Lap Shear Tests of Bolted and Screwed Ferritic Stainless Steel Connections

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Abstract

The development of design guidance for stainless steel structures requires more tests on ferritic grade connections. This paper deals with a series of lap shear tests which have been carried out on various configurations of bolted and screwed connections. The tests demonstrate net section failure, bearing failure and block tearing failure. The material is ferritic stainless steel of grade 1.4509 (AISI 441) with a thickness of 0.5–4.5 mm. The results are utilized in developing design guidance in accordance with Eurocodes.

Keywords

Stainless steel, ferritic, shear connection, strength, resistance, design, testing

1 Introduction

The strain hardening properties of the material are utilized in the design of shear connections. Therefore the design is based on the ultimate tensile strength of the steel. However, differences in the strain hardening of austenitic and ferritic stainless steels may affect the capacity of the connection. For example, for the usual austenitic grades EN 1.4301 and 1.4004 the ultimate tensile strength is typically 2–2.5 times 0.2 proof stress with elongation of 40–55%, but the corresponding values for the usual ferritic grades EN 1.4003 and 1.4509 are only 1.3–1.6 and 25–35%. Therefore, the behaviour of the connections and the design equations may depend on the steel grade.

The main objective of this article is to present test results for developing the design guidance for ferritic stainless steel. Few studies have been carried out to investigate the behaviour of stainless steel connections made with bolts or screws. This work seeks also to develop design guidelines for bolted and screwed connections in ferritic stainless steel members. To this end, a programme of lap shear tests was carried out on various configurations of bolted and screwed connections with various failure modes. The test programme concentrates only on ferritic grade EN 1.4509 (ASTM 441).

In the Eurocodes the design of connections cover bearing resistance, net section resistance and block tearing resistance (block shear failure) of the connected parts. In addition the shear resistance should be checked. The grade and thickness of the material may affect the design equations and therefore the guidelines given in the Eurocodes may differ from each other. The design EN 1993-1-1 [1] gives basic design rules for steel structures with material thickness of $t \geq 3$ mm; EN 1993-1-8 [2] shows the basic design rules for connections; EN 1993-1-3 [3] gives the basic design rules for connections of steel structures with material thickness of $0.4 \leq t \leq 4$ mm and EN 1993-1-4 [4] gives supplementary rules for stainless steel structures. The Design Manual for Structural Stainless Steel [5] brings together the design guidelines applicable for stainless steel structures.

2 Test Program

The test programme comprises both bolted and screwed connections. In the case of bolted connections (Figure 1), bolts of M12 and a hole diameter of d_0=13 mm are under consideration. The widths of the connected pieces depend on the type of specimen, but the length of the pieces is a constant 470 mm. Bolts of grade A2 austenitic stainless steel with property class 70 are used, except for some comparative carbon steel specimens where normal class 8.8 bolts is employed. The nominal values of 0.2 proof strength and ultimate tensile strength are for class 70 bolts 450 N/mm^2 and 700 N/mm^2 and for 8.8 bolts 800 N/mm^2 and 640 N/mm^2. The bolts are fully threaded so that the same bolts can be used in all specimens. In the single shear tests with the bolts in one row the bolts are provided with washers under both the head and the nut.

The specimen dimensions shown in Figure 2 and Table 1 have been chosen so that the relevant failure modes can be demonstrated. Failure types under consideration are net section failure (type A in Figure 1), bearing failure (types B and C) and block shear failure (type D). Also curling effects (out-of-plane deformations) are obvious in all tests with thin-walled materials. The spacing of holes agrees with the minimum values given in the Eurocodes.

Materials for different types of connections are shown in Table 2. In addition to tests for the usual more than 3 mm thickness, thin-walled material is also studied. Single lap specimens comprise all types of connections and double lap joints comprise only thick-walled flat specimens. In double shear tests, the intermediate plate has a thickness of about twice that of the surface plate. In addition, double shear tests comprise two comparative tests for carbon steel material S355. Each configuration has one or two test repeats.

The test programme for screwed connections comprises only single lap tests (Figure 3 and Table 3). The pieces of the connection have a constant width of 50 mm and length of 470 mm in all tests. The specimens demonstrate bearing failure, but also tilting, pull out or shear of screws may be obvious in final failure. Thin-walled materials are the same as those used for the bolted connections. Self-drilling austenitic stainless steel screws (corrosion class A2) with a nominal diameter of d=5.5 mm are used in joining. According to EN ISO 1478, the range of outer thread diameters is 5.28–5.46 mm, the range of inner diameter is 3.99–4.17 mm and the thread pitch is 1.8 mm. Because the self-drilling screws were not hard enough to drill ferritic stainless steel properly in all cases, pre-drilled clearance holes of 4.0 mm were used in all test specimens.

In the case of screwed connections, two thickness combinations of cover and back plates are under consideration. In the first case, the thickness of the back plate is equal to and in the second case thicker than the cover plate, but in both cases the thinner sheet is always next to the head of the screw. Based on ECCS guidance [6], the tests can be made either by using one screw with an edge distance e_1=30 mm (type 1a in Table 3) or two screws with an edge distance of e_1=30 mm and pitch distance of p_1=30 mm (type 2a). In addition, the tests comprise one screw specimen with a minimum value of e_1=3d=16.5 mm given in EN1993-1-3 (type 1b). Each configuration has three test repeats.

In manufacturing test specimens, it was ensured that the longitudinal direction of the pieces is the same as the rolling direction of the sheet. Thus the effect of possible material orthotrophy is the same in all tests. Holes were made by drilling. The bolts were tightened only to a little more than finger tight so that the friction did not affect to results, but the plates were in good contact. In the single shear tests with bolt in one row (types C1, E1) the bolts were provided with washers under both the head and the nut.

Tensile tests were carried out for determining the force-displacement behaviour of the connections. The gauge length for measuring the elongation over the connection was 500 or 600 mm for bolted connections (Table 2) and 300 or 400 mm for screwed connections (Table 3). Material properties in a longitudinal direction were determined for each material batch by three samples, which were taken from the mid-width and from both edges of the sheet of the raw material. The average values of the measured material properties are given in Table 4.

3 Design of Shear Connections

In the Eurocodes the design of connected parts cover bearing resistance, net section resistance and block tearing resistance. In addition, the shear resistance has to be checked. This study focuses on the resistance of the connected plates. However, the conditions given for the shear resistance of the fasteners should be noted. According to EN 1993-1-8 and the Design Manual, the shear resistance of each individual fastener shall not be less than the bearing resistance; otherwise the design resistance of the connection should be based on the smallest design resistance of any of the individual fasteners. In EN 1993-1-3 the condition is that the shear resistance of each fastener shall not be less than 1.2 times the bearing resistance, and in addition the sum of the bearing resistances of fasteners shall not be less than 1.2 times the net section resistance.

3.1 Net section resistance of bolted connections

Net section resistance of a plated part is calculated in Eurocodes by the equation

$$N_{u,Rd} = \frac{k_r A_{net}\, f_u}{\gamma_{M2}}$$

where A_{net} is the net cross-sectional area, f_u is the tensile strength of the material and γ_{M2}=1.25 is a partial safety factor.

EN 1993-1-1 gives k_r=0.9 for all cases. According to EN 1993-1-3, EN 1993-1-4 and the Design Manual, the factor is determined by the equation

$$k_r = [1 + 3r\left(\frac{d_o}{u} - 0{,}3\right)$$ but $k_r \leq 1.0$

Factor r is the number of bolts in net section divided by the total number of bolts in the connection; d_0 is the diameter of the hole and $u=2e_2$ but $u \leq p_2$ (e_2 and p_2, see Figure 2).

Net section resistance of angles connected by a single row of bolts in one leg is calculated in EN1993-1-8 and in Design Manual by the equations:

$$N_{u,Rd} = \frac{2.0(e_2+0{,}5d_0)tf_u}{\gamma_{M2}}$$ for one bolt in the row

$$N_{u,Rd} = \frac{\beta_2 A_{net} f_u}{\gamma_{M2}}$$ for two bolts in the row.

