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FINITE ELEMENT ANALYSIS OF A SINGLE LAP JOINT

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Abstract: A single shear lap joint of steel grade S355 is modelled with finite elements to investigate the influence of externally applied tensile loading on the loss of pretension in the engaged bolts. Additionally, a parameter study is performed to understand the effect of various steel grades on the loss of pretension. It is found that the slip resistance of the specimen depends on the steel grade of the clamped plates. Besides, the final resistance of the single shear lap joint has been found to increase after a slip of 0,15 mm has occurred due to a secondary bending moment. However, the final resistance of the specimen has been found to depend on the size of assembling tolerances; the bigger the distance between the clamped plates, the lower the resistance.

1 Introduction

A common problem in bolted connections is the self-loosening effect of bolts over time. Therefore, the remaining strength in a slip resistant connection can only roughly be estimated for a certain point of time. A possible solution to avoid self-loosening is the use of lockbolts, which have been studied in order to achieve recommendations for connections which are “free from maintenance” [1]. The pretension force in the bolt unavoidably reduces over time due to creep of primer, forces in bolts and in plates. To understand the influence of externally applied load on a connection and the effect of various steel grades, a single shear lap joint is modeled. Originally, a double shear lap joint had been both tested and modeled in [1]. This model has then been reduced to a single shear lap joint, as shown in this paper.

2 Description of finite element models

Fig. 1 shows a three dimensional finite element (FE) model including the meshed parts of a single shear lap joint. The model consists of three different parts: bolt, sleeve and plate. Plates and sleeves are modelled with realistic dimensions whereas the bolt’s head and nut are simplified as cylinders. It is based on the previously studied model of a symmetric friction connection [1]. Dimensions of plates and bolts can be found in Fig. 1.
Due to the fact that the middle bolt B2 is removed from the setup during the performance of the original test, it is not considered in this FE analysis, either.

The analysis has been performed in the following three sequential steps: First the bolts are pretensioned by applying a concentrated load, which is a self-equilibrating force carried across the pretension section in the shank, to the pretension node [2]. Then the bolts' length is fixed at their currents position, so that the force in the bolt changed according to the response of the model in the subsequent analysis. The last step contains the external load, which is applied to the model through a displacement at the end of the plates. During the first two steps all three translational degrees of freedom at both top and bottom of the specimen are restrained. When the pretension force in the bolts is reached, the degree of freedom in longitudinal direction of the plates at the bottom is released and a longitudinal displacement is applied to represent tensile load acting on the friction connection.

