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UTICAJ PODLIVKE NA PONAŠANJE SMIČUĆE VEZE SA ANKERIMA

Summary:

Montažna gradnja i zahtevi za ponovnom upotrebom pojedinih elemenata konstrukcije podrazumevaju primenu oslonačkih veza ostvarenih ankerima. Pored demontažnog karaktera, veza sa ankerima mora da zadovolji i sve proračunom usvojene granične uslove po pomeranjima. U radu je opisano ponašenje smičuće veze ostvarene ankerima. Analizirana je deformabilnost veze u zavisnosti od kvaliteta i debljine podlivke. U programskom paketu Abaqus sprovedena je parametrska analiza sa ciljem da se definiše zavisnost između debljine i mehaničkih svojstava podlivke i deformacije klizanja spoja za nivo opterećenja koji odgovara graničnim stanjima upotrebljivosti.

Ključne reči: ankeri, smičući spoj, podlivka, deformacija klizanja

GROUT EFFECT ON THE BEHAVIOUR OF THE ANCHOR SHEAR CONNECTION

Summary:

Prefabricated construction and requirements for reusing the particular structural element, request the application of a support joint realized with anchors. Besides demountability, the connection detail realized with anchors needs to satisfy all support conditions adopted during the structure design. This paper describes the behaviour of anchor shear connection. The connection slip was analysed concerning the grout material properties and the grout thickness. The parametric study was performed using Abaqus software to define the relationship between grout properties and thickness and the slip deformation for load levels corresponding to serviceability limit states.

Key words: anchor, shear connection, grout, slip

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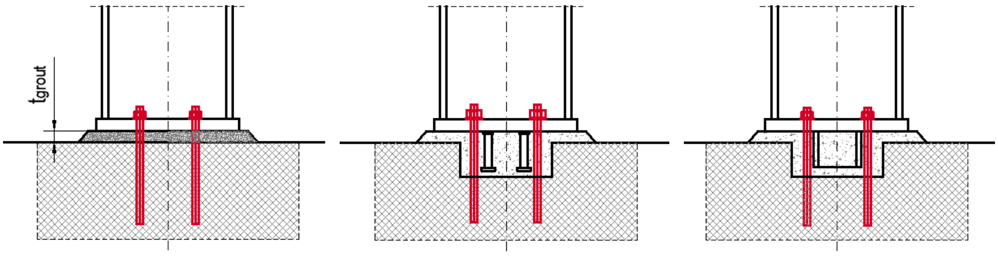
1. INTRODUCTION

The structural design of connection details for a steel structure with a reinforced concrete supporting structure must meet the boundary conditions adopted in the numerical calculation at the position of the supports. The connection must satisfy adopted criteria for load-bearing capacity and deformability. The anchors which are positioned between the steel structure and the reinforced concrete foundations can be cast-in-place or post-installed. For the shear force transfer in the base plate of steel column bases, the common practice, that can be met in structural design, comprise an additional element. This additional element is a shear key which is often constructed as group of elastic headed studs or as a rigid block element, as presented in Figure 1b and 1c. Without a shear key, the shear force transfer can be obtained by anchors or/and by friction in the contact surface. This type of column base is presented in Figure 1a.



a) anchors *b) headed studs* *c) shear key*

Figure 1 - Characteristic column bases detailing

Shear resistance verification of the connection between steel column and concrete foundations is defined in two parts of the Eurocode standards: SRPS EN 1993-1-8 [1] and SRPS EN 1992-4 [2]. The aforementioned parts of Eurocode present distinct design concepts: the "steel concept" vs. the "concrete/fastener concept". SRPS EN 1993-1-8 limits the application of anchors with strength classes up to 8.8, including this strength class. The calculation procedure is based on the research conducted by Gresnigt et al. [3] and it covers the application of cast-in-place long anchors. However, the concept of calculating the load capacity of column base plate connection with anchors, presented in SRPS EN 1992-4, defines the area of application in more detail, but also permits the usage of all anchors strength class, including strength class 10.9. Also, design procedure in SRPS EN 1992-4 allows application of cast-in-place and post-installed anchors. The standard SRPS EN 1992-4 defines the shear capacity of anchors by applying the CEB model which is also presented in the Technical Specification and Guideline for European technical approval of metal anchors for use in concrete preceding Eurocode 2 part 4.