For an equal-leg angle, A_{net} is the net area of the angle. The reduction factor is β_2=0.4 for pitch $p_1 \leq 2.5d_0$ and 0.7 for $p_1 \geq 5.0d_0$. For intermediate values of p_1, the value of β_2 is determined by linear interpolation.

The calculated net section resistances of test specimens are shown in Table 5. The values are expressed by using the calculated multiplication factor for $d_0tf_{u,}$.

3.2 Bearing resistance of bolted connections

The bearing resistance of a plated part is calculated in EN 1993-1-8 by the equation

$$F_{b,Rd} = \frac{k_1 \alpha_b f_u dt}{\gamma_{M2}}$$

where d is the bolt diameter, t is the ply thickness, and α_b is the smallest of α_d and 1,0.

$\propto_d = e_1/(3d_0)$ for end bolts in the direction of load transfer and

$\propto_d = p_1/(3d_0) - 1/4$ for inner bolts in the direction of load transfer.

For edge bolts perpendicular to the direction of load transfer, k_1 is the smaller of $2.8e_2/d_0$-1.7 or 2.5. For inner bolts perpendicular to the direction of load transfer, k_1 is the smaller of $1.4p_2/d_0$-1.7 or 2.5. In the case of single lap joints of flats with only one bolt row, the bolts should be provided with washers under both the head and the nut and the value of $k_1 \alpha_b$ for each bolt is limited to 1.5.

In EN 1993-1-4 and in the Design Manual the basic equation is equivalent to EN 1993-1-8, but the value of f_u is replaced by the reduced value $f_{u,red}=0.5f_y+0.6f_u \leq 1.0$.

In EN 1993-1-3 the bearing resistance is calculated by

$$F_{b,Rd} = \frac{2{,}5\alpha_b f_u k_t dt}{\gamma_{M2}}$$

where α_b is the smallest of 1.0 or $e_1/(3d)$. Factor $k_t=(0.8t+1.5)/2.5$ for t=0.75–1.25 mm and k_t=1.0 for t>1.25 mm. The range of validity of the equation is limited to t=0.75–3.0 mm.

The calculated bearing resistances of test specimens are shown in Table 6. The values are expressed using the calculated multiplication factor for $dtf_{u,}$. It should be noted that, depending on the material thicknesses of cover and back plate, the resistance of B1 and B2 type connections can be based on both the holes in one flat or on the end holes of separate flats.

3.3 Block tearing resistance of bolted connections

The design resistance for block shear failure of a symmetric bolt group is in EN 1994-1-8 and the Design Manual is calculated by:

$$V_{eff,1,Rd} = \frac{f_u A_{nt}}{\gamma_{M2}} + \frac{f_y}{\sqrt{3}} \frac{A_{nv}}{\gamma_{M0}}$$

where A_{nt} is the net area subjected to tension, and A_{nv} is the net area subjected to shear. The partial safety factor γ_{M0}=1.10.

EN 1993-1-3 and EN 1993-1-4 give no supplementary rules. The calculated areas of the test specimens subjected to tension and shear are shown in Table 7.

3.4 Bearing resistance of screwed connections

The bearing resistance of a plated part is calculated in EN 1993-1-3 by the equation

$$F_{b,Rd} = \frac{\alpha f_u dt}{\gamma_{M2}}$$

where

$\alpha = 3.2\sqrt{t/d} \leq 2.1$ for two cases, for (a) $t=t_1$ or for (b) $t_1 \geq 2.5t$ and $t<1.0$ mm

$\alpha=2.1$ for case (c) $t_1 \geq 2.5t$ and $t \geq 1.0$ mm and

α is obtained by linear interpolation for (d) $t<t_1<2.5t$

The range of validity of the equation is limited to t=0.5–1.5 mm.

In the Design Manual the value of f_u is replaced by the reduced value $f_{u,red}=0.5f_y+0.6f_u \leq 1.0$, but in EN 1993-1-4 the rule is not given.

The calculated α factors for the test specimens are shown in Table 8. The values in parentheses show the values if the condition (c) for $t_1 \geq 2.5t$ and $t \geq 1.0$ mm is used instead of the condition (b) for $t_1 \geq 2.5t$ and $t<1.0$ mm.

4 Results and Discussion

1.

4.1 Failure and design criteria in comparisons

In the interpretation of the test results it is essential, which criterion is applied to the ultimate limit state. The Commentary Part of the Design Manual [7] explains that the reason for using the reduced value of tensile strength $f_{u,red}$ is to limit the bearing deformation to 3 mm in the case of stainless steels. Elsewhere in the Commentary Part it is also proposed that a 1.75 mm permanent deformation of a cover plate connection is acceptable in the serviceability state, and a 5 mm permanent bearing deformation is acceptable in the ultimate limit state. Reference [8] informs us that the failure load corresponding to a deformation of 6.35 mm has been adopted in developing design guidance for carbon steel connections in the AISC Steel Construction Manual. However, in many recent studies [9][10][11] the ultimate limit state is determined based on the maximum load in test, although the deformations are large, e.g. 20–25 mm in reference [9] in the case of M12 bolts.

Reference [8] proposes different design equations for the serviceability limit state (SLS) and ultimate limit state (ULS). The equations base on a parametric FEM study which is verified by test results of stainless steel connections. The resistance for SLS is based on a hole elongation of 1.0 mm and the resistance for ULS is based on the maximum load attained in test. The equations for the bearing resistances of bolted connections are given for both thick and thin-walled materials. The comparison of design equations for SLS and ULS in Figure 4 shows that the serviceability limit is determining the design only in the case of thick materials if the edge distances e_1 and e_2 are large. This is due to the fact that usually the multiplication of load for the material safety factor exceeds the ratio 1.6 shown in Figure 4.

According to ECCS guidance [6] the failure load of screwed connections is the maximum load, when the corresponding total elongation is less than 3 mm; otherwise the failure load is the load at an elongation of 3 mm. The elongation is measured over the connection using a gauge length of 150 mm.

Because there is no single-valued approach for failure criterion, this study uses two criteria. The first is based on the maximum load without limited deformation (hereinafter F_{max} criterion) and the second on the elongation (hereinafter displacement criterion). For a screwed connection, the displacement criterion presented in ECCS guidance is used for all tests. For bolted connection, the approach is equal to EECS guidance, but the elongation of 3 mm is applied only to one plate. It means that in the tests where the cross sectional area in both ends of the connection are equal, the criterion is 6 mm, but the criterion is 3 mm if one of the ends is stronger than the other (the case with thin-walled materials with a back plate of 2.0 mm). The reasons for the selected quite large elongation is that it is very difficult to determine very small elongations from the load-displacement curves, and the true hole elongations were not measured in tests. Inaccuracies, as clearances of holes, uneven deformation of holes, differences in the hole distances, out-of plane deformations etc. affect load-displacement curve in the start-up phase of the test.

In the following comparisons the design resistances are calculated by using $\gamma_{M2}=\gamma_{M0}=1.0$ and the measured material strengths and thicknesses given in Table 4. Comparisons are made based on both f_u and $f_{u,red}$ independent of the failure mode. A nominal diameter of 12 mm is used in the calculation of bolted connections, but for screwed connections the mean diameter of 5.37 mm (according to EN ISO 1478) is applied. The bearing resistances of screwed connections are determined in test series S0520 and S0820 according to the condition given for $t_1 \geq 2.5t$ and $t \geq 1.0$ mm instead of the extra condition given for $t<1.0$ mm (Table 8, values in parenthesis are used), because otherwise the results are very different from other test series.