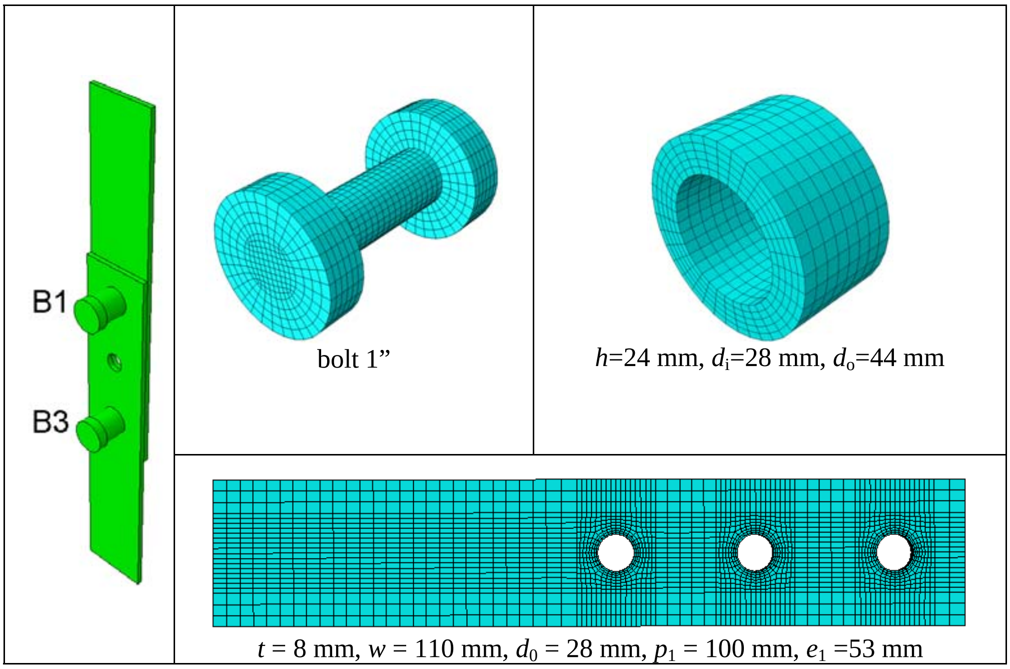

Fig. 1: Finite Element model of a single shear lap joint

For all different parts of the model the continuum element type C3D8R is used. This is an eight-node brick element with first order reduced integration. The reason for choosing a reduced integration element C3D8R is that it uses a lower order integration to form element stiffness and thus reduces the overall computation time especially in three dimensions. The shear locking phenomenon observed in C3D8 elements doesn't show, since it just has one integration point at the centroid. The downside to these elements, however, is that they are prone to hourglassing. These elements can therefore deform in such a manner that the strain, calculated at the integration point, is equal to zero, which further leads to uncontrolled distortion. C3D8R elements can still be used but with a reasonably fine mesh. At least four elements through the thickness are recommended. Hourglassing can normally be recognized in deformed shape plots or the Abaqus in-built hourglass control can be used. It has to be verified that the artificial energy used is small (<1 %) relative to the internal energy [2].

Fig. 2 shows an elastic-plastic relationship allowing for strain hardening to be used for structural steel (sleeves and plates), based on Swedish regulations for Steel Structures [3].
Tests in [1] have clearly verified that all bolts are just in the elastic range after the pretension is applied. Therefore, bolts' material is taken as elastic in all FE calculations with a Young's modulus of 210 GPa and Poisson's ratio as 0.3, respectively.

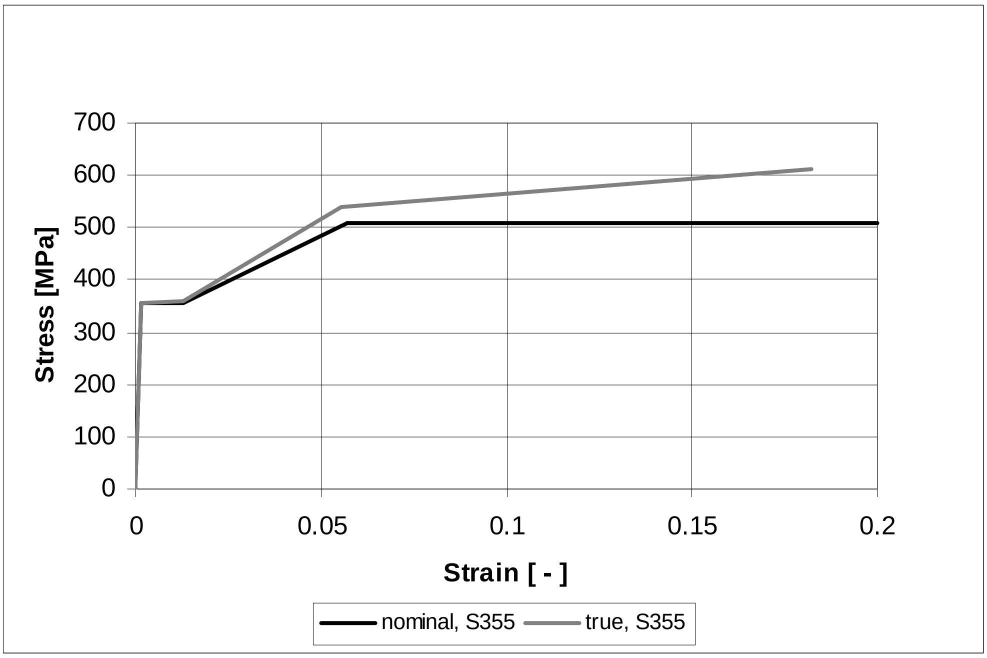

Fig. 2: Nominal and true stress – strain relationship of steel S355

All contact surfaces have been defined with a friction coefficient of 0,62 using the basic Coulomb friction model. A surface-to-surface formulation allowing for finite sliding has been used. For normal behaviour “Hard” contact is introduced, which means that contact pressure can be transmitted if surfaces are in contact, but also a separation of contact surfaces is allowed.
Finite Element models including contact problems are very sensitive to any applied load and may have problems to numerically converge at the beginning of a calculation. Convergence may be achieved by introducing a small load first before the actual load is applied.
For all interactions it is crucial to choose appropriate master and slave surfaces. Usually the master surface should be the surface of the stiffer body and/or should have a coarser mesh than the slave surface. If not followed the solution may become quite time consuming [2].