Some of the most important differences between the two design concepts are:

- plastic design in SRPS EN 1993-1-8 [1] vs. elastic design in SRPS EN 1992-4 [2],
- equilibrium condition and flexible base plate in SRPS EN 1993-1-8 vs. compatibility conditions and rigid base plate in SRPS EN 1992-4.

Many authors agree that in future editions of Eurocode standards for structural design, harmonization of these two different design concepts is required. In anticipation of new editions of Eurocodes, some open issues should be highlighted:

- Column bases realized with the cast-in-place anchors, implies the common practice that provides larger holes in the base plate for the accuracy of construction and welding of the thick washers after fitting of geometry. The transfer of horizontal force between the column and the anchor is performed via the additional washer. This case is not included in the current edition of Eurocode.
- Eurocode does not contain any information about bond strength and anchoring conditions for threaded rods, which are extensively used in engineering practice for cast-in anchors.
- Anchor material limitation f_y<300 MPa for anchors with a hook [1] is not completely clear.
- Serviceability limit states are not covered in detail by the actual part of Eurocode.

1.1. SHEAR RESISTANCE OF CAST-IN-PLACE ANCHORS

In this paper, analysis of column base with small compression force or with total exception of compression force is presented. Connections to the foundations of engineering structures, such as lattice antenna towers, usually need to be designed through interaction of shear and axial tension forces. This design situation of column base, with shear force or interaction of shear force and axial tension force, is also relevant for columns which are part of the steel building bracing systems, such as ground-floor buildings.

Transfer of shear force in column base could be realized with one of the following models:

- friction resistance of the base plate, in contact with a concrete supporting structure,
- shear resistance of the anchors,
- bending moment resistance of the anchors.

Friction resistance of the base plate in contact with a concrete foundation can be included in the calculation of shear resistance in cases where a pressure force is obtained in the support. The friction coefficient depends on the properties of the grout material, so SRPS EN 1993-1-8 [1] prescribes a value of the coefficient of friction of 0.2 for grouts based on sand-cement mortars. For other types of grout materials, it is necessary to determine the friction coefficient based on the technical specifications of the material. In the working document of the new edition of Eurocode 3 part 1-8 (prEN 1993-1-8:2020) [4], the 0.3 friction coefficient is prescribed. Friction in the calculation procedures defined by SRPS EN 1992-4 [2] for shear resistance calculation is not used. Additionally, recent discussions analyse models of shear force transfer by friction in a joint resulting from a bending moment that can occur in the support structures such as column bases.

Shear resistance of anchor is function of anchor diameter and material properties. Table 1 presents the expressions for determination the shear resistance of anchors. EN 1992-4 [2] defines two values of shear load capacity when the joint is constructed with grout (with lever arm) and when the anchor plate is directly supported on concrete without grout layer (without lever arm). The area of application of expression defined in EN 1993-1-8 [1] is for anchor classes lower than or equal to 8.8, while the procedure defined in the EN 1992-4 [3] can be used also for anchors with 10.9 strength class. With certain limitations, the expression provided in the standard EN 1992-4 [3] for the bearing capacity of anchor without grout can also be used for determination of the shear resistance of anchors with a grout having thickness t_{grout} < min (40 mm, 4d). Certain limitations are:

- the anchors are not stressed by the bending moment or axial tensile force,

- the connection needs to be realized with more than one anchor in line in the shear force direction.

