RESEARCH REPORT

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Structural Applications of Ferritic Stainless Steels (SAFFS)
WP 6 Bolted and screwed connections

Design recommendations

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Summary

The project Structural Applications of Ferritic Stainless Steels (SAFSS) seeks to develop the necessary information which will enable comprehensive guidance on ferritic stainless steels. This report deals with a series of lap shear tests 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 tests have been defined by VTT and carried out by IMT.

The results show that the design expression of bolted connections can be same for thicknesses of 0.8–4.5 mm. The use of EN 1993-1-1 approach is recommended for net section resistance and the use of EN 1993-1-8 approach with f_u is recommended for bearing and block tearing resistances. For screwed connections EN 1993-1-3 approach is recommended, but the extra condition for t < 1 mm given there does not appear to be necessary. If the failure criterion is the ultimate load in test, the design expression given in EN1993-1-1, EN 1993-1-3 and EN 1993-1-8 result in a safe outcome. However, in order to ensure that the deformations at the fasteners is limited to about 1 mm in SLS, an extra reduction factor of 0.9 should be considered in the case of design block tearing resistance of bolted connections and bearing resistance of screwed connections.

The conclusions above are based on characteristic resistances, which are determined according to Annex A of EN 1993-1-3. In the design based on the characteristic values, Annex A recommends the use of same γ_M-values as in the case of normal calculation. Statistical determination of resistance models according to Annex D of EN-1990 is proposed, because then more favourable results may be achieved. Then the study should also include test results from other sources and other steel grades.

Confidentiality	Confidential until May 2014

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Preface

The project Structural Applications of Ferritic Stainless Steels (SAFSS) seeks to develop the necessary information which will enable comprehensive guidance on ferritic stainless steels to be included in the relevant parts of the Eurocodes and other accompanying standards and guidance. In particular it will:

- Develop Eurocode-aligned structural guidance for grades not previously studied before which are included the in newly issued material specification for stainless steel EN 10088-4.
- Study construction-relevant aspects of structural design and corrosion resistance which have not been studied before (e.g. the performance of structural joints, structural fire resistance, corrosion performance of welded and bolted joints etc.).
- Study the structural performance and temperature regulation effects of ferritic stainless steel decking in a composite floor system.

The development of design guidance for stainless steel structures needs more tests on ferritic grade connections. Therefore WP2: Bolted and screwed connections is planned to investigate the behaviour of stainless steel connections for thick and thin-walled structures. The tests for connections are made for demonstrating net section, bearing and block tearing type failures. Material of connections is ferritic stainless steel of grade 1.4509 (AISI 441) with thickness of 0.5–5.5 mm. This report compiles the results of lap shear tests which have been carried out on various configurations of bolted and screwed connections and compares the test results with Eurocodes.

The work of WP6 was made in co-operation of Institute of Metals and Technology (IMT) and Technical Research Centre of Finland (VTT). The tests were defined by VTT, while the tests and manufacturing of the specimens were performed by IMT. This report was written by VTT. The detailed information relating to the tests is given in IMT's test report.

Espoo 16.11.2012

Authors

Contents

1 Introduction

Objective of the work is to develop design guidance in accordance with Eurocode 3 EN 1993-1-3, 1993-1-4 and EN 1993-1-8. Few studies have been carried out to investigate the behaviour of stainless steel connections made with bolts or screws. This work seeks to develop design guidelines for bolted and screwed connections in ferritic stainless steel members.

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 the 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 test programme consists of lap shear tests for different configurations of bolted and screwed connections with various failure modes. The test programme studies net section failure, bearing failure (deformations of holes) and block shear failure (block bearing). Also curling effects (out-of-plane deformations) may be apparent in double shear tests of thin plate connections. The dimensions of specimens are such that the relevant failure modes are demonstrated. The test programme concentrates on grade 1.4509 and consists in all 94 tests. In addition, the material properties are determined by standard material tension tests (three repeats). Only monotonically increasing load is used in all tests.

Test programme for bolted connections includes in all 50 tests, of which 24 are for thick plate connections 16 for thin plate connections. The test programme concentrates on grade 1.4509. One bolt size of M12 (diameter d = 12 mm) with hole diameter of d_0 = 13 mm is used in all tests. Thick-plate connections consists both single and double lap specimens. Material thicknesses are 3, 4.5 mm and 5.5 mm. Specimens comprise four types of bolt groups which demonstrate net section, bearing and block tearing failure modes. The thin-walled connections comprise only single lap specimens but dimensions are identical to thick-plate connections. Material thicknesses are 0.8, 1.2 and 2 mm.