3 Results

The failure criterion is defined as 0,15 mm slip for all numerical calculations. Practical importance of this chapter is in understanding of the so called HISTWIN joint [4], a lap joint used in tubular towers.

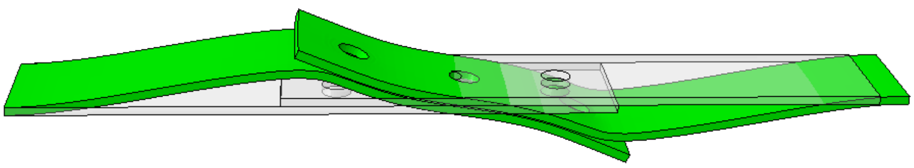

Fig. 3: Deformed shape of a single shear lap joint – scale factor 20

Fig. 3 shows the general deformed shape of a single shear lap joint. It is obvious that so called “secondary bending” occurs due the eccentricity, when loaded in tension.

3.1 Parametric study based on material properties of the plates

Due to Poisson effect the total thickness of the joined plates is decreasing in the area of the bolts while loading, as Fig. 4 and Fig. 5 visualize. While the total thickness of the connected plates decreases – positive values in Fig. 4 mean a decrease – the bolt loses pretension force at the same time. The reduction of plate thickness is measured at each hole as the relative change of the two outermost points on each plate. As simplification the rotation of the two plates, which occurs due to secondary bending, is neglected for determination of the reduction.