The characteristic minimum value of the test results is determined according to normative Annex A of EN 1993-1-3. The characteristic value for a group of test results is obtained from $R_k = R_m - ks$, where R_m is the mean value of results, s is the standard deviation and $k \geq 1.64$ is a coefficient depending on the number of tests. In the context of characteristic values, Annex A recommends using the same γ_M-values in design as proposed for design by calculation, if the detailed statistical analysis according to Annex D of EN 1990 is not made. Determination of γ_M-values according to Annex D needs statistical values for dimensions and strengths of the materials. Use of Annex D results usually to lower γ_M-values, e.g. in reference [12] $\gamma_M=0.96$ is calculated for net section resistance, when $R_m=1.06$ and $s=0.07$.

4.2 Results of bolted connections

Figure 5 shows some examples of different failures of test specimens. The elongations corresponding to F_{max} are in all tests between 6–24 mm. For detailed analysis of the results, the tests are grouped based on the failure type of the specimens. Table 9 shows the results for net section failure (specimens of types A and F), Table 10 for bearing failure (types B, C and E), and Table 11 for block tearing failure (type D).

Comparison with calculated resistances is shown in Figure 6 for criterion F_{max} and in Figure 7 for displacement criterion. The results for criterion F_{max} show that the results for tests B2-510, B2-510S, C2-510, C2-510S and D2-510S are more unsafe than other test results. This is due to the fact that in these experiments the shear strength of the bolts was exceeded. This was also observed in testing. When these test results are ignored, all other test results except A2-510S are higher than the values calculated by the methods under consideration. In the case bearing type failure tests (types B and C) and angle tests (types F and E), the ratio is as much as 1.5. Also in tests B1-55, C1-55, E1-55 and D2-510, the final failure was a shear failure of the bolts, but these results are in line with other results. When displacement criterion is studied, shear failure of bolts does not appear as clearly in the results. Also the scatter of test result is less, but more results are on the unsafe side.

In the following study, the experimental results are divided into four groups: (a) tests on net section failure of flats, (b) tests on net section failure of the angles, (c) tests on bearing failure and (d) tests on block tearing failure. In these groups, the results are consistent with each other if the results where the resistance is affected by bolt shear are excluded from the comparisons. Also the results in different groups do not substantially depend on the material thickness and therefore all results of each group can be studied in one set.

Statistical values of net section resistances of bolted connections are given in Table 12. The results related to net section resistance of the flats show the following:

- Criterion F_{max} gives in average 10% higher failure loads than the displacement criterion, and calculation by $f_{u,red}$ gives in average 4 % lower resistances than calculation by f_u.
- When the failure criterion in tests is F_{max}, CoV=0.04 is the same for all design approaches, but the best characteristic value of 1.01 is obtained by using f_u in EN 1993-1-3 design. All other approaches lead to safer results.
- When the failure criterion is displacement, again CoV=0.04 is the same for all design approaches, but the best characteristic value of 1.00 is obtained by using f_u in EN 1993-1-1 design. EN 1993-1-3 underestimates the resistance in both cases f_u and $f_{u,red}$.

- The results agree with the results given in reference [12]. There 17 test results for austenitic and ferritic steels are compared and it is proposed that the design equation given in EN 1993-1-1 is used with factor k_r=1.0 instead of k_r=0.9. Then the average ratio between tested F_{max} and calculated value is 1.06 with CoV=0.07. The values agree well with the results of 1.08 and CoV=0.04 in this study, after the values given in Table 12 are converted corresponding to k_r=1.0. Also the characteristic value from Table 12 is reduced to 1.01 after the modification.

The conclusion is that in the case of net section resistance of flats, both EN 1993-1-1 with modification of k_r=1.0 and present EN 1993-1-3 are the best design approaches if the failure criterion is F_{max} and f_u is used in design. If the criterion is displacement, the best agreement is obtained by using f_u in EN 1993-1-1with k_r=0.9 as it is in the existing EN 1993-1-1.

The three results related to net section resistance of the angles (Table 12) show the following:

- Criterion F_{max} gives in average 26 % higher failure loads than the displacement criterion, and calculation by $f_{u,red}$ gives in average 6 % lower resistances than calculation by f_u.
- When the failure criterion in tests is F_{max}, EN 1993-1-8 design using f_u gives the best results with the characteristic value of 0.96 and CoV=0.10.
- When the failure criterion is displacement, EN 1993-1-8 design using f_u is slightly unsafe with the characteristic value of 0.94 and CoV=0.05. It must be noted in reviewing the results that small number of tests negatively affects the characteristic value (*k*=3.37). The lowest value of the three results is 1.07 and the average is 1.16.

The conclusion is that, in the case of net sections resistance of angle sections, the number of test tests is too low to provide reliable conclusions, but the results do not indicate that EN 1993-1-8 with f_u would be unsafe.

Statistical values of the bearing resistances of bolted connections are given in Table 13. The results show the following:

- Criterion F_{max} gives on average 25% higher failure loads than the displacement criterion, and calculation by $f_{u,red}$ gives in average 5 % lower resistances than calculation by f_u.
- When the failure criterion in tests is F_{max}, CoV=0.06–0.08 is smaller for EN 1993-1-8 design than CoV=0.09–0.10 for EN 1993-1-3 design. The best characteristic value of 1.25 is obtained by using f_u in EN 1993-1-3 design. All other approaches lead to even safer results.
- When the failure criterion is displacement, EN 1993-1-3 design using f_u or $f_{u,red}$ results in the best agreement, with a characteristic value of 0.98–1.02 and CoV=0.10. The corresponding results for EN 1993-1-8 approach with f_u or $f_{u,red}$ are 1.11–1.16 and CoV=0.07. If an extra correction factor of 1.10 is used in EN 1993-1-8 design with f_u, the characteristic value decreases to 1.01.
- The results agree with the results given in other studies. Reference [13] has 12 test results for austenitic and ferritic steels and the results are compared with EN-1993-1-1 approach. The average ratio between tested F_{max} and the calculated value is 1.40 with CoV=0.18 (1.57 and 0.06 in this study). Reference [8] has 10 test results for ferritic plate materials and the results are compared with the EN-1993-1-3 approach. The ratio between tested F_{max} and the calculated value is 1.59 with CoV=0.21 (1.48 and 0.09 in this study).

The conclusion is that, in the case of bearing resistance, both EN1993-1-8 and EN 1993-1-3 result in a very safe design if the failure criterion is F_{max} and f_u is used in the design. If the criterion is displacement, the best agreement is obtained by using f_u in EN 1993-1-8 with an extra correction factor of 1.10, or EN 1993-1-3 as it is at the moment. When the superiority of these methods is considered, it must be detected that in multi-bolt connections the resistances of the individual fasteners is taken into account more precisely in EN 1993-1-8 than in EN 1993-1-8.

The deformations in bearing type tests are about 15-20 mm before the maximum load F_{max} is reached. Therefore, the deformation criterion should be taken into account in the development of design equations. If the design equations are based on F_{max}, too large deformations may be adverse in SLS or they may affect the design of structural system in ULS, especially in the case of cyclic loads. Results of the bearing tests in this study show that the average ratio of loads corresponding to displacement criterion and F_{max} criterion is 0.8. In addition, Figure 4 shows that the load ratio of design resistances between ULS and SLS is less than 2.0 for the case when the hole deformation is limited to 1 mm. Therefore, it is obvious that, if the failure criterion is 3 mm as used in this study, the hole deformations are no larger than 1 mm in SLS. The condition for this is that the load factor is 1.5 and γ_M is not less than 1.1. Furthermore, when displacement criterion is used, no additional equations for SLS are necessary.

Statistical values of the block tearing resistances of bolted connections are given in Table 13. The results show the following:

- Criterion F_{max} gives on average 25% higher failure loads than the displacement criterion, and calculation by $f_{u,red}$ gives in average 3 % lower resistances than calculation by f_u.
- When the failure criterion in tests is F_{max}, CoV=0.04–0.06 is almost same for all design approaches. The best characteristic value of 1.20 is obtained by using f_u in EN 1993-1-8 design.
- When the failure criterion is displacement, EN 1993-1-8 design using f_u results in a characteristic value of 0.91 with CoV=0.06. If an extra correction factor of 0.9 is used in EN 1993-1-8 design with f_u, the characteristic value increases to 1.01.