Test programme for screwed connections consists in all 54 tests. Self-drilling screws (5.5 mm diameter) joining thin-walled material with thickness of 0.5, 0.8 and 1.2 mm are used. One ferritic stainless steel of grade 1.4509 is under consideration. Tests made for single lap specimens with varying material thicknesses and screw arrangements demonstrate different failure modes (shear failure, bearing failure, tilting failure). Each configuration comprises three test repeats. The selection of the screws is based on the preliminary tests studying the thread cutting properties of the screws.

The work of WP6 was made in co-operation of Institute of Metals and Technology (IMT) and Technical Research Centre of Finland (VTT). The tests are defined in VTT report [1], while the test results detailed information relating to the tests is given in IMT report [2].

2 Design of bolted shear connections

In shear lap connections the shear forces are transferred by bearing between the bolts and the connected parts. Different failure modes in shear lap joints are possible. Depending on the dimensions of the specimen one or more of next failures in connected parts can be observed:

- Net section failure
- Bearing failure, shear out (end tear out) failure
- Block shear failure
- Curling (out-of-plane) failure.

The different failure modes in connected parts are taken into account in standards by the design rules given for bearing resistance, net section resistance and block shear resistance. The European design rules are given in following standards:

- EN 1993-1-1 [2]: The standard gives basic design rules for steel structures with material thicknesses $t \geq 3$ mm. The resistance of joints is calculated according to EN 1993-1-8.
- EN 1993-1-8 [3]: The standard gives basic design rules for connections of steel structures with material thicknesses $t \geq 3$ mm.
- EN 1993-1-3 [4]: The standard gives basic design rules for connections of steel structures with material thickness of $0.4 \leq t \leq 4$ mm.
- EN 1993-1-4 [6]: The standard gives supplementary rules for connections of stainless steel structures.

Summary of the design rules applicable for stainless steels is presented in Design Manual for Structural Stainless Steel [7].

This study focuses on the resistance of the connected plates. However, it need to be noted also some conditions given for the shear resistance of the fastener $F_{v,Rd}$. For example, EN 1993-1-3 gives for self-tapping screws and bolted connections following conditions:

$$F_{v,Rd} \geq 1{,}2\, F_{b,Rd} \quad \text{or} \quad \Sigma F_{v,Rd} \geq 1{,}2\, F_{n,Rd}$$

Where $F_{b,Rd}$ is bearing resistance and $F_{n,Rd}$ is net section resistance.

In EN 1993-1-8 and in Design Manual the condition for bolted connections is that the design shear resistance $F_{v,Rd}$ of each individual fastener shall be greater than or equal to the design bearing resistance $F_{b,Rd}$. Otherwise the design resistance of a group of fasteners shall be taken as the number of fasteners multiplied by the smallest design resistance of any of the individual fasteners.

2.1 Design of bearing resistance

2.1.1 Design Manual for Structural Stainless Steel

The appropriate resistance of a bolted connection in stainless steel will usually be governed by serviceability criteria in which the hole elongation at serviceability loads is to be limited. In order to avoid carrying out a separate check for serviceability, a limit on hole elongation at ultimate load is placed by using a reduced value of the ultimate tensile strength

$$f_{u,red} = 0.5 f_y + 0.6 f_u \quad \text{but} \leq f_u$$

Where f_y is the 0.2% proof strength and f_u is the ultimate tensile strength of the connected ply.

Bearing resistance $F_{b,Rd}$ of one ply is given by

$$F_{b,Rd} = \frac{k_1 \alpha_b f_{u,red} d t}{\gamma_{M2}}$$

Where d is the bolt diameter
t is the ply thickness and
α_b is the smallest of α_d, $f_u / f_{u,red}$ and 1.0.