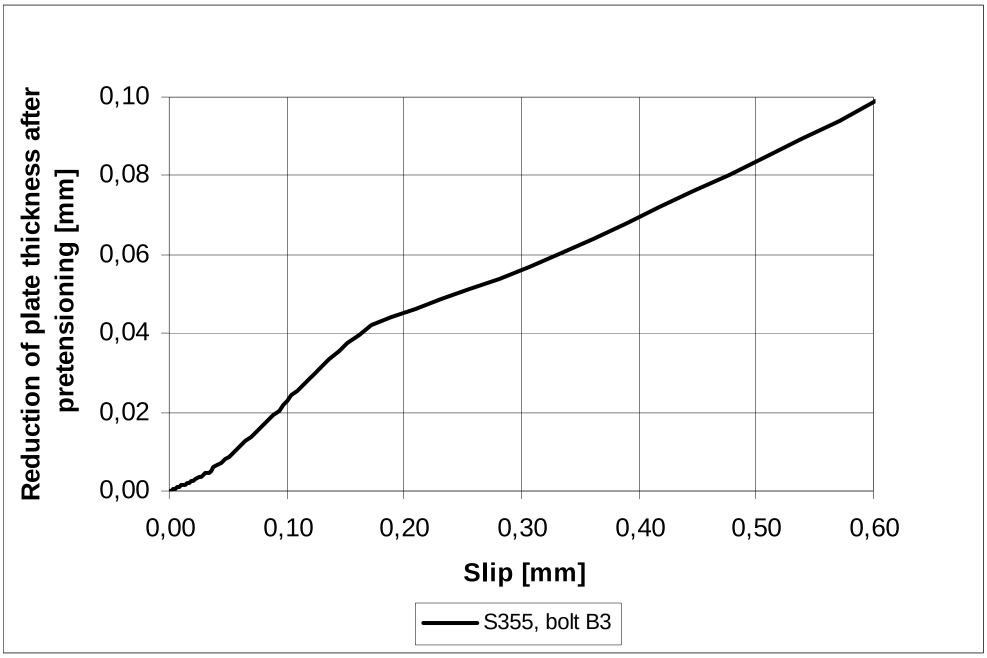

Fig. 4: Reduction of plate thickness during loading – bolt B3, S355

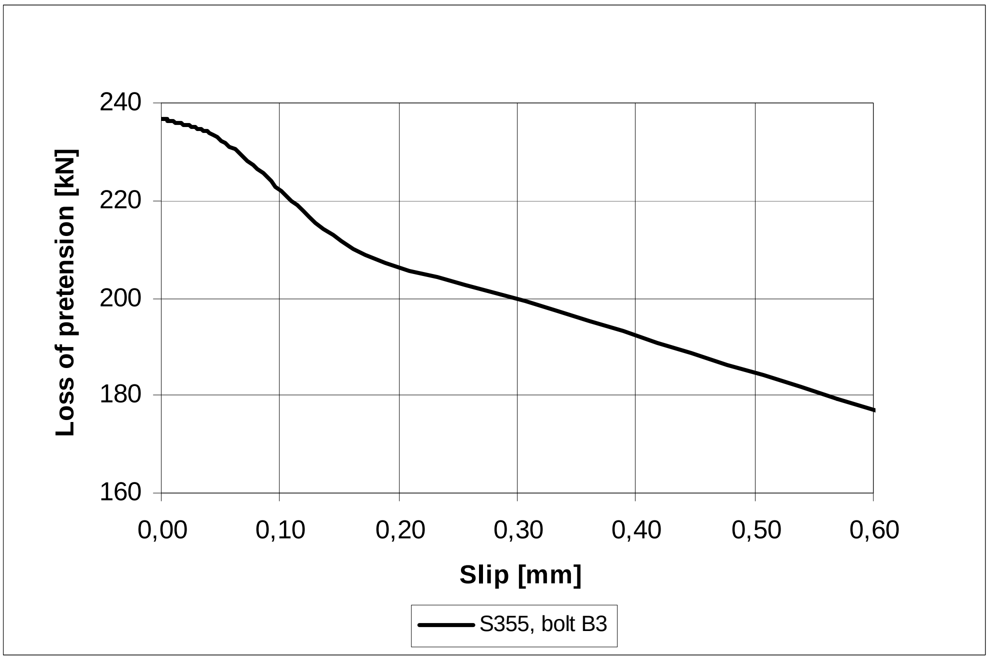

Fig. 5: Loss of pretension – bolt B3, S355

Considering the applied load on the plate and bearing the reduction in area due to the bolt holes in mind, it is realistic that the plates start yielding around the holes although force is transferred through friction to the other plates. However, yielding may start even earlier due to secondary bending. It can clearly be seen in Fig. 6 to Fig. 8 that high stresses arise from this bending.
As mentioned before, yielding depends on the material used. Thus, it is expected that the loss of pretension and therefore the total slip resistance are related to the material properties of the plates.