Table 1 - Anchor shear resistance

SRPS EN 1993-1-8 [1]	$F_{2,\mathrm{vb,Rd}} = \dfrac{\alpha_{\mathrm{bc}} \cdot f_{\mathrm{ub}} \cdot A_{\mathrm{s}}}{\gamma_{\mathrm{M2}}}$ with $\alpha_{\mathrm{bc}} = 0,44 - 0,0003 f_{\mathrm{yb}}$
SRPS EN 1992-4 [2] $t_{\mathrm{grout}} < 0{,}5d$	$V_{\mathrm{Rk,s}} = (1 - 0,01 \cdot t_{\mathrm{grout}}) \cdot k_6 \cdot k_7 \cdot A_{\mathrm{s}} \cdot f_{\mathrm{uk}}$
SRPS EN 1992-4 [2] with grout $t_{\mathrm{grout}} > 0{,}5d$	$V_{\mathrm{Rk,s,M}} = \dfrac{\alpha_{\mathrm{M}}}{l_{\mathrm{a}}} \mathrm{M}_{\mathrm{Rk,s}}$
f_{yb} yield strength of the anchor bolt	
f_{ub} ultimate tensile strength of the anchor bolt	
f_{uk} characteristic steel ultimate tensile strength	
f_{yk} characteristic steel yield strength	
A_{s} stressed cross section of anchor	
W_{el} elastic section modulus calculated from the stressed cross section	
t_{grout} thickness of grout layer	
l_{a} effective lever arm	
$k_7 = 1,0$ or 0,8	
$k_6 = 0,5$ for $f_{\mathrm{uk}} \leq 500$ MPa; $k_6 = 0{,}6$ for 500 MPa < $f_{\mathrm{uk}} \leq 1000$ MPa	
* Characteristic bending resistance of the single anchor can be calculated according: $\mathrm{M}_{\mathrm{Rk,s}} = 1,2 \cdot W_{\mathrm{el}} \cdot f_{\mathrm{uk}}$ ili $\mathrm{M}_{\mathrm{Rk,s}} = 1,5 \cdot W_{\mathrm{el}} \cdot f_{\mathrm{yk}}$	
** Value for coefficient k_6 is not harmonized with value of coefficient α_{v} in SRPS EN 1993-1-8 [1]	

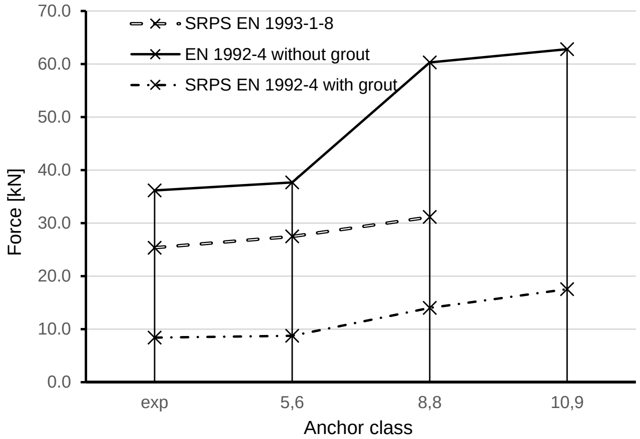


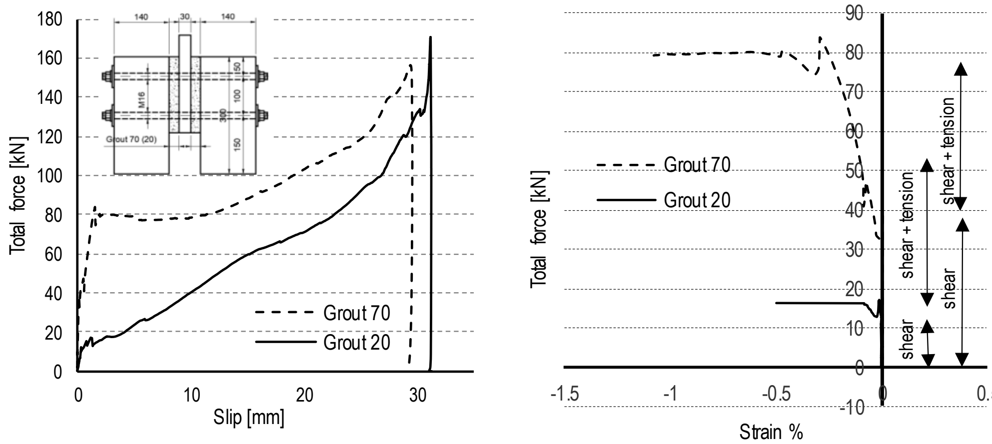
Figure 2 - Shear resistance of the single anchor for different strength classes

Figure 2 shows a comparative analysis of shear resistance for 16 mm anchors diameter, with different strength classes, using expressions presented in Table 1. Considerable differences in the calculated values of anchor shear resistance according to the above expressions are observed. To investigate the influence of the grout on the behaviour of the anchors in shear connection, a pilot experimental test and advanced numerical simulation are made.