$\alpha_d = e_1 / 3d_0$ for end bolts in the direction of load transfer

$\alpha_d = \frac{p_1}{3d_0} - \frac{1}{4}$ for inner bolts in the direction of load transfer

k_1 is the smaller of $2{,}8 \frac{e_2}{d_o} - 1{,}7$ or 2,5 for edge bolts perpendicular to the direction of load transfer

k_1 is the smaller of $1{,}4 \frac{p_2}{d_o} - 1{,}7$ or 2,5 for inner bolts perpendicular to the direction of load transfer

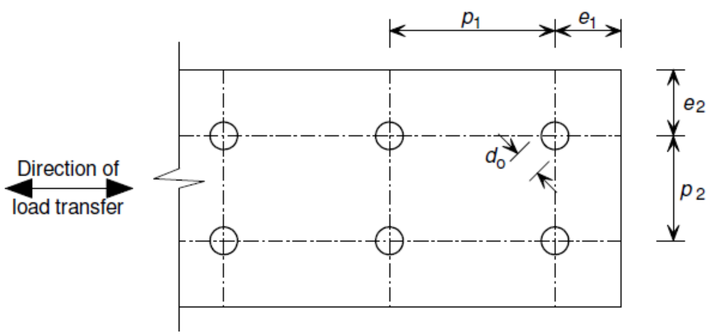

Figure 1. Specimen dimensions of lap joints.

The minimum value of e_1 and e_2 should be $1{,}2d_0$, where d_0 is the diameter of the bolt hole.

The minimum centre-to-centre bolt spacing p_1 is $2{,}2d_0$. The corresponding minimum spacing p_2 is $2{,}4d_0$.

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 bearing resistance for each bolt should be further limited to

$$F_{b,Rd} = \frac{1{,}5\, f_{u,red}\, d\, t}{\gamma_{M2}}$$

2.1.2 EN Standards

EN 1993-1-1: The resistance of joints is calculated according to EN 1993-1-8.

EN 1993-1-8: Basic equations are equivalent to Design Manual, but value of f_u is used instead of $f_{u,red}$.

EN 1993-1-4: The provisions given in EN 1993-1-8 are applied except that f_u is replaced by $f_{u,red}$.

EN 1993-1-3: Bearing resistance of the thinner connected part is given by

$F_{b,Rd} = 2{,}5 \alpha_b\, k_t\, f_u\, d\, t \,/\, \gamma_{M2}$ with α_b is the smallest of 1,0 or $e_1 / (3d)$ and
$k_t = (0{,}8\, t + 1{,}5) / 2{,}5$ for $0{,}75 \text{ mm} \leq t \leq 1{,}25 \text{ mm}$; $k_t = 1{,}0$ for $t > 1{,}25$ mm

Range of validity:

$e_1 \geq 1{,}0\, d_o$	$p_1 \geq 3\, d_o$	$3 \text{ mm} > t \geq 0{,}75 \text{ mm}$	Minimum bolt size:	M 6
$e_2 \geq 1{,}5\, d_o$	$p_2 \geq 3\, d_o$		Strength grades:	4.6 - 10.9

2.2 Design of net section resistance

2.2.1 Design Manual for Structural Stainless Steel

The design ultimate resistance of the net cross-section at holes of fasteners is

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

where:

A_{net} is the net cross-sectional area

f_u is the characteristic ultimate tensile strength (generally taken as the minimum specified value)

$k_r = [1 + 3r(d_0 / u - 0{,}3)]$ but $k_r \leq 1{,}0$

r = [number of bolts at the cross-section]/[total number of bolts in the connection]

d_0 is the nominal bolt hole diameter

$u = 2e_2$ but $u \leq p_2$.

Angles connected by a single row of bolts in one leg may be treated as concentrically loaded and the design ultimate resistance of the net section determined as follows:

With 1 bolt: $$N_{u,Rd} = \frac{2.0\,(e_2 - 0.5d_0)\,t\,f_u}{\gamma_{M2}}$$

With 2 bolts: $$N_{u,Rd} = \frac{\beta_2\,A_{net}\,f_u}{\gamma_{M2}}$$

With three or more bolts: $$N_{u,Rd} = \frac{\beta_3\,A_{net}\,f_u}{\gamma_{M2}}$$

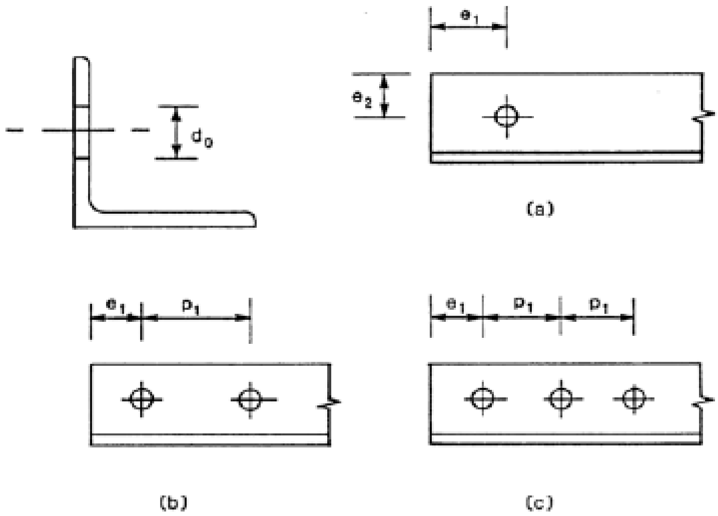

Figure 2. Specimen dimensions of angle bar joints.