The results agree quite well with the results given in reference [9], which shows 10 test results for ferritic steels and the results are compared with EN-1993-1-8 approach. The ratio between tested F_{max} and the calculated value is 1.46 with CoV=0.09, which are somewhat higher than the value of 1.29 with CoV=0.04 in this study.

The conclusion is that, in the case of block tearing resistance, EN1993-1-8 results in safe results if the failure criterion is F_{max} and f_u is used in design. If the criterion is displacement, the best agreement is obtained by using f_u in EN 1993-1-8 with an extra correction factor of 0.9.

4.3 Results of screwed connections

Figure 8 shows some examples of different failures in experiments. The displacements corresponding to F_{max} are in all tests between 2–16 mm. Table 14 shows experimental resistances per fastener.

Comparison with calculated resistances is shown in Figure 9 for both F_{max} and deformation criterion. When F_{max} criterion is used, all results are safe. If the displacement criterion is used, some of the results are unsafe, but the scatter of the results is less. The comparison also shows that the results of three identical tests may differ significantly from each other. In some tests the final failure was not bearing type, in S1220-1a tests the final failure was break of the screw and in S1220-1b tests the failure was screw pull-out from the hole of the thicker plate. However, the failure occurred after large deformations of 7–9 mm, and the results are in line with other test results.

Statistical values of results of screwed connections are given in Table 15. The results show the following:

Criterion F_{max} gives on average 26% higher failure loads than the displacement criterion and calculation by $f_{u,red}$ gives in average 3 % lower resistances than calculation by f_u.

When the failure criterion in tests is F_{max}, CoV=0.16–0.17 for design by f_u and $f_{u,red}$. The best characteristic value of 1.01 is obtained by using f_u in EN 1993-1-3 design.

When the failure criterion is displacement, EN 1993-1-3 design using $f_{u,red}$ results in the characteristic value of 1.00 with CoV=0.10. If an extra correction factor of 0.9 is used in EN 1993-1-3 design with f_u, the characteristic value increases to 1.03. An almost equivalent effect is achieved if the average diameter of the screw is used instead of the outside diameter of the screw. This results in the correction factor 0.88 and characteristic value 1.06.

The conclusion is that, in the case of bearing resistance of screwed connections, EN1993-1-3 results in safe design if the failure criterion is F_{max} and f_u is used in design. If the criterion is displacement, the best agreement is obtained by using f_u in EN 1993-1-3 with an extra correction factor of 0.9.

5 Conclusions

An experimental study for bolted and screwed connections has been carried out in order to develop design guidelines in EN 1993-1-4 for ferritic stainless steels. Bolted connections comprise single and double shear tests with a material thickness of 0.8-4.5 mm and a bolt diameter of 12 mm. The dimensions of the joints have been defined so that the results represent bearing resistance, net section resistance and tearing resistance. Screwed connections comprise single shear tests with material thickness of 0.5–1.2 mm. The joint is connected by a single or two self-tapping screws with a nominal diameter of 5.5 mm. In all the tests the steel grade is EN 1.4509 (ASTM 441).

The failure load of the joint is based on two failure criteria. The first is based on the maximum load F_{max} without limited deformation and the second on limited elongation. For screwed connections, the total elongation of the joint is limited to 3 mm as proposed in ECCS guidance, and for bolted connections the elongation is limited to 3 mm per one connected part. The results are compared with the values calculated by different equations given in Eurocodes. EN 1993-1-1 gives general rules for steel structures, EN 1993-1-8 gives rules for the design of joints, EN 1993-1-3 give supplementary rules for thin-walled members, and EN 1993-1-4 gives supplementary rules for stainless steels. In addition EN 1993-1-4 uses reduced strength $f_{u,red}$=0.5f_y+0,6f_u instead of f_u in calculation of bearing resistance.

The results show that the deformations can be very large in all type of connections before the maximum load F_{max} is reached. For example, in the case of bolted connections the deformations are 6–24 mm. Therefore, the deformation criterion is important, and the deformation should also be taken into account in the case of net section failure and block shear failure, not only in the case of bearing failure. If the design equations are based on F_{max}, too large deformations can be adverse in SLS or they may affect the design of structural system in ULS, especially in the case of cyclic loads. Therefore, this study prefers to use deformation criterion as the basis for the design equations. Then also the deformation of the hole is limited to about 1 mm in SLS and no additional equations for SLS are necessary.

The results show that identical design equations are valid for both thin and thick materials. There is no systematic difference between the results of bolted connections with thickness of 0.8–4.5 mm and between the results of screwed connections with thickness of 0.5–1.2 mm. The results show also that, because ferritic steels have lower strain-hardening properties than austenitic steels, the effect of the use of reduced strength $f_{u,red}$ is less important. For material 1.4509 in this study, the use of reduced strength $f_{u,red}$ in design results in average only in 6 % lower resistances than the use of f_u.

When the failure criterion is deformation, the best result is obtained by EN 1993-1-1 with f_u for net section resistance and EN 1993-1-8 with f_u for bearing resistance. Also three test results for net section resistance of angle sections are safe compared to EN 1993-1-1 with f_u. In the case of block tearing resistance of bolted connections and in the case of bearing resistance of screwed connections, the best results are obtained by EN 1993-1-8 and EN 1993-1-3 when f_u and an extra reduction factor of 0.9 is used in design. This means that the existing design approach may lead to larger deformations than allowed in the used failure criterion. The loads corresponding to failure criterion F_{max} are in average about 25% higher than the loads corresponding to deformation criterion, except of net section failure of flat specimens with bolts in which the value is 10%. Therefore, in the case of criterion F_{max}, all the calculation methods under consideration result in a safe outcome.

The conclusions are based on characteristic resistances, which are determined according to Annex A of EN 1993-1-3. When the design based on characteristic values, Annex A recommends the use of same γ_M-values as used in normal calculation. More favourable results may be achieved, if statistical determination of resistance models according to Annex D of EN-1990 is used. Then the study should also include test results from other sources, also including other steel grades, so that the design approach is consistent for all steel grades and thicknesses. In addition, the influence of strain-hardening and other design parameters should could studied by finite element calculations.

Acknowledgements

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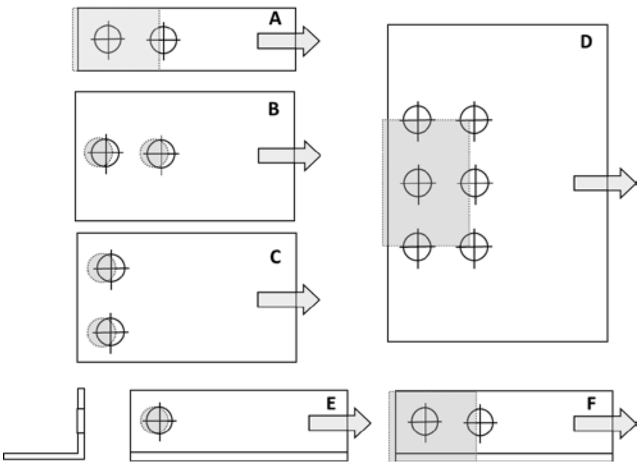

Figure 1. Types of shear lap specimens for bolted connections with predicted failure modes

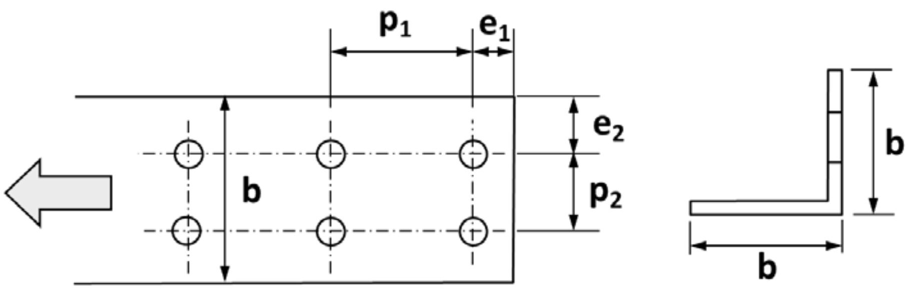

Figure 2. Dimensions of specimens.

