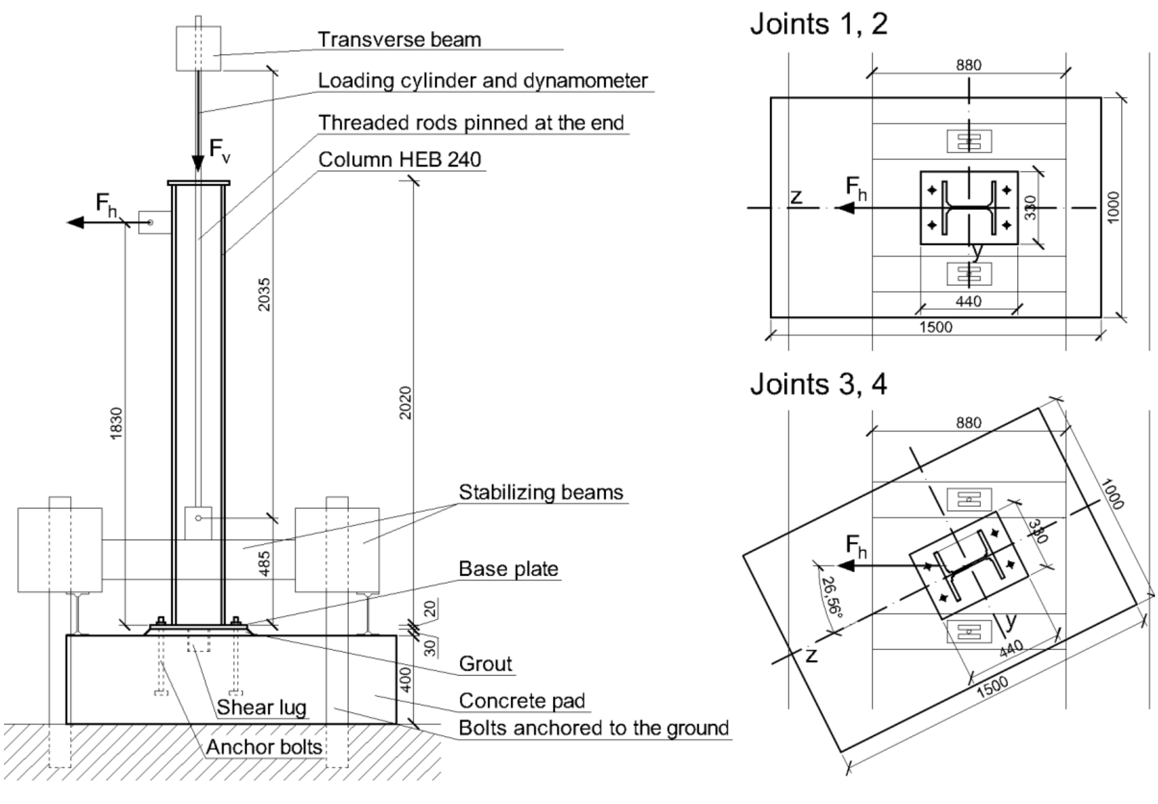

Figure 2: The test set-up scheme

Figure 3: The test set-up of joint 2 — axial force and in-plane bending

3 RESULTS AND DISCUSSION

Tests to determine the compressive cube strength and modulus of elasticity of the concrete were performed 136 days after the casting of both the concrete pads and the test specimens. The average compressive cube strength and modulus of elasticity were 22.6 MPa and 20.9 GPa, respectively. These values were used for calculation purposed in Eurocodes and in FEM models.