The FE analyses of column base were performed, using the software package ABAQUS 6.14 [5], in order to analyse the behaviour of the shear connection. The values of the deformation for service loads are not defined in standards. Deformations of the joint can be significant in the case with a greater thickness of the grout layer.

2. EXPERIMENTAL RESEARCH

The bearing capacity of the column base realized with two anchors with a 16 mm diameter made of threaded rods was determined experimentally. The post-installed anchors were made without tightening after grouting. A push-out test of samples formed with two reinforced concrete slabs, 30 mm thick anchor plate, two anchors and 25.0 mm thick grout was performed. Specimen layout is presented in Figure 3. The strength of the grout was varied. Specimens with the grout characteristic compressive strength of 20 MPa and 70 MPa were examined. A cement-based material with reduced shrinkage values, non-shrinking mortar, was used for the grout. The strength of the used grout according to the Technical Specifications of the Manufacturer (SIKA) is f_{ck} >70 MPa seven days after casting. The first sample was tested after seven days when the grout reached the expected strength. The second sample was tested after 28 hours when the grout reached the strength f_{ck} > 20 MPa. Determination of mechanical properties of the grout was performed through examination of standard prisms. Prisms were tested for bending and pressure. The standard coupon tensile tests of anchors were performed to determine material properties of the anchor steel. The obtained values of yield strength and ultimate tensile strength correspond to the anchor with strength class 5.6.



a) slip - total force of specimens *b) anchor strains – total force*

Figure 3 - Experimental results for two grout strengths

During the examination, the values of the applied force and slip deformation of the specimen were collected using HBM acquisition system. The obtained values of the specimen ultimate shear capacity P_u are the same regardless of the characteristic strength of the grout material, as shown in Figure 3a. The axial tensile force in the anchor was monitored by placing strain gauges on the anchors. According to the strain measurements, the loading step when the tensile force occurs in the anchors was defined, see Figure 3b. The measured values of total slip and the value of shear force, which correspond to the axial tensile force that occurs in the anchor, indicate considerable differences in the behaviour of joints made with grouts of different compressive strengths. The specimen ultimate shear capacity P_u is the same despite of the grout strength which is the result of the interaction of the shear and tensile force in anchors. Using a lower grout strength, the onset of significant deformations occurs at strength forces of 0.10-0.15P_u compared to a specimen made with a higher grout strength where considerable connection deformation occurs at the shear force corresponding to the 0.3P_u.

The experimental results are compared with the characteristic loads obtained according to the design procedures described in Table 1. The best prediction of the results is given by the procedure defined in SRPS EN 1993-1-8 [1]. SRPS EN 1992-4 [2] gives underestimated or even overestimated strength values depending on whether a model with no grout/small thickness grout is used t_{grout}<0,5d or a model with grout. Result recapitulation is presented in Table 2.

Table 2 - Experimental vs calculated results per one anchor

Grout	EXP_{SLS} P_u [kN]	EXP_{ULS} P_u [kN]	EN 1993-1-8 [1] P_{Rk} [kN]	EXP_{SLS} / P_{Rk} [-]	EXP_{ULS} /P_{Rk} [-]
20 MPa	4.50	42.0	25.4	0.17	1.65
70 MPa	20.7	37.5	25.4	0.82	1.47
Grout	EXP_{SLS} P_u [kN]	EXP_{SLS} P_u [kN]	EN 1992-4 [3] P_{Rk} [kN] t_{grout}=0	EXP_{SLS} / P_{Rk} [-]	EXP_{ULS} /P_{Rk} [-]
20 MPa	4.50	42.0	36.2	0.12	1.16
70 MPa	20.7	37.5	36.2	0.57	1.03
Grout	EXP_{SLS} P_u [kN]	EXP_{SLS} P_u [kN]	EN 1992-4 [3] P_{Rk} [kN] $t_{grout}\neq0$	EXP_{SLS} / P_{Rk} [-]	EXP_{ULS} /P_{Rk} [-]
20 MPa	4.50	42.0	8.4	0.38	5.00
70 MPa	20.7	37.5	8.4	2.46	4.46

