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“EXECUTION AND RELIABILITY OF SLIP RESISTANT CONNECTIONS FOR
STEEL STRUCTURES USING CS AND SS (SIROCO)”

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Execution and Reliability of Slip Resistant Connections for
Steel Structures Using CS and SS (SIROCO)
WP5 Preloading of Stainless Steel Bolts.

Task 5.1 Material Data on the Strength and Relaxation Behavior of Stainless Steel Plates.

Estimation of Load Level for the Short Term Dead Weight Creep Tests on 1.4404 plates

Abstract

In the work package 5, short term creep tests will be carried out at six different loading levels in order to generate data on the room temperature creep and stress relaxation behavior of stainless steel plates. The technical annex determines that the lowest stress level will be 30% of the yield strength of the plate material. The other five loading levels need to be determined based on the stress level in the plates after the bolts have been preloaded. In the present work, finite element simulations have been carried out in order to estimate to stress level in the plate caused by bolt preloading. The purpose of the simulations was to obtain a rough estimate for the stress level in the plate due to bolt preloading. The results show that small plastic deformations may occur throughout the plate thickness under the bolt head when the bolt preloading. In the worst case scenarios studied, peak value of the Von Mises equivalent stress in the plate was between 10% and 16% higher than the 0.2% proof strength of the material. The peak value was typically concentrated in one element in the mesh. Outside the local stress concentration, the Von Mises equivalent stress values were typically below the 0.2% proof strength of the plate materials.

Based on the results in the present work, it is proposed that in the short term creep tests, the first five stress levels are evenly distributed between $0.3 \times R_{p0,2}$ and $1,0 \times R_{p0,2}$ and last sixth value equals to $1.2 \times R_{p0,2}$. The same values can be used and will be conservative also for the other grades studies in the work package 5.

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1. INTRODUCTION

In the work package 5, short term creep tests will be carried out at six different loading levels in order to generate data on the room temperature creep and stress relaxation behaviour of stainless steel plates. The technical annex determines that the lowest stress level will be 30% of the yield strength of the plate material. The other five loading levels need to be determined based on the stress level in the plates after the bolts have been preloaded.

Originally, it was thought that the loading in the plates caused by bolt preloading could be estimated by the VDI guideline VDI 2230 for systematic calculation of high duty bolted joints. Table A9 in the VDI guideline gives upper limit values for the surface contact pressure under the bolt nut for different materials. A closer inspection of the limiting surface pressure values, however, revealed that the limiting surface pressure values given in the table cannot be used for determining the stress levels for the short term creep tests. The reason is that the limiting surface pressure values given in guideline are very high, sometimes higher than the tensile strength of the material. For example, in the case of austenitic stainless steel X5CrNi 18 12, the limiting surface pressure value given by the guideline is 630 MPa. This value is almost 25% higher than the tensile strength of the steel by the same source. Therefore it is clear that the surface pressure values given in the VDI 2230 cannot be used for determining the loading levels for the short term creep tests.

In the present work, finite element simulations are carried out in order to estimate to stress level in the plate caused by bolt preloading. The purpose of the simulations was to obtain a rough estimate for the stress level in the plate due to bolt preloading. The purpose is to find a conservative estimate for the stresses and strains in the plate after the bolt preloading.

2. MODELLING APPROACH

The case studied contains one M16 bolt pre-loaded through two 8 mm plates as shown in the Figure 1. The FE-model is axisymmetric and contains only the section highlighted in the figure.