The resistances N_{Rk} and M_{Rk} and stiffness S_j of the above described joint were calculated according to the Component Method in ČSN EN 1993-1-8 [3], the concrete resistance according to ČSN EN 1992-1-1 [4] and the interaction curve was determined using the guideline in [5]. The axial resistance N_{Rk} was 1760 kN. The joint resistance in in-plane bending moment perpendicular to the stronger axis is dependent on the axial force. With the chosen compressive axial force, F_v = 400 kN, the resistance was M_y = 128 kNm. The stiffness is also dependent on the direction and magnitude of forces. For the above described case the initial stiffness $S_{j,ini}$ was 22.168 MNm/rad. According to the Component Method in Eurocode the stiffness starts to decrease at 2/3 of maximal resistance in bending moment. The bending moment resistance and stiffness can be calculated only for simple joint set-ups, in-plane case and for specific points in the joint interaction diagram.

The anchor bolts can fail in 3 modes — steel rupture, pull-out failure and concrete cone breakout. Calculation according to ETAG [6] was performed and although the concrete cone breakout mode had the lowest characteristic resistance (230 kN for both bolts in tension). However, it did not occur during any of the experiments. In all cases the steel failure was governing the ultimate resistance of the joint. Nevertheless the concrete cone breakout is known to have great variation of results and the concrete pad exhibited many cracks and in case of cyclic loading the concrete cone breakout could be decisive.

The evaluation of the tests involved reducing horizontal force F_h with stabilizing effect of vertical force F_v caused by the difference of heights of the point around which the column turned and the pins connecting the threaded rods holding the cylinder inducting vertical force F_v. Also the elastic deformation of the column was subtracted to determine the value of rotation φ of the joint. Initial stiffness $S_{j,ini}$ was calculated from the difference between M_y = 100 kNm and 20 kNm and corresponding values of rotation φ. In both experiments the initial stiffness was more than twice lower than according to the Component Method in Eurocode: $S_{j,ini}$ = 9,32 MNm/rad for joint 1 and 10,77 MNm/rad for joint 2.

The bending moment - rotation diagram of calculation and results of two experiments of joints with in-plane bending can be seen in Fig. 4.

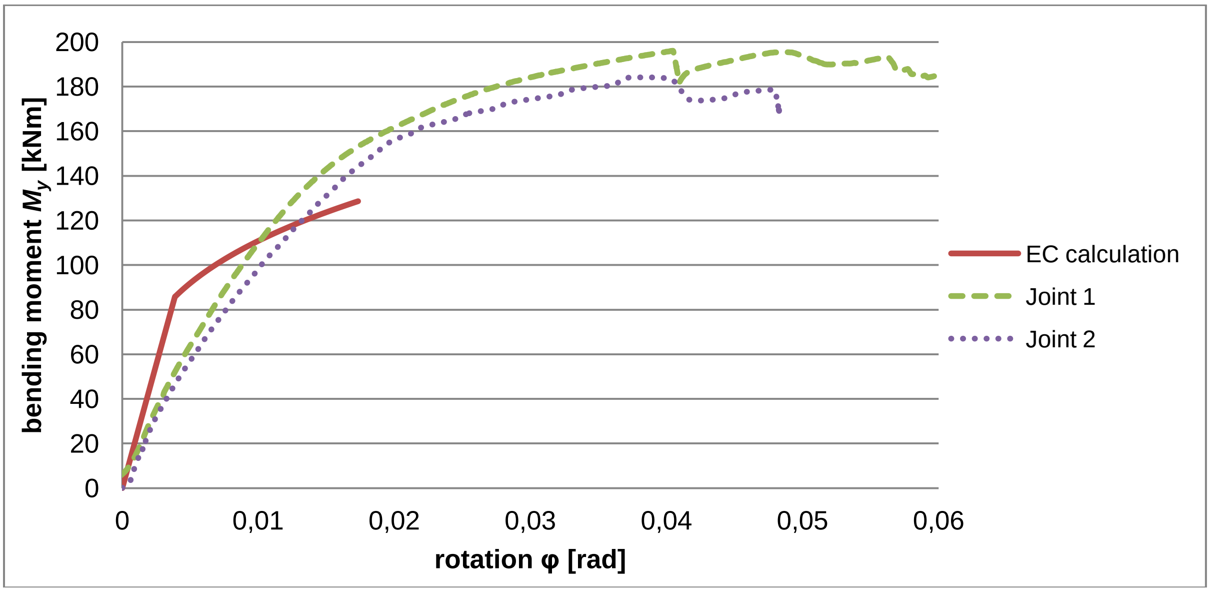

Figure 4: Bending moment - rotation diagram of specimens 1 and 2 subjected to axial force and in-plane bending moment and calculation according to EC