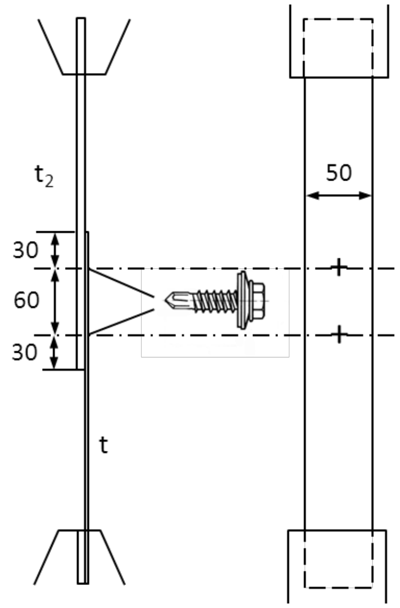

Figure 3. Shear lap tests for bolted connections.

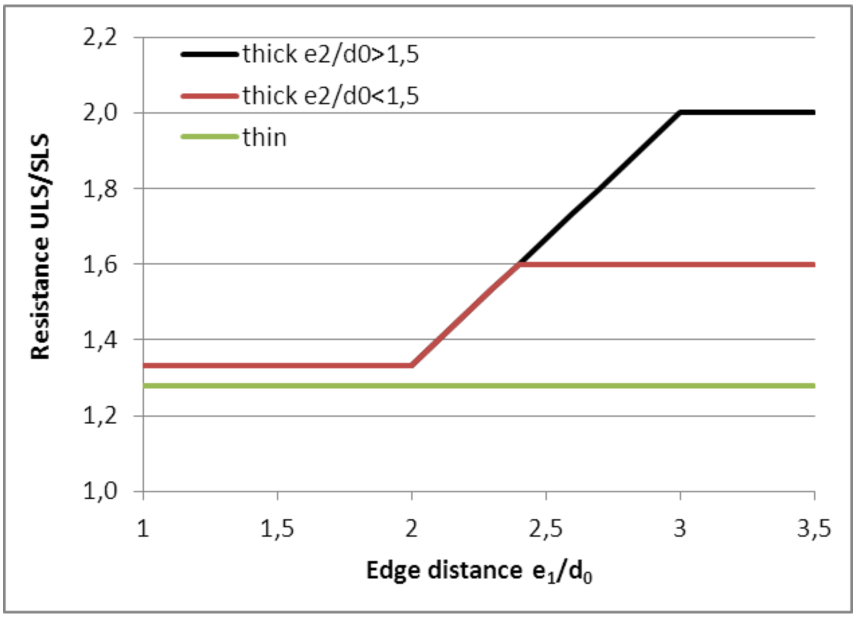

Figure 4. Calculated ratio of the resistances corresponding to ULS and SLS.

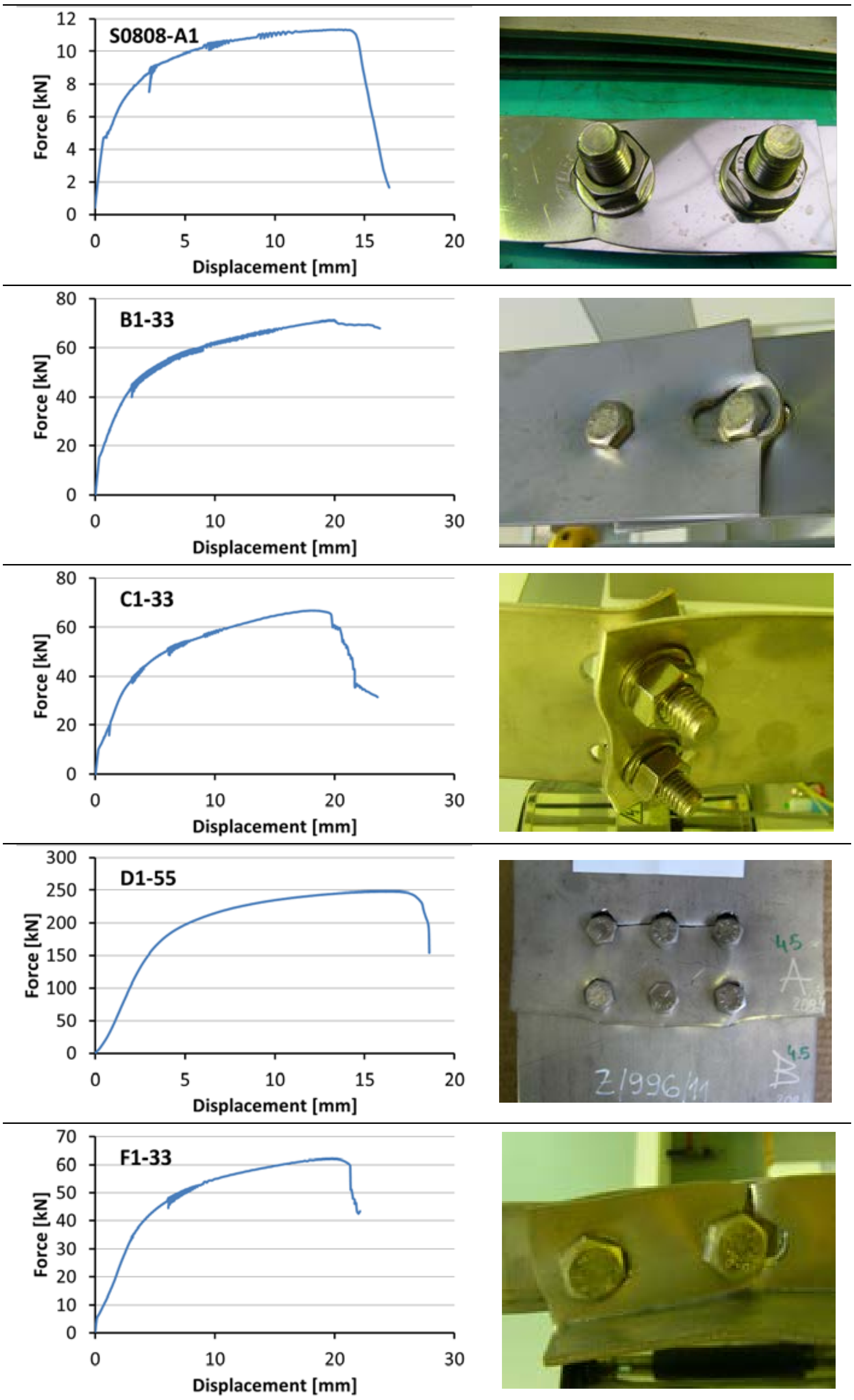

Figure 5. Examples of different failure types of bolted connections.