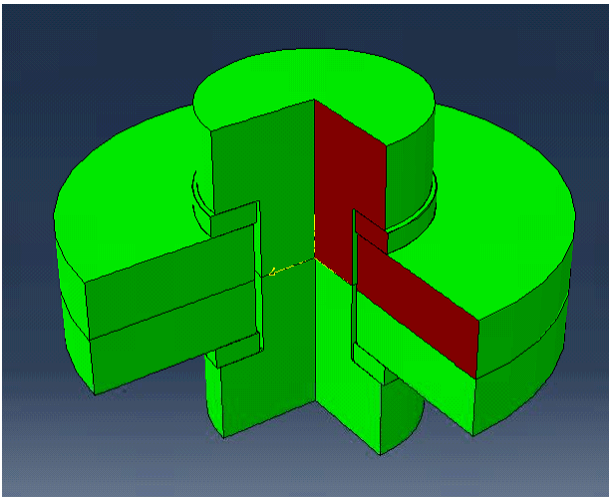


Figure 1. Schematic illustration of the example case studied. Due to symmetry of the problem, only the highlighted section is included in the numerical model.

The example case consists of a class 8.8 or class 10.9 M16 bolt joining two 8 mm grade 1.4404 plates together. Due to symmetry of the problem only one plate is included in the analysis. The preload is applied as a gradually increasing surface tension in the end of the bolt shaft. The amount of preload corresponds to 80% of the yield strength of the bolt material.

A flat or chamfered washer is used under the bolt head and a flat bolt nut when required by the norm EN 1090-2:2008. Four different cases were examined in order to find the worst case scenario corresponding to maximum loading in the plate:

- Class 8.8 bolt head without washer (nut is rotated).
- Class 10.9 bolt head with chamfered hardened (HV300) washer.
- Class 10.9 bolt nut with flat hardened (HV300) washer.

BOLT

The M16 bolt was modelled as an elastic body. The elastic properties were $E=150 \text{ GPa}$ and $\nu = 0.35$. These values correspond to typical measured values for hardened bolts. The dimensions of the bolt are

- Nut radius: 28.8 mm
- Bolt diameter: 16.0 mm
- Nut thickness: 11.2 mm
- Corner rounding radius: 0.25 mm

WASHERS

The norm EN 1090-2:2008 “Execution of steel structures and aluminium structures - Part 2: Technical requirements for steel structures”, requires that washers are used under preloaded bolts as follows:

- For class 8.8 bolts, a chamfered washer shall be used under the bolt head or a flat washer under the nut, whichever is to be rotated.
- For class 10.9 bolts, a chamfered washer shall be used under the bolt head and a flat washer under the nut.

Consequently, three cases were examined in order to find the maximum stress level in the plate:

- a) Class 8.8 bolt head without washer (nut is rotated).
- b) Class 10.9 bolt head with chamfered hardened (HV300) washer.
- c) Class 10.9 bolt nut with flat hardened (HV300) washer.

The dimensions of the M16 washers used in the analyses are as follows:

- Inner diameter: $D_i = 17.0 \text{ mm}$.
- Outer diameter: $D_o = 30.0 \text{ mm}$.
- Thickness: $t = 4.0 \text{ mm}$.
- Inner chamfer: $\alpha = 45^\circ$, $h = 1.5 \text{ mm}$.
- Outer chamfer: $\alpha = 45^\circ$, $h = 1.9 \text{ mm}$.

An additional corner rounding 0.25 mm was added to improve the behaviour of the contact algorithm.

The washers were modelled as elastic-plastic bodies. The elastic properties of the washers were similar to those of the bolts, $E=150 \text{ GPa}$ and $\nu = 0.35$. Based on the Vickers hardness value it was estimated that the yield strength of the hardened HV300 washer is 700 MPa . Since measurement data on the work hardening behaviour of hardened washer material is not available, it was assumed that the material behaves like type 1.4404 austenitic stainless steel cold worked in uniaxial tension. The stress-strain curve used for the washer material together is shown in the Figure 2. The stress strain curve for 316L type austenitic stainless steel in annealed condition is shown for reference.