The M-φ diagram plotting the results of 2 experiments of joints with out-of-plane bending can be seen in Fig. 5. Curves φ, φy and φz show the dependence of bending moment M on rotation φ in the direction of the horizontal force, perpendicular to the stronger axis y and perpendicular to the weaker axis z, respectively. The instant when the anchor bolts in tension were torn are clearly seen in the graph where bending moment plummets. This occurred at the horizontal displacement of 270 mm in case of joint 3, where only one anchor was cut, and 185 mm and 268 mm in case of joint 4, where both anchors were torn. The maximal horizontal displacement allowed by the cylinder was about 300 mm.

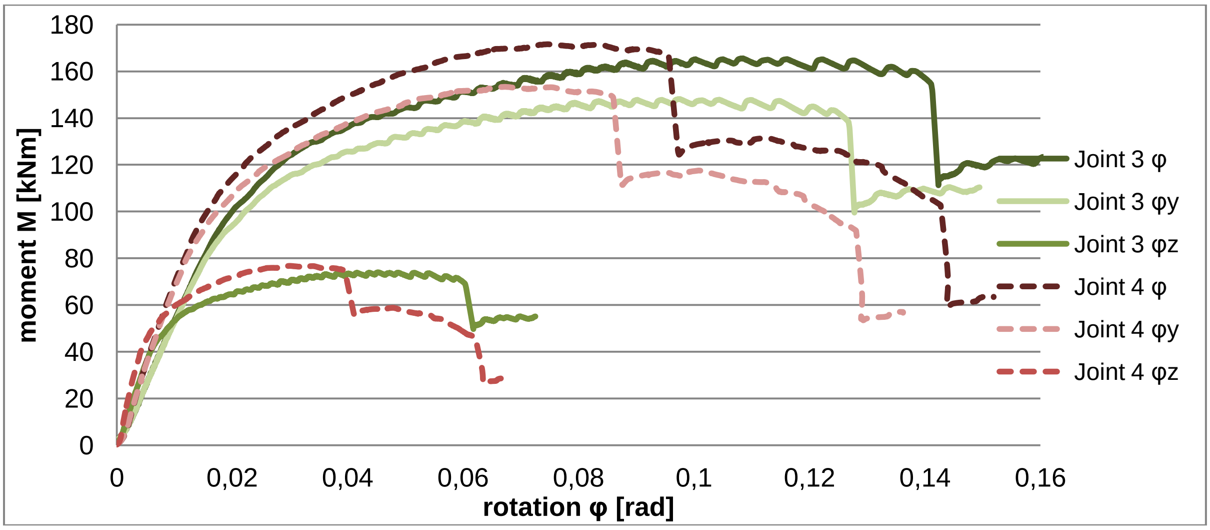

Figure 5: Bending moment - rotation diagram of specimens 3 and 4 subjected to axial force and out-of-plane bending moment

The forces on anchors in tension were measured by strain gauges and force washers. Force washers measure directly the force but the strain obtained from strain gauges had to be multiplied by modulus of elasticity (E = 210 GPa) and reduced cross sectional area of an anchor bolt (A = 220 mm^2) in the place where parts of the thread on the anchor bolts in tension were milled off so the strain gauge could be glued to the bolts' surface. The results are plotted in Fig. 6.