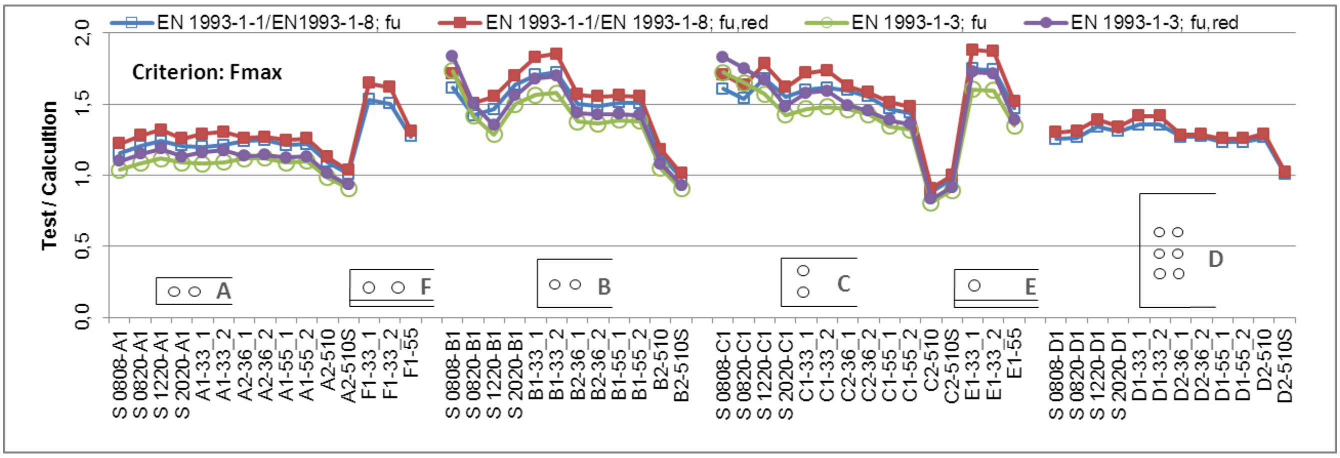

Figure 6. Experimental results of bolted connections compared to calculated resistances, failure criterion is F_{max}.

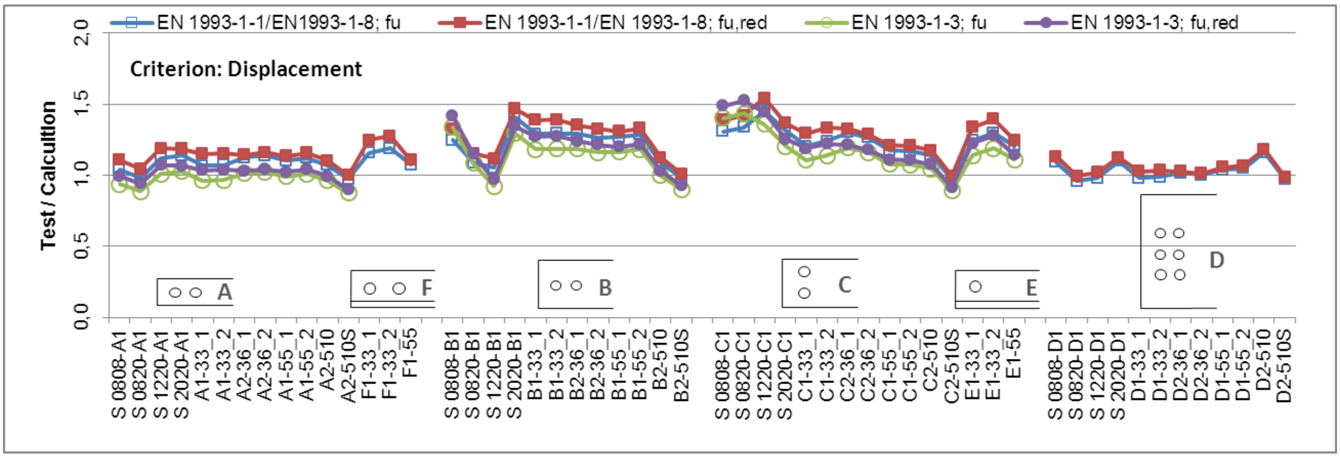

Figure 7. Experimental results of bolted connections compared to calculated resistances, failure criterion is displacement.

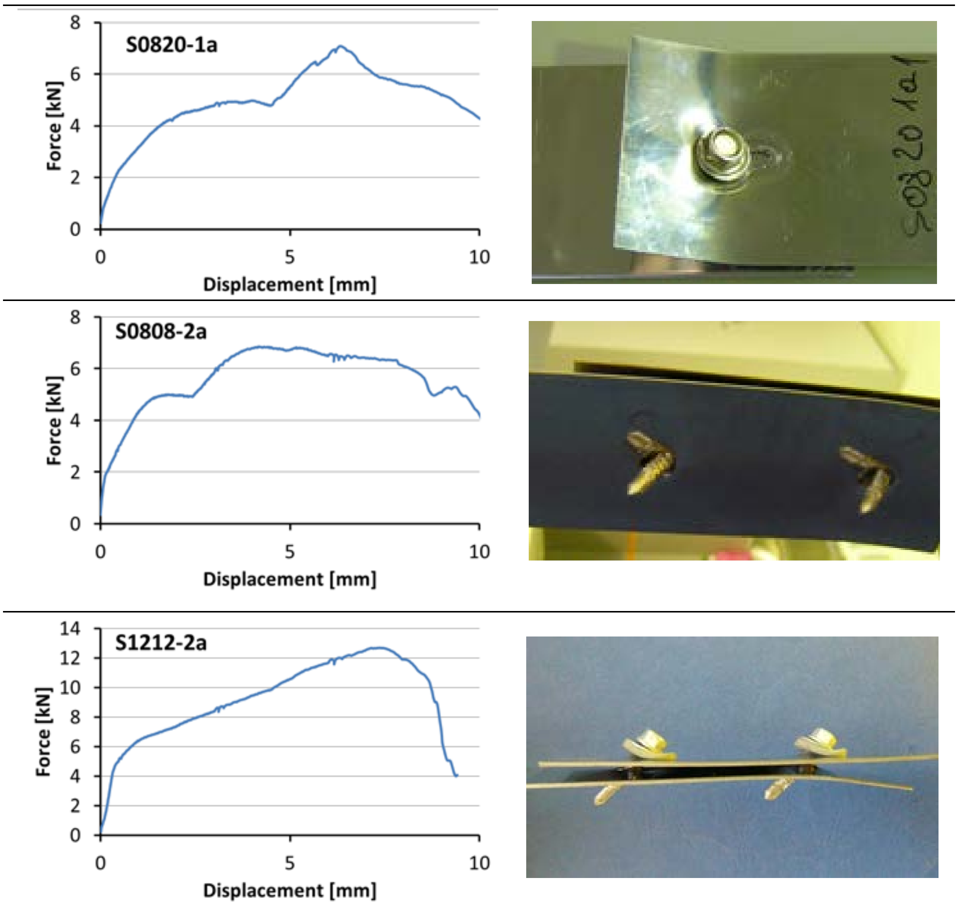

Figure 8. Examples of different failure types of screwed connections.

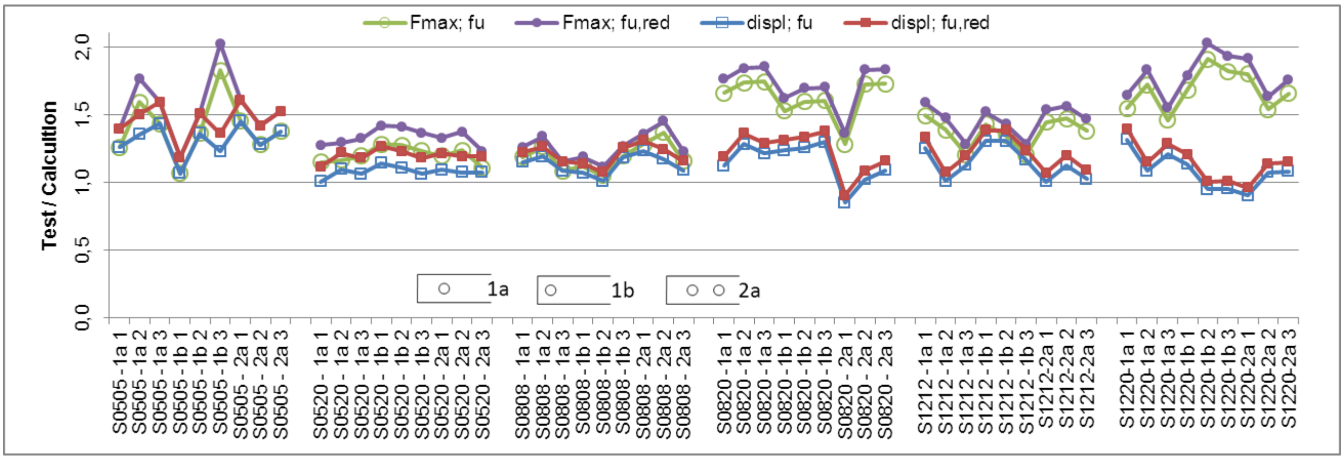

Figure 9. Experimental results of screwed connections compared to calculated resistances. Failure criteria F_{max} and displacement.