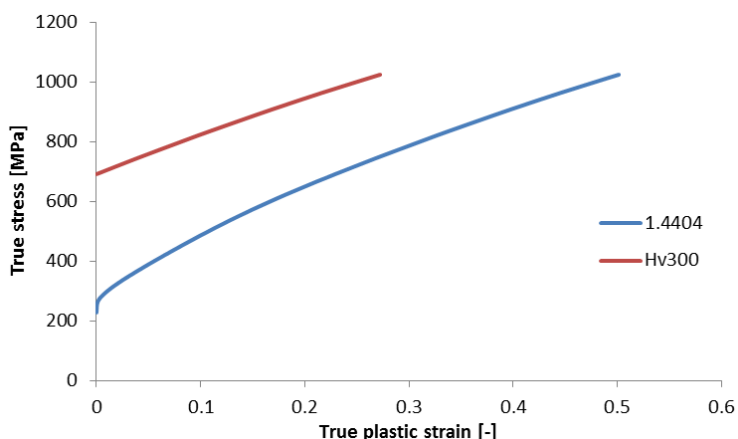


Figure 2. Stress-strain curve for the hardened washer material. The stress-strain curve for annealed 1.4404 is shown for reference.

PLATE

The 8 mm plate was modelled as an elastic-plastic body. The elastic properties of the plate were $E = 200 \text{ GPa}$ and $\nu = 0.35$. The work hardening behaviour of the plate material was determined based on typical properties of 1.4404 produced by the Outokumpu Tornio Works. The stress-strain curve of the plate material is shown in the Figure 2.

The diameter of the bolt hole is $D=18.0 \text{ mm}$. The edges of the bolt hole have a rounding with the radius of 0.25 mm .

COEFFICIENT OF FRICTION

According to the values given in the guideline VDI 2230, table A5, the coefficient of friction between the bolt, washer and plate surfaces might obtain values in the range $\mu = (0.08, 0.35)$ depending on the surface quality and lubricant used. Different values in the given range were used in to determine the worst case scenario. It was found that low friction yields high stress in the plate. Consequently, the value $\mu = 0.10$ was used in the analyses.

BOLT PRELOADING

The preloading was applied as a gradually increasing surface load in the end of the bolt shaft. The amount of preload corresponds to 80% of the yield strength of the bolt material. Two different values were used:

1. For class 8.8. bolts, the preload was $p = 512 \text{ MPa}$.
2. For class 10.9 bolts, the preload was $p = 720 \text{ MPa}$.

FINITE ELEMENT MODELLING

The example problem was simulated using Abaqus version 6.12-3 as a materially and geometrically nonlinear problem. The element type used was CAX4R. The mesh was graded and constructed using the advancing front meshing tool. The edge length of the smallest elements in the mesh was 0.1 mm and that of the largest elements was 1.0 mm . The total number of elements was approximately 5000 and the number of degrees of freedom approximately 11000. Default settings were used with the penalty contact algorithm.

3. RESULTS

The results show that small plastic deformations occur in throughout the plate thickness when the bolt is preloaded. The equivalent plastic strain distribution under class 10.9 bolt nut is shown in the Figure 3. It can be seen that small permanent deformations extend throughout the plate thickness under the whole washer area. The outer perimeter of the washer is marked with an arrow in the figure. The maximum plastic strain equals to 1.6% in this case.