The manufacturer guarantees the error of measurement only 2 % for strain gauges and 12 % for force washers. On the other hand, if a bolt is subjected also to bending moment, it is paramount to place a strain gauge to a neutral axis or to use more strain gauges. In case of in-plane bending (joints 1 and 2) the results of forces obtained from force washers show good agreement with results calculated from strain acquired from strain gauges. In the experiments with out-of-plane bending moment (joints 3 and 4) the strain gauges were glued to the sides parallel to the flange of the column and showed results completely corrupted by significant strain caused by bending. With only one strain gauge on each bolt, it is impossible to differentiate the parts of the strain caused by tension and bending. Another disadvantage of strain gauges is the fact that after the yield strength is reached, the real stress-strain diagram has to be used to calculate stress and force. The moment when results from strain gauges starts to differ from results from force washers and rise sharply is the moment of yielding.

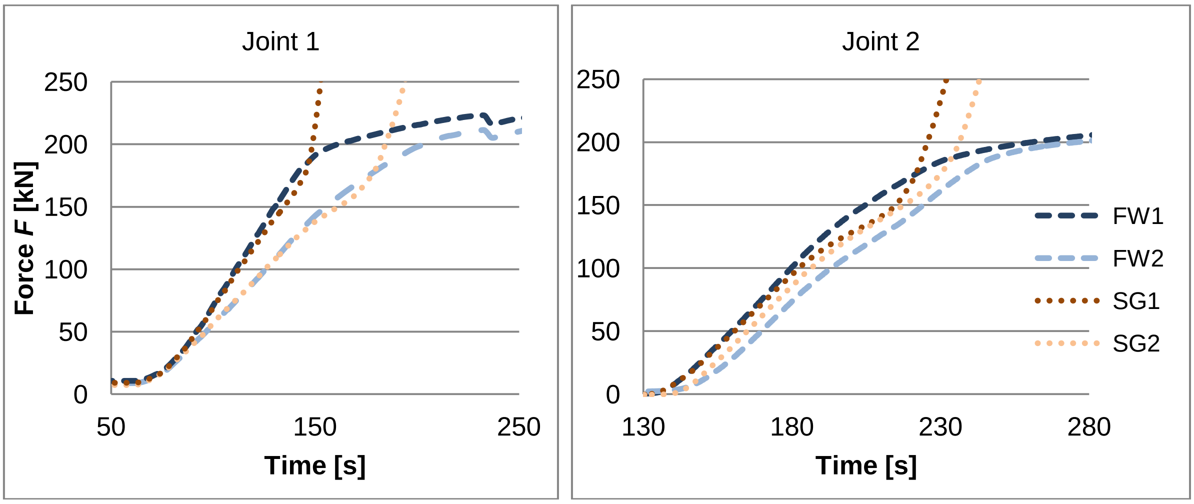

Figure 6: Forces on anchors measured with force washers (FW) and strain gauges (SG)

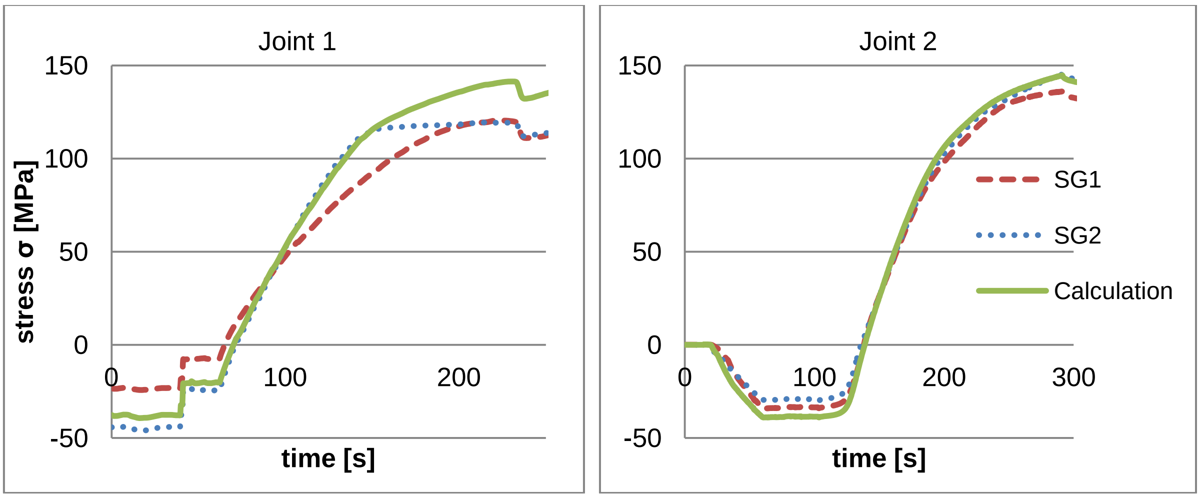

Figure 7: Stress obtained from strain gauges on the edges of the flange and by calculation