- A_{net} is the net area of the angle. For an unequal-leg angle connected by its smaller leg, A_{net} should be taken as equal to the net section area of an equivalent equal-leg angle of leg size equal to that of the smaller leg.
- β_2 and β_3 are reduction factors dependent on the pitch p_1. For intermediate values of p_1 the value of β may be determined by linear interpolation.

Table 1. Reduction factors β2 and β3.

Connection	Factor	Pitch, p_1	
		$\leq 2{,}5d_0$	$\geq 5{,}0d_0$
2 bolts	β_2	0,4	0,7
3 bolts or more	β_3	0,5	0,7

2.2.2 EN Standards

EN 1993-1-8: Deduction for holes in the member design should be made according to EN 1993-1-1. The equations for angle sections are equal to Design Manual.

EN 1993-1-1: The design ultimate resistance of the net cross-section at holes for fasteners is

$$N_{u,Rd} = \frac{0{,}9A_{net}\,f_u}{\gamma_{M2}}$$

Angles connected through one leg, reference to EN 1993-1-8.

EN 1993-1-3: The design of the net cross-section at holes for fasteners is equivalent to Design Manual. No alternative procedure for angle sections.

EN 1993-1-4: The equations for the resistance of the net cross-section at holes for fasteners are equivalent to Design Manual. No alternative procedure for angle sections.

2.3 Design of block tearing resistance

2.3.1 Design Manual for Structural Stainless Steel

The guidance in EN 1993-1-8 is applicable.

2.3.2 EN Standards

EN 1994-1-8: For a symmetric bolt group subject to concentric loading the design block tearing resistance$V_{eff,1,Rd}$ is given by:

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

where:

A_{nt} is net area subjected to tension;

A_{nv} is net area subjected to shear.

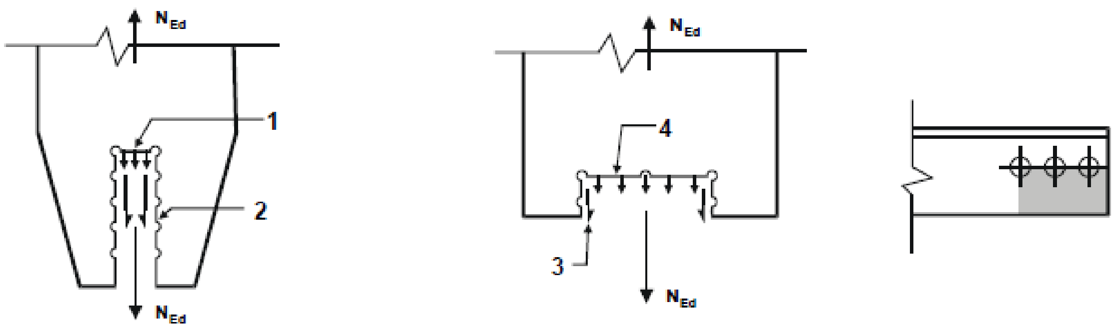

Figure 3. Block shear failure modes.

EN 1993-1-4: No alternative procedure.

EN 1993-1-1: The resistance of joints is calculated according to EN 1993-1-8.

EN 1993-1-3: No alternative procedure.

3 Design of connections using self-tapping screws

3.1 Design Manual for Structural Stainless Steel

The design of connections for stainless steel sheets using self-tapping screws can be calculated in accordance with EN 1993-1-3, but the reduced value $f_{u,red}$ for the tensile strength should be used in place of f_u.

3.2 EN Standards

EN 1993-1-4: The design of connections for stainless steel sheets using self-tapping screws should be in accordance with EN 1993-1-3. [Note: Use of reduced value $f_{u,red}$ is not presented.]