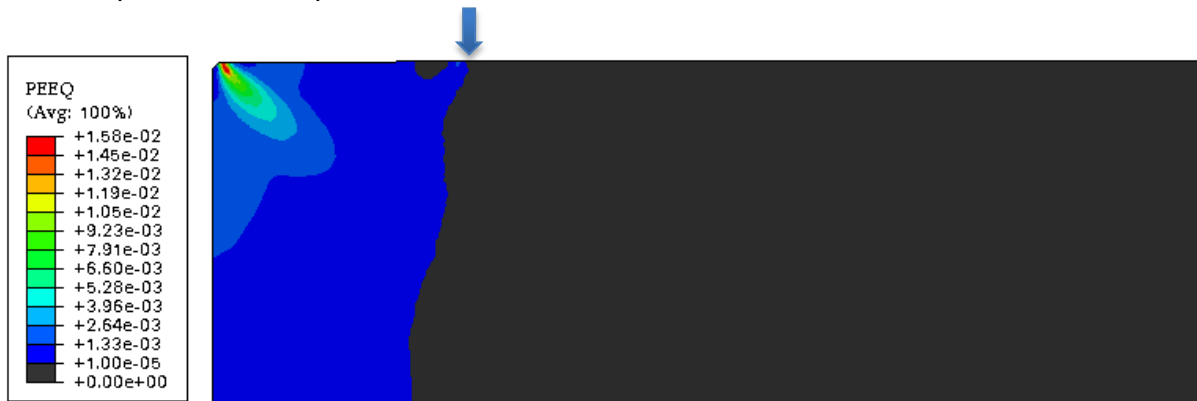


Figure 3. Small plastic strains occur under the whole washer diameter and throughout the plate thickness. The washer outer diameter is marked with an arrow.

The Von Mises equivalent stress in the plate under the class 10.9 nut is shown in the Figure 4. The proof stress value corresponding to the 0.2% plastic strain equals to $R_{p0,2} = 270 \text{ MPa}$.

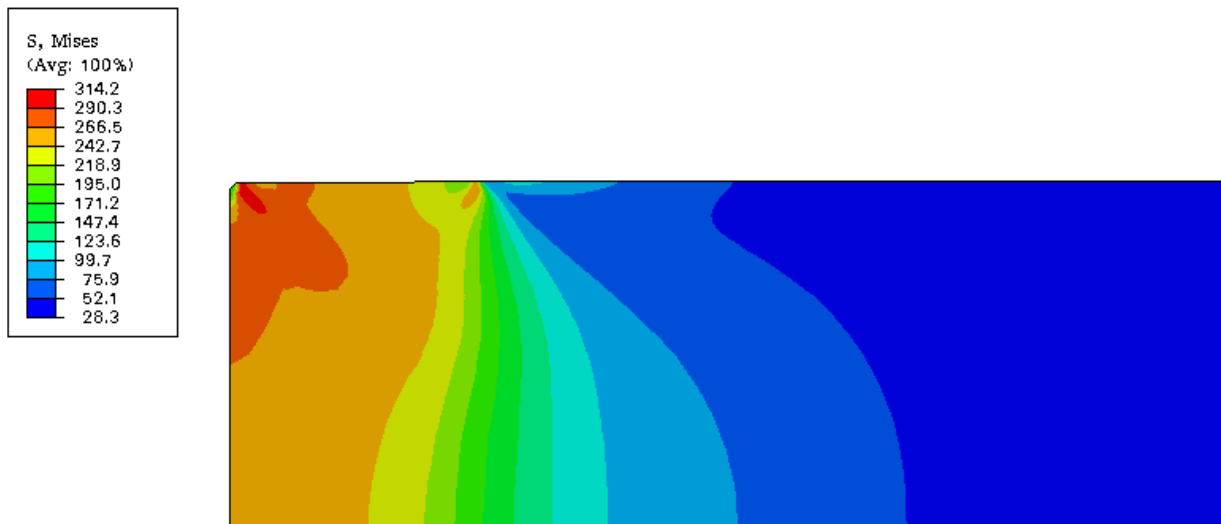


Figure 4. The Von Mises equivalent stress in the plate.

The results for the three investigated cases are summarized in the Table 1. The tensile test results for the plate material are given for reference in the Table 2 for comparison purposes. It is worth noting that the peak values of maximum equivalent plastic strain and maximum equivalent stress given in the Table 1 were typically obtained in only one element as illustrated in the Figure 5.

Table 1. Summary of results for the three studied cases.

Case	Max. eq. plastic strain	Max. Von Mises stress	Max. Von Mises / Rp0,2
8.8 bolt head	1.4%	303 MPa	1.12
10.9 bolt head	0.9%	296 MPa	1.10
10.9 bolt nut	1.6%	314 MPa	1.16

Table 2. Tensile test results for the 1.4404 plate material.