Stress on the edges of a flange in tension is plotted in Fig. 7. The stress was rising very differently on two edges of the flange of the column in joint 1. The same behaviour can be seen in

Fig. 6. At the time around 140 s the bolt reached its yield stress and also the stress on this edge of the flange near yielding bolt flattened out. Later the stress on both flanges remained very similar on both edges and slightly lower than the calculation which was caused by yielding of bolts. The initial differences could be ascribed to joint imperfections, e.g. not completely straight column, non-uniform grout or slightly eccentric application of forces. In case of joint 2 all three curves fit each other very well.

The case of out-of-plane bending is plotted in Fig. 8. The increment of stress from bending was higher in direction perpendicular to the weaker axis even though the angle between force and direction perpendicular to the stronger axis was 26.65˚. This means that the flanges of a column started to yield much sooner than in in-plane bending case. The yielding caused the stress on the most tensioned edge of a flange to decrease and the stress on the other side of this flange to get from compression into tension.

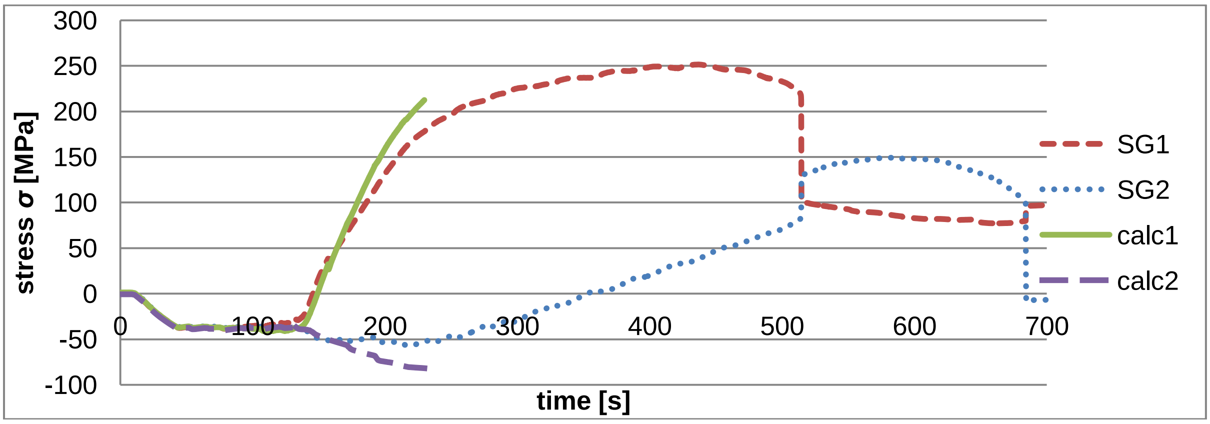

Figure 8: Joint 4 — Stress on the edges of flanges — out-of-plane bending

The typical sequence of resistance failing is described on the case of joint 2. First the cracks in concrete could be heard around M_y = 100 kNm and soon they started to be visible on the surface. At t = 175 s and M_y = 110 kNm the base plate started to yield according to the strain gauge near the flange in tension. Then at t = 215 s and M_y = 163 kNm the first anchor bolt started to yield and soon after, at t = 222 s the second anchor bolt as well. The elastic resistance of a column was reached at t = 255 s and M_y = 185 kNm according to the calculation. Then the bending moment stayed nearly constant around 195 kNm until the maximum horizontal displacement allowed by the loading cylinder was reached. At that moment the joint was practically destroyed, many cracks with about 1 mm thickness could be seen in the concrete pad and steel components were extensively yielded, which can be seen in Fig. 9.