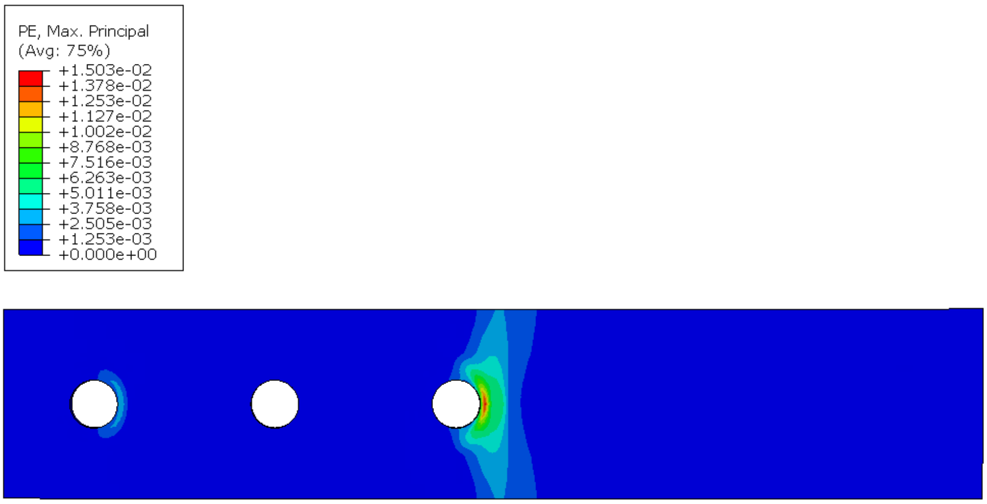

Fig. 6: Plastic strains – 0,15 mm slip, S355

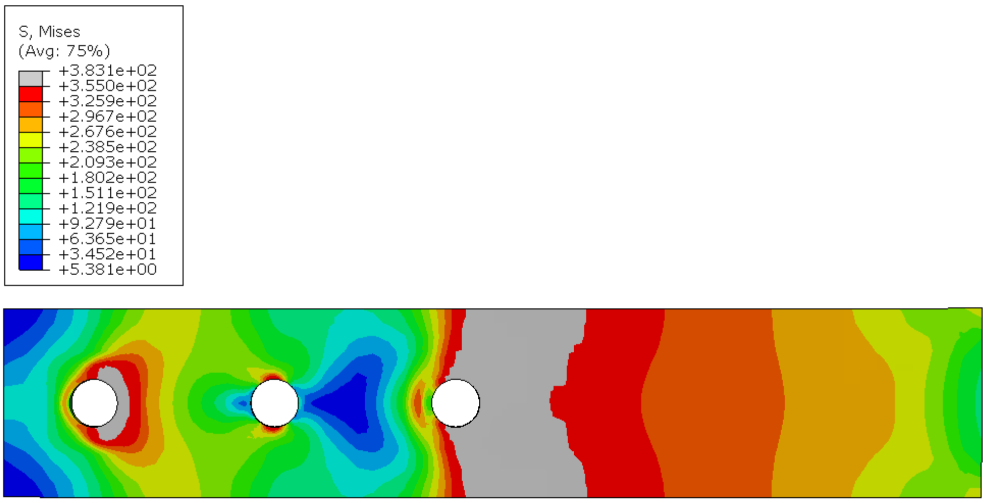

Fig. 7: Von Mises Stresses – 0,15 mm slip, S355

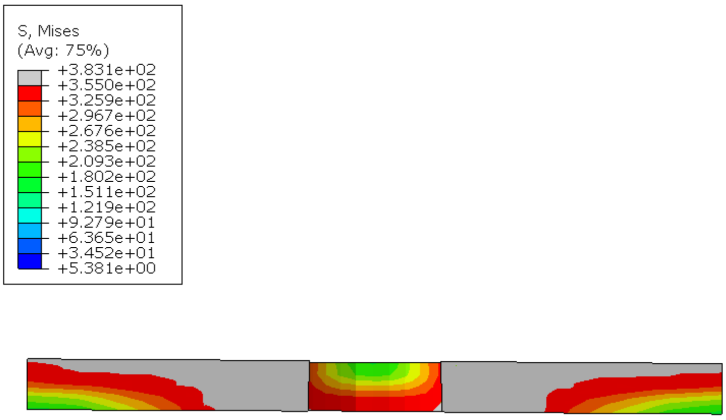

Fig. 8: Von Mises Stresses through thickness – 0,15 mm slip, S355

In the following, results of a parametric study based on different nominal steel grades (S235, S275, S355, S450 and S690) are presented.

Table 1: Characteristic resistances acc. to EN1993-1-8 [5]

Material	$N_{net,R}$ [kN]	$F_{b,R}$ [kN]	$F_{s,R}$ [kN]	**Abaqus** [kN]	**Abaqus/EC** [-]
S235	154,2	(461,6)	296,6	195,0	1,26
S275	180,4	(551,3)	296,6	223,2	1,24
S355	232,9	(653,9)	296,6	266,5	1,14
S450	288,6	(705,2)	296,6	288,6	1,00
S690	452,6	(987,2)	296,6	300,0	1,01

The characteristic slip resistance according to [5] is equal to 296,6 kN. Even the design slip resistance (237,3 kN) overestimates the resistance obtained by FEA for S235 and S275. However, with regard to the characteristic plastic resistance of the net cross-section all results are on the safe side, cp. Table 1.