EN1993-1-3: For design by calculation the resistances of mechanical fasteners subject to predominantly static loads should be determined from:

Bearing resistance: $F_{b,Rd} = \alpha f_u d t / \gamma_{M2}$

In which α is given by the following:

- if $t = t_1$: $\alpha = 3{,}2\sqrt{t/d}$ but $\alpha \leq 2{,}1$
- if $t_1 \geq 2{,}5t$ and $t < 1{,}0$ mm: $\alpha = 3{,}2\sqrt{t/d}$ but $\alpha \leq 2{,}1$
- if $t_1 \geq 2{,}5t$ and $t \geq 1{,}0$ mm: $\alpha = 2{,}1$
- if $t < t_1 < 2{,}5t$: obtain α by linear interpolation.

Net-section resistance: $F_{n,Rd} = A_{net} f_u / \gamma_{M2}$

- f_u is the ultimate tensile strength of the supporting member into which a screw is fixed
- d is the nominal diameter of the fastener [Note: Nominal size of tapping screws is usually given by outer diameter. Inner diameter of EN ISO 1478 tapping screws is normally only 70–80% of the nominal diameter]
- t is the thickness of the thinner connected part or sheet
- t_1 the thickness of the thicker connected part or sheet.

Range of validity:

Generally:	$e_1 \geq 3d$	$p_1 \geq 3d$	$3{,}0 \text{ mm} \leq d \leq 8{,}0 \text{ mm}$
	$e_2 \geq 1{,}5d$	$p_2 \geq 3d$	

EN 1993-1-1: The resistance of joints is calculated according to EN 1993-1-8.

EN 1994-1-8: No rules for connections of sheets using self-tapping screws.

4 Deformation criterion of connections

4.1 Bolted connections

4.1.1 Design Manual

The Design Manual informs that to restrict irreversible deformation in bolted connections, the stresses in bolts and net cross-sections at bolt holes under the characteristic load combinations should be limited to the yield strength.

In the Commentary part of Design Manual [7] there is given additional background information. There is mentioned that the reduced value of $f_{u,red} = 0.5 f_y + 0.6 f_u$ is used in design equations to limit the deformations. The formula has been derived by examining the loads at which the deformations is 3 mm for those specimens undergoing bearing deformation. At the ultimate limit state, the deformation will be rather less than 3 mm because of the application of γ_{M2}. At serviceability loads the deformation will be substantially less, due to absence of the load factor, and is likely to be of the order of 1 mm. This must be seen in the context of a possible slip of up to 2 mm (for M16 bolts and upwards) as the bolt goes into bearing.

In the Commentary of Design Manual there is in the context “New data from CTICM” proposed that 1.75 mm permanent deformation of a cover plate connection is acceptable at the serviceability state and a 5 mm permanent bearing deformation is acceptable at the ultimate limit state. The test programme also confirmed that the design rule for austenitic and duplex stainless steel bolted joints could be applied to ferritic stainless steels.

4.1.2 Other literature

In reference [9] is presented a study of the bearing failure in stainless steel bolted connections. There is mentioned 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, there is also mentioned that many researchers have used in development of bearing design equations the maximum load attained in the tests, regardless of the associated deformation. Therefore new bearing design equations for both thick and thin material are given. They cover two cases – one restricting and one ignoring serviceability deformations (Table 2). When strength is the determining factor, the bearing capacity is taken as the maximum load attained in loading regardless of the associated deformation. When serviceability deformations are a determinant, the service load is limited to a value which is corresponding to 1.0 mm hole elongation. Parametric FEM studies verified by test results have been utilised as the basis for the design provisions.

Table 2. Bearing design equations proposed in ref. [9].

	Connections composed of thick plates
Deformation under service loads is not a design consideration	$N_{b,frac,prop} = \alpha_1\, t\, d f_u$ where: $\alpha_1 = \begin{cases} 2.5\left(\frac{e_1}{3d_0}\right) \le 2.5 \text{ for } e_2/d_0 > 1.5 \\ 2.5\left(\frac{e_1}{3d_0}\right) \le 2.0 \text{ for } e_2/d_0 \le 1.5 \end{cases}$
Deformation under service loads is a design consideration	$N_{b,def,prop} = \alpha_2\, t\, d f_u$ where: $\alpha_2 = 1.25\left(\frac{e_1}{2d_0}\right) \le 1.25$