Figure 9: Joint 2 — deformed base plate and bolts after the experiment

Results from engineering model from software IdeaCON with axial force F_v = 400 kN and bending moment M_y = 128 kNm are shown in Fig. 10. The anchor bolts were modelled only as truss element and the concrete pad was only a Winkler foundation model. Von Mises stress on steel shell elements corresponds well with calculation and experiment. Future work is to set the correct stiffness parameters to anchor bolts and Winkler foundation model for various types of anchorage, concrete and shapes of foundation pad.

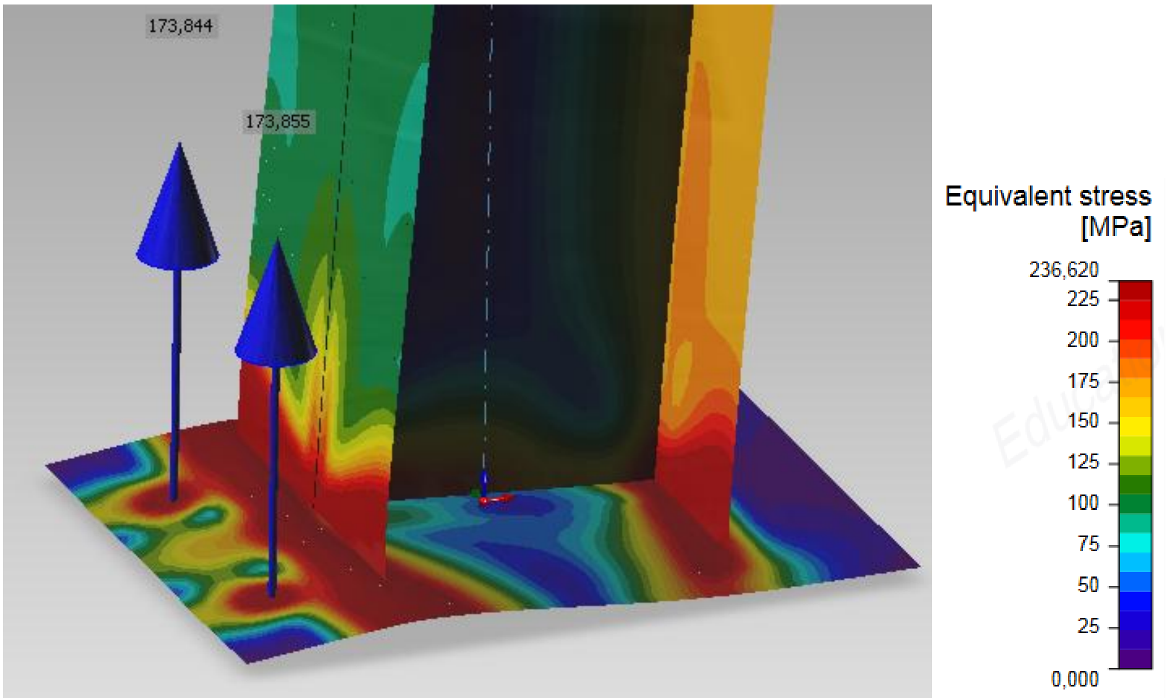

Figure 10: Von Mises stress on deformed shape and forces on anchor bolts from IdeaCON