3. PARAMETRIC STUDY

In order to analyse the behaviour of anchors in shear connections, a FE model was realized. The ABAQUS 6.14 [5] software package was used. The model defines column base and the connection of the column with the concrete foundation. Parameters of analysis are the compressive strength of grout, grout thickness, and number of anchors in the joint. The anchor used in the experiment and numerical analysis is an anchor of strength class 5.6. The anchor material model is based on the stress-strain results obtained in the coupon test. The procedure described by Pavlović et al. [7] was used to define the damage parameter for the anchor material. A concrete damage plasticity model was used for the grout material. For the nonlinear behaviour of the grout, a nonlinear diagram of stress dilatations for concrete was used, applying the appropriate model matching the grout strength. For the part of the diagram up to the value of dilatation ε_{cu}, a nonlinear diagram defined by SRPS EN 1992-1-1 [6] was used. The descending part of the diagram for values of dilatation higher than ε_{cu} was defined following Pavlović et al. [8]. The connection behaviour is also influenced by the tensile strength of the grout as well as the onset and propagation of cracks in the grout. The nonlinear behaviour of concrete is described by a stress-displacement curve. The displacement at which a crack occurs in concrete was determined according to the recommendations given in the FIB Model Code 2010 [8].

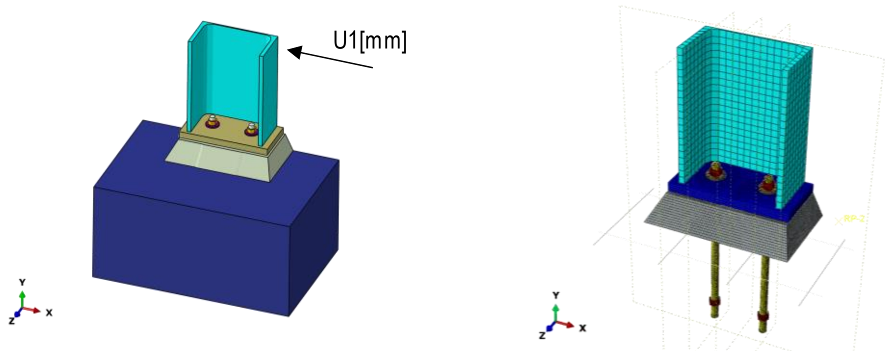
Fracture energy of concrete *GF* [N/m] is defined as the energy required to propagate a tensile crack, as presented in Eq. 1. Fracture energy is equal to the area below the descending part of the stress-displacement curve and presented with Eq. 2. The displacement corresponding to the onset of a crack in the grout was determined based on default recommendations given in Abaqus [5], and given with Eq. 3. Concrete tension damage parameter is defined according to Birtel and Mark [9]. The descending part of the stress-displacement curve which was used in the material model of the grout was defined by Hordijk [10] as given with Eq. 4.

$$GF = 78 \cdot f_{cm}^{0,18} \tag{1}$$

$$GF = \int_0^{w_c} \sigma_c(w) \cdot dw \tag{2}$$

$$w_c = 2 \cdot GF / f_{ct} \tag{3}$$

$$\sigma_t(w) = f_{ct} \cdot \left\{ \left[1 + \left(c_1 \cdot w / w_c \right)^3 \right] \cdot e^{-c_2 \cdot \frac{w}{w_c}} - \frac{w}{w_c} \cdot \left(1 + c_1^3 \right) \cdot e^{-c_2} \right\} \quad c_1 = 3,0 \quad c_2 = 6,93 \tag{4}$$