Table 1. Specimen dimensions for bolted connections.

	Single shear	Double shear	Number of bolts	b	e_1	e_2	p_1	p_2
Net section failure	A1	A2	2	3.2 d_0	1.6 d_0	1.6 d_0	3.2 d_0	-
Bearing failure	B1	B2	2	6.4 d_0	1.6 d_0	3.2 d_0	3.2 d_0	-
Bearing failure	C1	C2	2	6.4 d_0	1.6 d_0	1.6 d_0	-	3.2 d_0
Block tearing failure	D1	D2	6	16 d_0	1.6 d_0	4.8 d_0	3.2 d_0	3.2 d_0
Bearing failure	E1	-	1	3.2 d_0	1.6 d_0	1.6 d_0	3.2 d_0	-
Net section failure	F1	-	2	3.2 d_0	1.6 d_0	1.6 d_0	3.2 d_0	-

Table 2. Test identification and materials of bolted connections.

Type of test	Test identification code				Plate 1, t [mm] and grade		Plate 2, t_2 [mm] and grade	
Single shear tests $t<3$ mm	S0808-A1	S0808-B1	S0808-C1	S0808-D1*	0.8	1.4509	0.8	1.4509
	S0820-A1	S0820-B1	S0820-C1	S0820-D1*	0.8	1.4509	2	1.4509
	S1220-A1	S1220-B1	S1220-C1	S1220-D1*	1.2	1.4509	2	1.4509
	S2020-A1	S2020-B1	S2020-C1	S2020-D1*	2	1.4509	2	1.4509
Single shear tests $t\geq3$ mm	A1-33	B1-33	C1-33	D1-33*	3	1.4509	3	1.4509
	A1-55	B1-55	C1-55	D1-55*	4.5	1.4509	4.5	1.4509
Double shear tests $t\geq3$ mm	A2-36	B2-36	C2-33	D2-36*	3	1.4509	5.5	1.4509
	A2-510*	B2-510*	C2-510*	D2-510*	4.5	1.4509	10	S355
	A2-510S*	B2-510S*	C2-510S*	D2-510S*	5.0	S355	10	S355
Angle bar test $t\geq3$ mm	E1-33	F1-33			3	1.4509	3	1.4509
	E1-55	F1-55			4.5	1.4509	4.5	1.4509

* In these tests the gauge length for measuring elongation was 600 mm, in other tests the length was 500 mm

Table 3. Test identification and materials of screwed connections.

Plate thicknesses in test						
plate 1, t [mm]	0.5	0.5	0.8	0.8	1.2	1.2
plate 2, t_2 [mm]	0.5	2	0.8	2	1.2	2
1 screw, e_1=30 mm	S0505-1a	S0520-1a	S0808-1a	S0820-1a*	S1212-1a	S1220-1a*
1 screw, e_1=3d=16,5 mm	S0505-1b	S0520-1b	S0808-1b*	S0820-1b*	S1212-1b	S1220-1b*
2 screws, e_1/p_1=30/60 mm	S0505-2a	S0520-2a	S0808-2a	S0820-2a	S1212-2a	S1220-2a

* In these tests the gauge length for measuring elongation was 400 mm, in other tests the length was 300 mm

Table 4. Measured material properties.

ID	Grade	t	a	$R_{p0.2}$	R_m	A_{LO}
S05	1.4509	0.5	0.52	276	457	32
S08	1.4509	0.8	0.80	327	478	30
S12	1.4509	1.2	1.20	311	456	33
S20	1.4509	2.0	1.97	334	463	34
M-3	1.4509	3.0	2.93	295	447	36
M-5	1.4509	4.5	4.50	353	478	24
M-6	1.4509	5.5	5.50	345	451	32
S-5	S355	5.0	4.97	395	526	26
S-10	S355	10	9.96	400	545	27

ID – test identification code $R_{p0.2}$ – 0.2 proof stress [MPa]
t – nominal thickness [mm] R_m – tensile strength [MPa]
a – measured thickness [mm] A_{LO} – elongation after fracture [%]
The gauge length in measuring elongation was 80 mm

Table 5. Multiplication factor for d_0tf_u in calculating net section resistance.

Connection type	EN 1993-1-1 EN 1993-1-8	EN 1993-1-3
A1* and A2*	1.98	2.20
B1 and B2	4.86	4.23
C1 and C2	3.96	4.40
D1 and D2	11.7	13.0
E1	2.20	–
F1*	2.38	–

* Net section failure is determining only in these tests

Table 6. Multiplication factor for dtf_u in calculating bearing resistance; equal to $k_1\alpha_b$ in EN1993-1-8 and $2.5\alpha_b k_t$ in EN1993-1-3.

Connection type	Thickness	EN 1993-1-1			EN 1993-1-3		
		End bolts	Inner bolts	Sum	End bolts	Inner bolts	Sum
A1* and A2*	*t*=0.8 mm	1.33	2.04	3.37	1.24	2.14	3.38
B1 and B2	*t* =1.2 mm	1.33	2.04	3.37	1.42	2.46	3.88
	t >1.25 mm	1.33	2.04	3.37	1.45	2.50	3.95
C1 and C2	*t* =0.8 mm	2.66	–	2.66	1.24	1.24	2.48
	t =1.2 mm	2.66	–	2.66	1.42	1.42	2.84
	t >1.25 mm	2.66	–	2.66	2.90	–	2.90
D1 and D2**	*t* =0.8 mm	4.00	6.58	10.6	3.42	6.42	9.84
	t=1.2 mm	4.00	6.58	10.6	3.93	7.38	11.3
	t >1.25 mm	4.00	6.58	10.6	3.99	7.50	11.5
E1	*t* >1.25 mm	1.33	–	1.33	1.45	–	1.45
F1*	*t* >1.25 mm	1.33	2.04	3.37	1.45	22.50	3.95

* Net section failure is determining in these tests

** Block shear failure is determining in these tests

Table 7. Block shear failure: Areas subjected to tension and shear according to EN1993-1-8.

Connection type	Tension area, subjected to f_u	Shear area, subjected to $f_y/\sqrt{3}$
D1 and D2	4.40 d_0t	6.60 d_0t

Table 8. Coefficient α for screwed connections according to EN1993-1-3.

Connection type	t	t_1	α
S0505-1a/1b/2a	0.52	0.52	0.984
S0520-1a/1b/2a	0.52	1.97	0.984 (2.10)
S0808-1a/1b/2a	0.80	0.80	1.220
S0820-1a/1b/2a	0.80	1.97	1.220 (2.08)
S1212-1a/1b/2a	1.20	1.20	1.495
S1220-1a/1b/2a	1.20	1.97	1.754

Table 9. Measured and calculated resistances [kN].Net section failure of bolted connections.

Test	Measured		Calculated by f_u	
	F_{max}	Displ.	Part 1-1	Part 1-3
S0808-A1	11.3	10.2	9.84	10.9
S0820-A1	11.9	9.68	9.84	10.9
S1220-A1	17.5	15.8	14.1	15.7
S2020-A1	28.4	26.8	23.5	26.1
A1-33_1	40.4	36.0	33.7	37.5
A1-33_2	40.9	36.1	33.7	37.5
A2-36_1	79.2	71.7	63.9	70.9
A2-36_2	79.5	72.7	63.9	70.9
A1-55_1	67.0	61.0	55.4	61.5
A1-55_2	67.5	62.0	55.4	61.5
A2-510	120.9	118.5	110.7	123.0
A2-510S	135.9	130.9	134.6	149.5
F1-33_1	62.1	46.9	40.5	–
F1-33_2	60.9	48.1	40.5	–
F1-55	84.7	71.4	66.6	–

Table 10. Measured and calculated resistances [kN].Bearing failure of bolted connections.