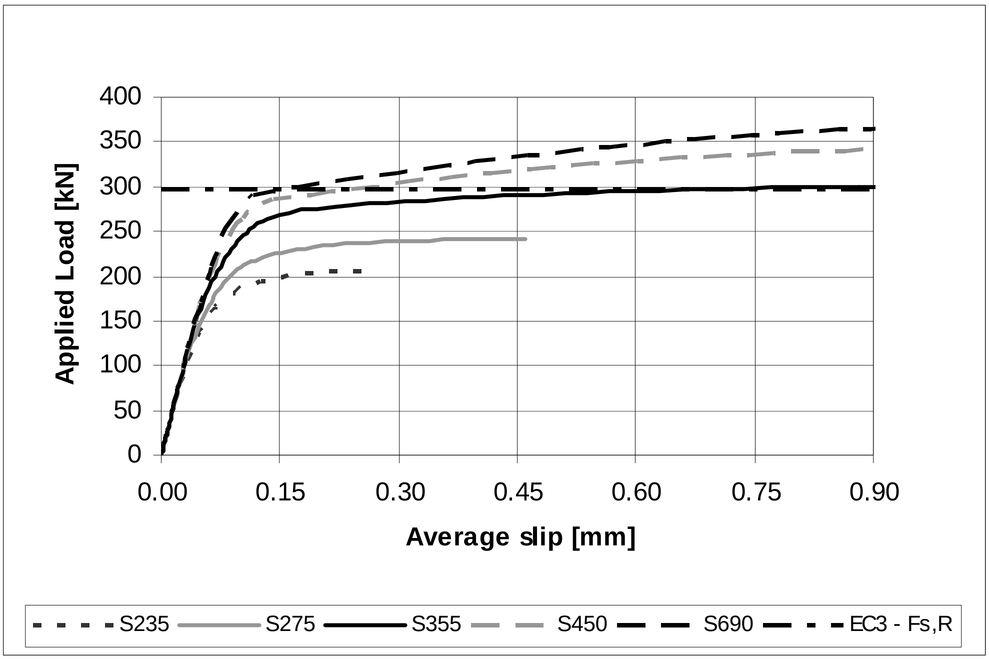

Fig. 9: Comparison of load vs. slip curves for different materials

Fig. 9 illustrates that a scattering in slip resistance, varying from 195,0 kN for S235 to 300,0 kN for S690, exists depending on the yield strength of the plates. Furthermore, none of the considered materials has reached a flat plateau, where just slip occurs without increase of load, at the defined failure criterion of 0,15 mm. This indicates that the ultimate slip resistance of the connection will be higher.

Table 2: Results from parametric study on material properties of plates

Material	σ_{gross} **[MPa]**	σ_{net} **[MPa]**	$\sigma_{\max,hole}$ **[MPa]**	$\frac{\sigma_{net}}{f_y}$ **[-]**	$\frac{\sigma_{\max,hole}}{f_y}$ **[-]**	**Loss of pretension [%]**
S235	221,5	297,2	115,8	1,26	0,49	21,8
S275	253,7	340,3	186,0	1,24	0,68	18,1
S355	302,8	406,2	303,4	1,14	0,85	10,7
S450	328,0	440,0	386,3	1,00	0,86	5,9
S690	340,9	457,3	574,8	0,66	0,83	2,5

Table 2 summarizes the results obtained from this parametric study with regard to longitudinal stresses and loss of pretension. The gross stress is defined as the applied load divided by the gross area of the plates. This is the nominal longitudinal stress in the plate due to external loading. The net stress considers the reduction in area due to the hole, neglecting the influence of secondary bending stresses. The expected maximum stress at the hole is obtained around the holes of the plates in the FE model in exactly the same way as for the double shear lap joint. It can be seen that the ratio of this stress to the yield stress is always smaller than one. This fact and Fig. 6 emphasize that plastification is shifted away from the hole. Major reason for that is secondary bending. However, Table 2 shows that for this specific specimen configuration a loss of pretension up to 21,8 % may be expected.

3.2 Parametric study to access level of assembling tolerances

The modelled single lap joint is studied as part of a bigger structure in which assembling tolerances play an important role. Therefore, feasibility tests have been performed with gaps up to 5 mm [4].Here minor gaps between 1 and 3 mm aren taken into account, cp. Fig. 10. In real constructions these gaps are limited by the tolerances given in EN1090-2 [6], depending on the structures' geometry. The considered gap may be closed by applying pretension forces into the bolts and therefore causes additional bending stresses in the plates. As tensile load is applied on the plates, secondary bending stresses arise due to the eccentricity of the two plates.