a) specimen layout *b) FE mesh*

Figure 4 - FE model

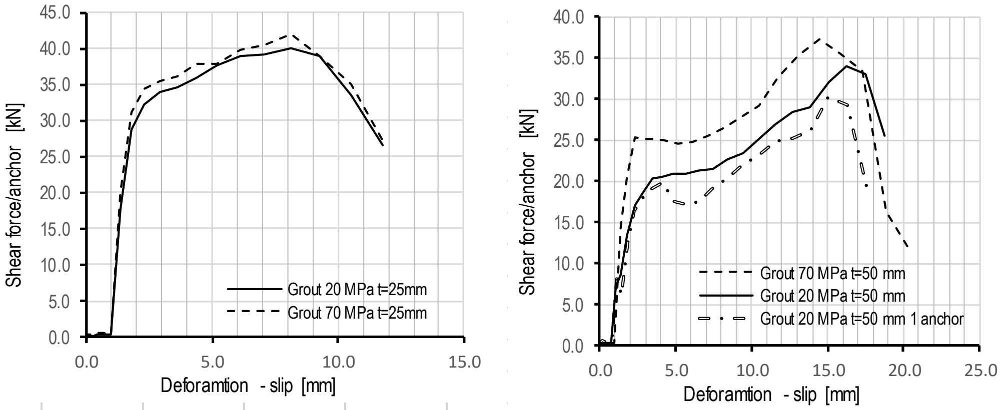
FE model of the column base developed in Abaqus software [5] is presented in Figure 4. In FE modelling of the column base, tie constrain was applied as contact between nuts and anchors and embedded region contact for reinforcement in the concrete foundation. For all other contacts in FE model General contact with normal-hard contact and tangent behaviour was adopted. The applied value of the friction coefficient in the whole FE model is 0.3.

The parametric analysis included the thickness of the grout and the compressive strength of the grout, as well as the number of anchors in the connection. The analysis of the characteristic detail of the pillar support was conducted. The hot-rolled profile HEA 240 was adopted for the cross-section of the column. Table 3 gives an overview of the analysed parameters and obtained results through parametric analysis. Presented results are ultimate shear resistance per one anchor P_u and slip corresponding to the ultimate shear resistance δ.

Table 3 - Analysed parameters and results of parametric study

Model	Grout material	Grout thickness	Number of anchors	P_u [kN]	δ[mm]
G20T25	C20/25	25 mm	2 in row	40.1	8.2
G70T25	C70/85	25 mm	2 in row	41.9	8.5
G20T50	C20/25	50 mm	2 in row	34.0	16.3
G70T50	C70/85	50 mm	2 in row	37.3	14.5
G20T50 1 anchor	C20/25	50 mm	1 in row	30.2	15.1

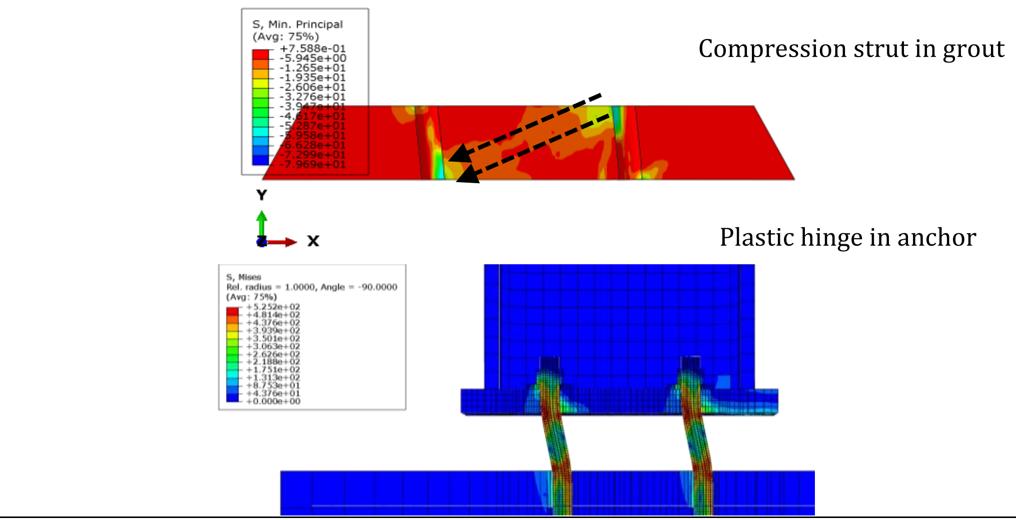
Analysing the presented results, it can be concluded that parameter of significance for shear resistance of anchors is grout thickness. When the grout thickness exceeds the value of anchor diameter, it is necessary to account the shear resistance of anchors with lever arm with the appropriate design procedure.