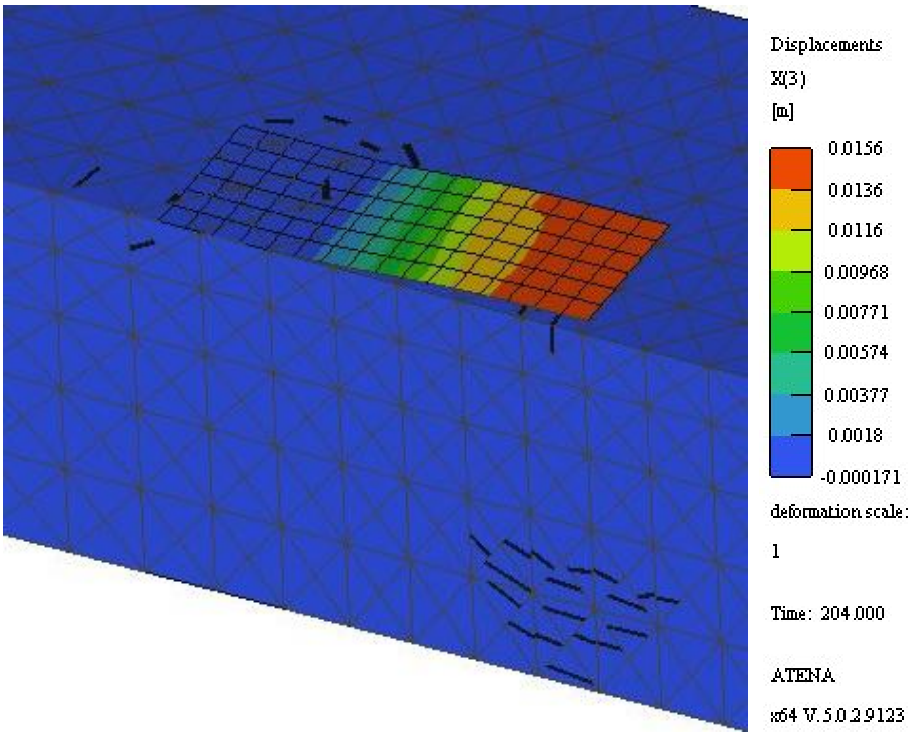

Figure 11: Vertical displacement and cracks in concrete from ATENA

Detailed FEM model was created in ATENA [7], which is a software especially dedicated to nonlinear analysis of concrete material. The detailed FEM model is used for comparison with the experiment, to determine magnitude and direction of main stresses in concrete, the contact area between steel base plate and concrete pad and to create parametrical studies, for example with various external forces, properties of concrete, interface bond between anchor bolt and concrete or various dimensions and shapes of steel column and concrete pad. The results of vertical displacement of base plane and cracks in concrete of this detailed FEM model is shown in Fig. 11. The comparison of forces acting on anchor bolts between FEM model and force washer readings from experiments can be seen in Fig. 12.