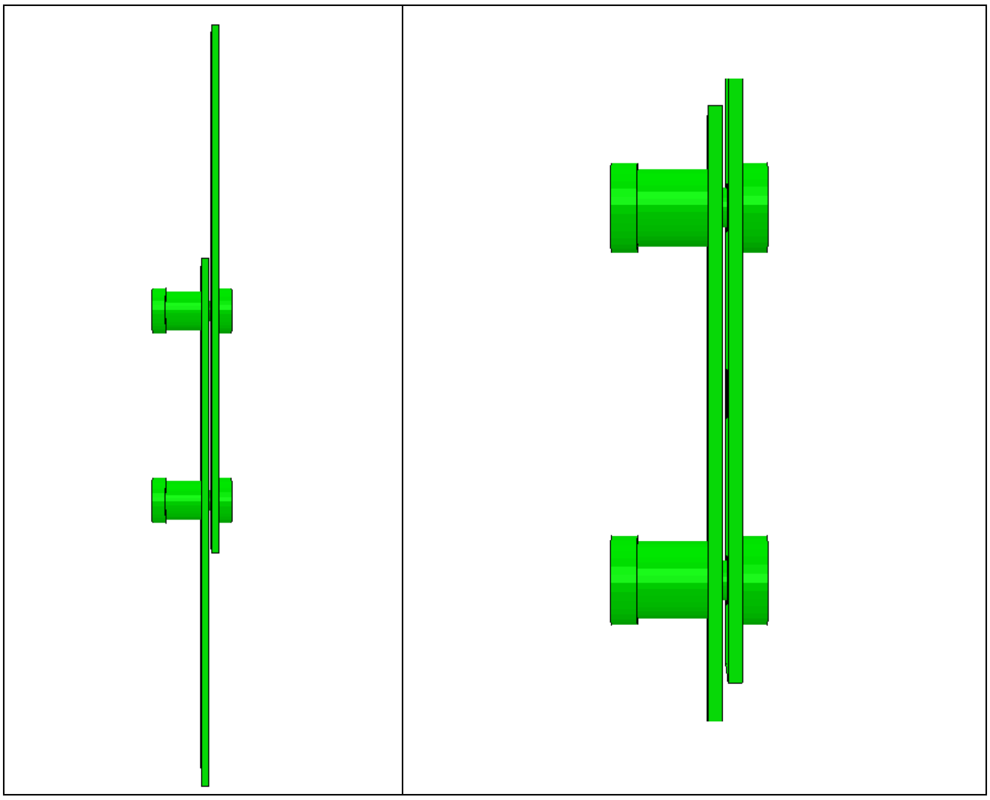

Fig. 10: Detail of assembling tolerances

A parametric study has been carried out with two different steel grades (S355 and S450) and gaps between the two plates of one, two and three mm in order to investigate the effect on the slip resistance. Fig. 11 and Fig. 12 clearly prove the bigger gap is used the lower resistance can be achieved. A reduction of resistance up to 10,7 % at a slip level of 0,15 mm is identified. It can also be observed that the defined failure does not correspond to the ultimate load. The specimens can still increase their load after a slip level of 0,15 mm is reached.