Direction	Rp 0,01 (N/mm ²)	Rp 0,05 (N/mm ²)	Rp 0,1 (N/mm ²)	Rp 0,2 (N/mm ²)	Rp 1,0 (N/mm ²)	Rp 2,0 (N/mm ²)	Rm (N/mm ²)	Ag (%)	A80 (%)
RD	239	256	263	270	300	324	618	65	74

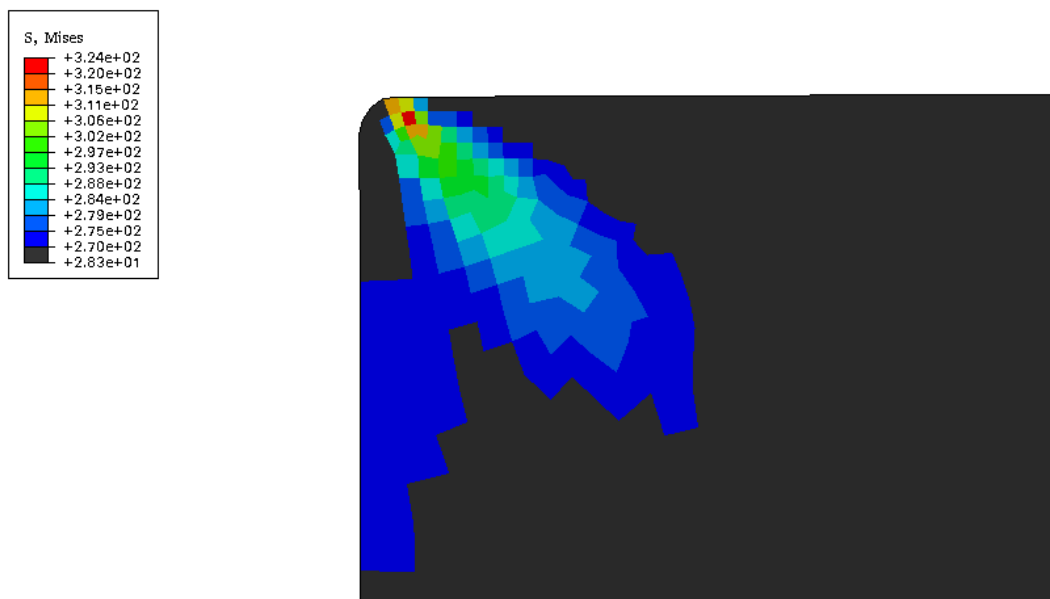


Figure 5. Detail of stress distribution in the plate under the 10.9 bolt nut. The peak stress is concentrated in a single element. The size of the element edge near the contact surface is 0.1 mm. The stress values are not averaged over nodal values like in the other figures.

4. DISCUSSION AND CONCLUSIONS

Small plastic deformations occur in throughout the plate thickness under the contact region between the plate and washer / bolt head. The peak value of the Von Mises equivalent stress in the plate was ranging from 1.10 to 1.16 times the 0.2% proof strength of the plate materials. The peak values were, however, highly localized and typically only found in one single element in the mesh. Outside the local stress concentration, the Von Mises stress in the plate was typically below the 0.2% proof strength of the plate material.

Based on the present results it is proposed that the stress levels given in the Table 3 are used for the short term creep tests of the grade 1.4404 plates. The first five stress values are evenly distributed between $0.30 \times R_{p0,2}$ and $1.0 \times R_{p0,2}$ and the last value is above the highest stress values in the finite element simulations carried out in the present work.

Table 3. Proposed stress levels for the short term creep tests on the grade 1.4404 plates.

Loading level number	Nominal Stress ($\times R_{p0,2}$)
1	0.300
2	0.475
3	0.650
4	0.825
5	1.000
6	1.200

The stress levels given in the Table 3 can be used and will be conservative also for the other plate material studied in the work package five. In the strain range below 2% of plastic strain, the grade 1.4404 is softer than the other grades 1.4003, 1.4462 and 1.4162. Since the bolt preload will be less than or equal to the values used in this study for the 1.4404, it follows that the plastic strains in the other plate materials will be smaller than those in the 1.4404.

ACKNOWLEDGEMENTS

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