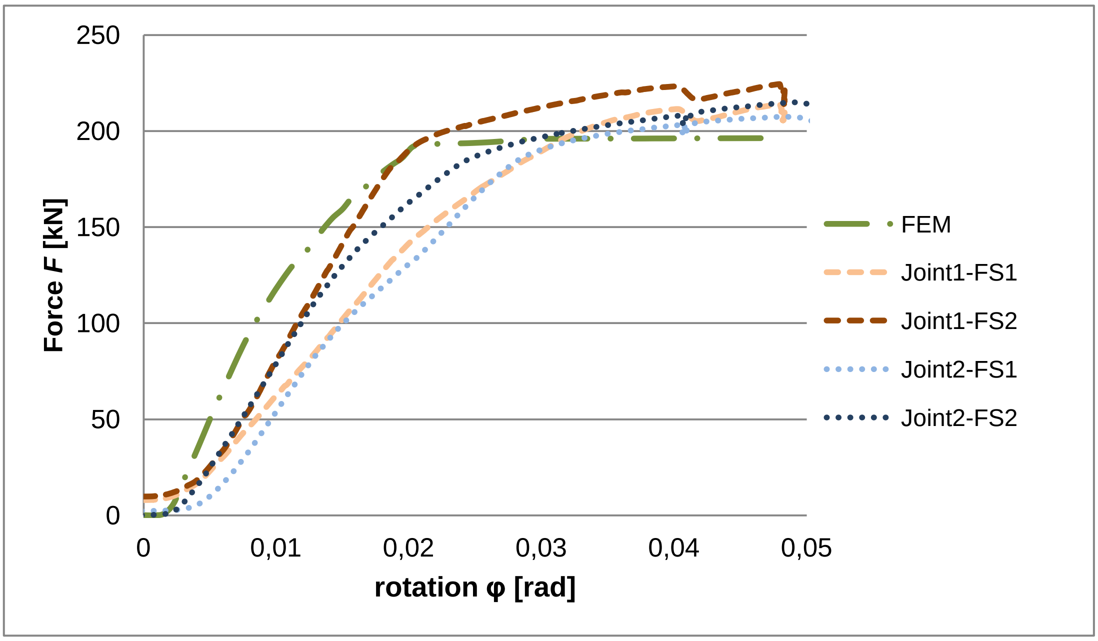

Figure 12: Comparison of forces on anchors

4 CONCLUSION

Even a very simple joint of steel into concrete is a very complex problem with many various modes of failure. Different failure modes, e.g. concrete cone failure or steel yielding, can occur at different load and rotational displacement and some are allowable under certain conditions, for example anchor bolts yielding under the condition of sufficient rotational capacity of the joint and calculation of ultimate strength. There are many types of anchors to concrete, which are dependent on many factors. While steel is more ductile and engineers often allow yielding, concrete is quasi-brittle material with very low strength in tension. Thus, both materials exhibit different behaviour in monotonic and cyclic loading.

Analytical solution for such problems is possible only for certain shapes of column, position of bolts and in-plane bending. Even simplified and not accurate, it is very time consuming. Detailed FEM modelling requires vast knowledge about material and contact parameters, elaborate software and good hardware equipment. Still, to achieve accurate results, it is often necessary to validate the detailed model with an experiment. Therefore simplified engineering model, allowing to create and solve a joint in minutes is very welcome. In this simplified model, it is clear that certain problems have to be solved analytically rather than using detailed FEM elements, for example the resistance of anchor bolts.

Regarding the experiment, it is very convenient to apply redundant measuring devices; for example force washers and strain gauges can be used together and in case of malfunction of one device, there are still results from the other one available. Also, even though strain gauges should be more accurate, force washers can be used to measure force even without the precise knowledge of stress-strain diagram.

The experiments provided necessary inputs into both engineering model and detailed FEM model. Both of them are going to be updated and the simplified engineering model is to be provided to engineering society.

5 ACKNOLEDGEMENT

The article was elaborated with the financial support of TA03010680, FAST-S-13-2077 and GAČR P104/11/0703.

REFERENCES

[1] M. Bajer, J. Barnat, *The Glue-Concrete Interface of Bonded Anchors,* In Construction and building materials, (2012), 34(9). p. 267 - 274. ISSN 0950-0618.

[2] Z. Kala, J. KALA, *Sensitivity Analysis of Stability Problems of Steel Columns using Shell Finite Elements and Nonlinear Computation Methods*, In Proc. of the 17th Int. Conf. Engineering mechanics 2011, Svratka, Czech Republic (2011), pp.271-274, ISBN 978-80-87012-33-8.

[3] *ČSN EN 1993-1-8 Eurokód 3: Navrhování ocelových konstrukcí - Část 1-8: Navrhování styčníků*, Český normalizační institut, Prague, Czech Republic (2006).

[4] ČSN *EN 1992-1-1 Eurokód 2: Navrhování betonových konstrukcí - Část 1-1: Obecná pravidla a pravidla pro pozemní stavby*, Český normalizační institut, Prague, Czech Republic (2006).

[5] F. Wald, *Column Bases*, Ediční středisko ČVUT, Prague, Czech Republic (1995).

[6] Europian Organization for Technical Approvals, *ETAG 001 Guideline for European Technical Approval of Metal Anchors for Use in Concrete*, EOTA, Brussels, Belgium (2001).

[7] V. Červenka, L. Jendele, *ATENA program documentation - Part 1 - Theory,* Červenka Consulting, s.r.o., Prague, Czech Republic (2013).