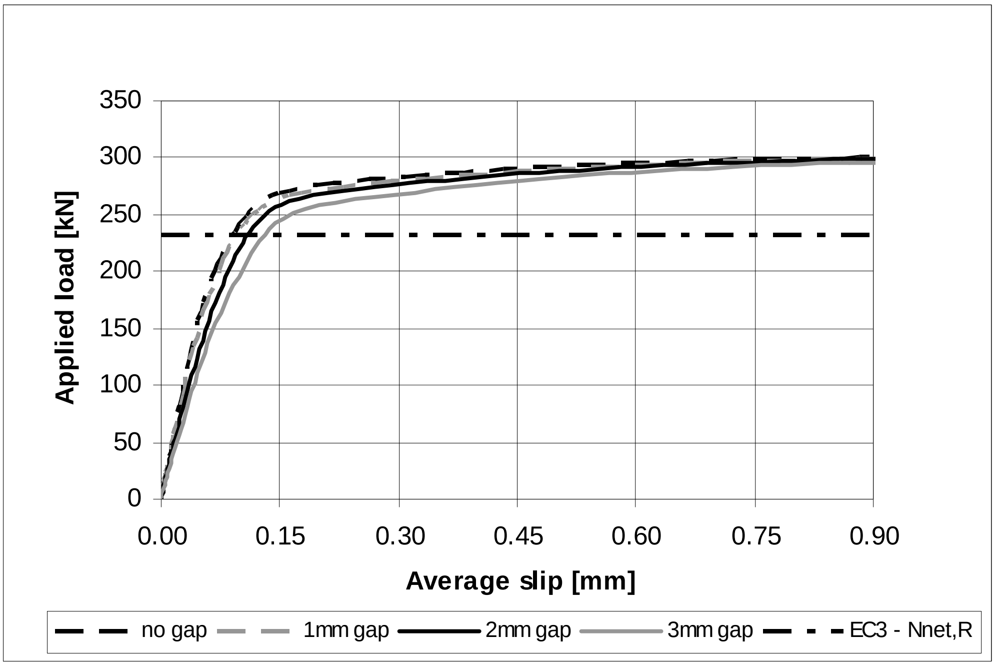

Fig. 11: Comparison of load vs. slip curves for different gaps, S355

Fig. 11 clearly visualizes that in this case with regard to the lower boundary according to [5], plastic resistance of the net cross-section, even assembling tolerances up to 3 mm are on the safe side. Contrary to those results Fig. 12 shows that this doesn't hold for S450. [5] overestimates the resistance by 3,0 % for 1 mm gap, 6,4 % for 2 mm gap and 11,0 % for a gap of 3 mm.

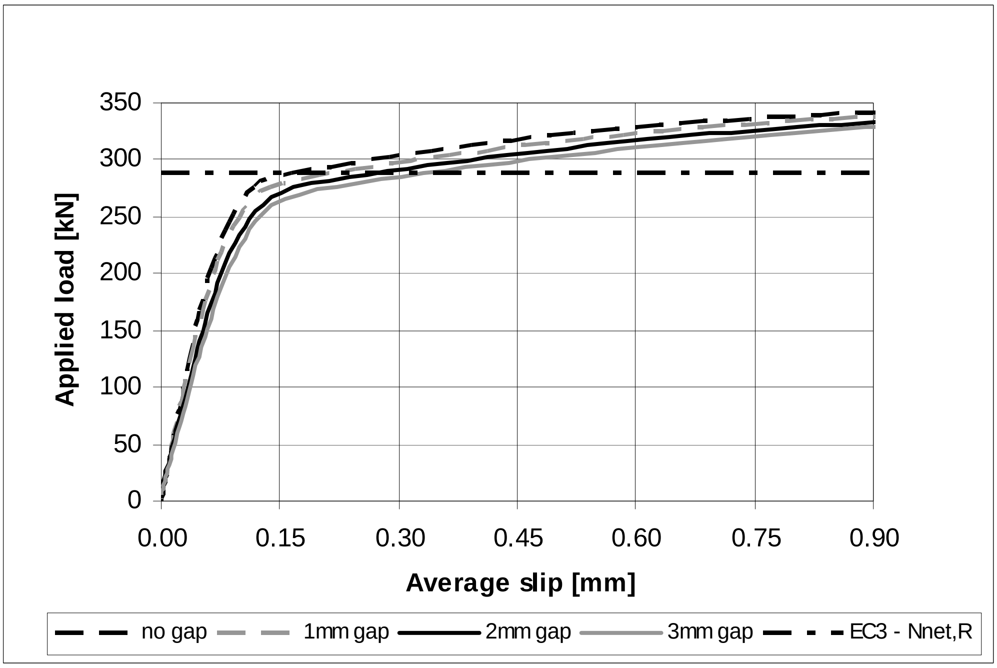

Fig. 12: Comparison of load vs. slip curves for different gaps, S450

4 Conclusions

The slip resistance depends on the steel grade of the connected plates. It is shown that the slip resistance of a single shear lap joint depends on the material grade of the connected plates. Premature yielding around the holes results into higher losses of pretension in the bolts and therefore reduces the slip resistance.

Assembling tolerances have a negative effect on the total resistance. The bigger the modelled gap the lower resistance is achieved. However, the joint sustains higher load when the slip of 0,15 mm is passed. This effect becomes more obvious with increased material grades. Clear plateaus, where major slip occurs without increase of load, are not obtained due to secondary bending effects.

Characteristic resistances according to [5], [7] are on the safe side compared to FEA for all considered materials, but assembling gaps may result into unsafe estimations.

Acknowledgements

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