Test	Measured		Calculated by f_u	
	F_{max}	Displ.	Part 1-8	Part 1-3
S0808-B1	19.7	15.2	12.2	11.4
S0820-B1	22.0	16.8	15.5	15.5
S1220-B1	32.4	23.3	22.1	25.2
S2020-B1	47.6	41.0	29.1	31.7
B1-33_1	71.2	53.9	41.8	45.6
B1-33_2	72.0	54.1	41.8	45.6
B2-36_1	122.1	105.1	81.4	88.7
B2-36_2	120.9	103.1	81.4	88.7
B1-55_1	103.8	87.0	68.7	74.9
B1-55_2	103.4	88.4	68.7	74.9
B2-510	177.4	169.0	155.3	169.3
B2-510S	167.4	166.9	170.1	185.4
S0808-C1	19.6	16.0	12.2	11.4
S0820-C1	18.8	16.3	12.2	11.4
S1220-C1	29.3	25.3	17.5	18.7
S2020-C1	45.2	38.2	29.1	31.7
C1-33_1	66.9	50.3	41.8	45.6
C1-33_2	67.5	51.8	41.8	45.6
C2-36_1	126.5	103.1	79.2	86.3
C2-36_2	123.1	100.1	79.2	86.3
C1-55_1	100.6	80.5	68.7	74.9
C1-55_2	98.7	80.3	68.7	74.9
C2-510	120.9	156.5	137.3	149.7
C2-510S	162.2	162.1	166.9	182.0
E1-33_1	37.5	26.6	21.4	23.3
E1-33_2	37.3	27.7	21.4	23.3
E1-55	50.4	41.5	34.3	37.4

Table 11. Measured and calculated resistances [kN].Block tearing failure of bolted connections.

Test	Measured		Calculated by f_u	
Criterion	F_{max}	Displ.	Part 1-8	Part 1-3
S0808-D1	43.7	38.0	34.8	33.6
S0820-D1	44.0	33.4	34.8	33.6
S1220-D1	66.7	48.8	49.8	47.9
S2020-D1	111.0	93.0	84.8	82.7
D1-33_1	159.5	115.4	117.7	112.5
D1-33_2	159.5	116.4	117.7	112.5
D2-36_1	299.6	239.3	235.9	233.4
D2-36_2	300.4	236.1	235.9	233.4
D1-55_1	248.8	209.1	201.7	197.9
D1-55_2	248.9	211.3	201.7	197.9
D2-510	510.2	468.0	403.5	395.9
D2-510S	497.9	480.0	493.6	486.2

Table 12. Statistical values of net section resistances of bolted connections, flat bars (series A1and A2) and angle bars (series F1).

	Flat specimens without test A2-510S, *N*=11, *k*=1.90								Angles *N*=3, *k*=3.37			
	EN 1993-1-1				EN 1993-1-3				EN 1993-1-8			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.
Average	1.20	1.09	1.26	1.14	1.08	0.98	1.13	1.02	1.44	1.14	1.53	1.21
StDev	0.04	0.05	0.05	0.04	0.04	0.04	0.05	0.04	0.14	0.06	0.19	0.09
CoV	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.10	0.05	0.12	0.08
Characteristic	1.12	1.00	1.16	1.06	1.01	0.90	1.04	0.95	0.96	0.94	0.90	0.90

Table 13. Statistical values of bolted connections, bearing resistance (series B1, B2 and E) and block tearing resistance (series D1 and D2).

	Bearing tests without tests B2-510,B2-510S, C2-510, C2-510S; *N*=23, *k*=1.75								Block tearing without test D2-510S; *N*=11, *k*=1.90			
	EN 1993-1-8				EN 1993-1-3				EN 1993-1-8			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.
Average	1.57	1.26	1.66	1.33	1.48	1.19	1.56	1.25	1.29	1.03	1.32	1.06
StDev	0.10	0.09	0.13	0.10	0.13	0.12	0.15	0.13	0.05	0.06	0.06	0.06
CoV	0.06	0.07	0.08	0.07	0.09	0.10	0.10	0.10	0.04	0.06	0.05	0.06
Characteristic	1.40	1.11	1.43	1.16	1.25	0.98	1.29	1.02	1.20	0.91	1.21	0.95

Table 14. Measured and calculated resistances per one fastener [kN]. Screwed connections.

Test Criterion	Measured F_{max}	Measured Displ.	Calc. by f_u Part 1-3	Test	Measured F_{max}	Measured Displ.	Calc. by f_u Part 1-3
S0505 -1a 1	1.58	1.58		S0520 - 1a 1	3.08	2.69	
S0505 -1a 2	2.00	1.70		S0520 - 1a 2	3.12	2.94	
S0505 -1a 3	1.80	1.80		S0520 - 1a 3	3.20	2.85	
S0505 -1b 1	1.34	1.34		S0520 - 1b 1	3.43	3.06	
S0505 -1b 2	1.71	1.71	1.26	S0520 - 1b 2	3.41	2.97	1.26 (2.68)
S0505 -1b 3	2.29	1.54		S0520 - 1b 3	3.30	2.85	
S0505 - 2a 1	1.82	1.82		S0520 - 2a 1	3.21	2.93	
S0505 - 2a 2	1.61	1.61		S0520 - 2a 2	3.32	2.88	
S0505 - 2a 3	1.73	1.73		S0520 - 2a 3	2.97	2.88	
average	1.76	1.65		average	3.23	2.89	
stdev	0.27	0.15		stdev	0.15	0.10	
S0808 - 1a 1	2.97	2.88		S0820 -1a 1	7.08	4.79	
S0808 - 1a 2	3.16	2.98		S0820 -1a 2	7.41	5.47	
S0808 - 1a 3	2.72	2.72		S0820 -1a 3	7.45	5.18	
S0808 -1b 1	2.80	2.68		S0820 -1b 1	6.52	5.28	
S0808 -1b 2	2.63	2.53	2.51	S0820 -1b 2	6.82	5.36	2.51 (4.27)
S0808 -1b 3	2.99	2.96		S0820 -1b 3	6.84	5.53	
S0808 - 2a 1	3.21	3.09		S0820 - 2a 1	5.47	3.64	
S0808 - 2a 2	3.43	2.93		S0820 - 2a 2	7.37	4.36	
S0808 - 2a 3	2.90	2.73		S0820 - 2a 3	7.38	4.66	
average	2.98	2.83		average	6.93	4.92	
stdev	0.25	0.18		stdev	0.64	0.62	
S1212 -1a 1	6.56	5.50		S1220-1a 1	7.97	6.77	
S1212 -1a 2	6.09	4.43		S1220-1a 2	8.87	5.58	
S1212 -1a 3	5.30	4.94		S1220-1a 3	7.52	6.24	
S1212 -1b 1	6.28	5.72		S1220-1b 1	8.67	5.85	
S1212 -1b 2	5.91	5.72	4.39	S1220-1b 2	9.83	4.88	5.15
S1212 -1b 3	5.30	5.11		S1220-1b 3	9.37	4.90	
S1212-2a 1	6.34	4.42		S1220-2a 1	9.28	4.66	
S1212-2a 2	6.45	4.95		S1220-2a 2	7.93	5.53	
S1212-2a 3	6.07	4.50		S1220-2a 3	8.53	5.57	
average	6.03	5.03		average	8.66	5.55	
stdev	0.46	0.53		stdev	0.76	0.68	

Table 15. Statistical values of screwed connections.

	N=54, k=1.70 EN 1993-1-3			
Calculation	f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.
Average	1.41	1.15	1.52	1.24
StDev	0.23	0.13	0.24	0.15
CoV	0.16	0.11	0.16	0.12
Characteristic	1.02	0.93	1.11	0.98