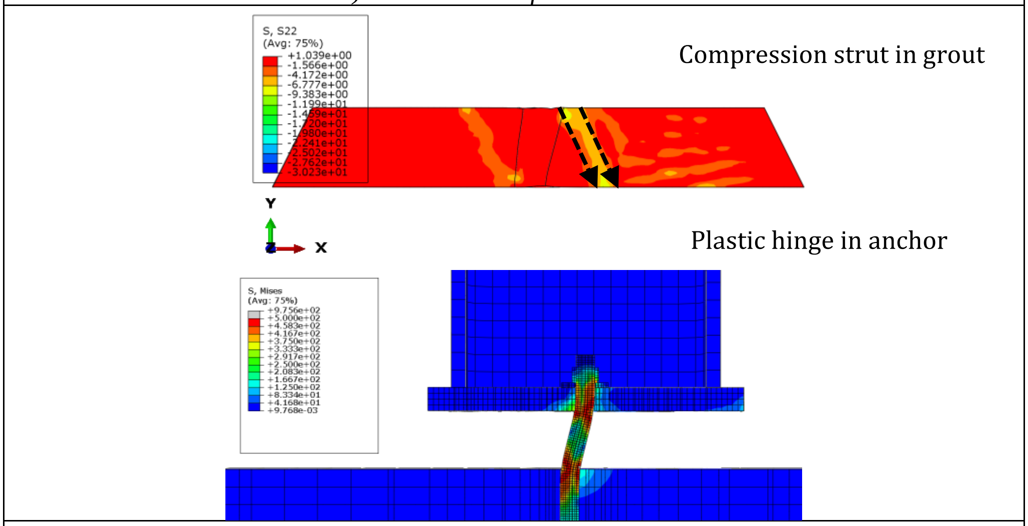
a) influence of grout strength *a) influence of grout strength and thickness*

Figure 5 - Force – displacement curves per one anchor

The grout material properties have a negligible influence on shear resistance for connections with grout thickness up to the anchors diameter, as presented in Figure 5a. Differences in shear resistance are within the limit of 3%. For larger grout thicknesses, the lower value of the characteristic compressive strength of grout material could reduce shear resistance for more than 15 %. Nevertheless, the considered pars of Eurocode do not consider the positive influence of grout, enhancing the shear strength of the connection. SRPS EN 1992-4 [2] considers the effect of the bending length of the anchor by calculating the moment capacity of the anchor (threaded rod). The number of anchors in the row in the force direction has an impact on the resistance of the connection, as shown in Figure 5b. According to Figure 6, the compression strut in grout is formed for the level of shear force up to the grout crack initiation load value. For the higher value of shear force, the crack propagation in grout and the large increment of joint deformation is observed on the slip-force curves presented in Figure 5b, for various grout strengths and grout thickness of 50 mm.



a) Two anchor in force direction



b) One anchor in force direction

Figure 6 - Compression strut in grout material

Existing concepts in various standards of Eurocodes for structures give a well prediction of the column base joint shear resistance. Nevertheless, the shear limits which corresponding to the serviceability load level is not defined. The latest experimental research performed by Shaheen et al. [11] deals with the serviceability limit state of column base joint realized by grout thickness up to 80 mm. Further research and a new revision of Eurocodes need to give answers on the slip values corresponding to serviceability shear resistance, which is of particular interest for common engineering practice.

4. CONCLUSION

The determination of the anchor shear resistance should be done according to both parts of Eurocode SRPS EN 1993-1-8 and SRPS EN 1992-4. It is necessary to analyse and choose the right approach which is appropriate for every single connection. Depending on the type of construction and internal forces that occur at the position of the analysed connection, the calculation model should be selected. Based on performed analysis and results presented in this paper, it is clear that the behaviour of anchors in shear connections depend on the properties and thickness of the grout. Friction as a model for shear resistance should be included in the connection resistance calculation. Friction as a shear load transfer model guarantees the minimal slip values of the connection. The deformations of the connection realized with anchors, which correspond to the anchors shear resistance, are not defined in the current editions of Eurocodes. There are significant differences, with more than 50%, in the anchors shear resistance depending on the used calculation model. In the case of connections without axial compression force or with axial tensile force, the additional analyses should be done in order to consider the slip in the connection.

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