Connections composed of thin plates	
Inner sheets in double shear connections	Single shear connections and outer sheets in double shear connections
$N_{b,frac,prop} = \alpha_1\, t\, d f_u$ where: $\alpha_1 = \begin{cases} 2.5\left(\frac{e_1}{3d_0}\right) \le 2.5 \text{ for } e_2/d_0 > 1.5 \\ 2.5\left(\frac{e_1}{3d_0}\right) \le 2.0 \text{ for } e_2/d_0 \le 1.5 \end{cases}$	$N_{b,frac,prop,c} = \alpha_3\, t\, d f_u$ where: $\alpha_3 = 1.6\left(\frac{e_1}{2d_0}\right) \le 1.6$
$N_{b,def,prop} = \alpha_2\, t\, d f_u$ where: $\alpha_2 = 1.25\left(\frac{e_1}{2d_0}\right) \le 1.25$	$N_{b,def,prop} = \alpha_2\, t\, d f_u$ where: $\alpha_2 = 1.25\left(\frac{e_1}{2d_0}\right) \le 1.25$

In reference [10] strength at 3 mm hole elongation, predicted by FEM, has been used as the basis for bearing strength of stainless steel bolted plates in tension. Considering the average values for the ultimate strength ratios between FE and code predictions for both standard (n = 8) and high strength Duplex (n = 5) grades, the numerically achieved ultimate strengths are in average 20–25% higher than the predictions based on Design Handbook, when the partial safety factor is set as unity.

Paper [11] is focused on the structural behaviour of the single shear bolted connections with thin-walled ferritic stainless steel. Ultimate strength has been taken as proof strength even if the deformations at limit state have been even 20–25 mm. An experimental study for single shear bolted connections with thin-walled ferritic stainless steel (plate thickness 3,0 mm, bolt diameter 12 mm) have been performed in order to investigate the structural behaviour of connections, such as the ultimate strength, the fracture mode and the curling effect. End distance parallel to the direction of applied load (24–60 mm) and bolt arrangements (4 types) were chosen as main variables in the specimens. The ultimate strength obtained from test results was compared with those predicted by the current design standards such as AISC, AIJ, AISI NAS, SEI/ASCE and EN. It has been concluded that the current standards underestimated the ultimate strength of ferritic stainless single shear bolted connections except block shear failure and some curled specimens of four bolt series, where the resistance was overestimated by existing codes. Revised equations were proposed.

Reference [12] examines the mechanisms for block shear failure of bolted connections in steel plates postulated in the design equations specified in the North American, European, and Australian steel structures codes. The paper proposes a rational equation that is demonstrated to provide more accurate results than all the code equations in predicting the block shear capacities of bolted connections in G450 steel sheets subjected to concentric loading. The criterion of the proposed equation is the ultimate load in tests. The resistance factor of 0.8 for the proposed equation is computed with respect to the LRFD approach given in the North American specification for the design of cold-formed steel structures. The equations are based on test series for 1.5 and 3 mm thick double lap specimens with f_y of 605 and 530 MPa. Connections had bolts M12 and M16 in single row and in two rows. Total number of test was 19.

Reference [13] examines net section tension capacity of bolted connections in flat steel sheets postulated in the design equations specified in the North American, European, and Australian steel structures codes. The resistance factor of 0,8 for the proposed equation is computed with respect to the load and resistance factor design (LRFD) approach specified in the North American specification for the design of cold-formed steel structures. The criterion of the proposed equation is the ultimate load in tests. The equations based on test series for 1.5 and 3 mm thick single and double lap specimens with f_y of 605 and 530 MPa. The configurations of specimens tested in the laboratory included single shear- and double-shear connections, with single or double bolts in a line parallel or perpendicular to the force. Connections had bolts M12 and M16 in parallel or transverse positions. Total number of test was about 60. The work points out that the shear lag factors embedded in the code equations either yield 'anomalous' results or become irrelevant when they exceed unity. The 'anomaly' was demonstrated through laboratory tests and is explained by using simple calculus. A proper mathematical expression for the in-plane shear lag factor, which does not suffer from the anomaly of the code equations and never implies shear lag factors greater than unity for any configuration, is presented and shown to yield improved results compared to the current specifications.

4.2 Connections using self-tapping screws

4.2.1 Design Manual

No information about deformations is given either in Design Manual or in its Commentary, but however in Design Manual it is mentioned that he reduced value for the tensile strength $f_{u,red}$ should be used in design.

4.2.2 Other literature

In ECCS guidance for testing of mechanical fasteners in shear [14] it is recommended to define the failure load by the peak load at deformation of 3 mm (Fig. 4). Load deformation is measured over the connection using gauge length of 150 mm (fastener diameter ≤ 6.5 mm).

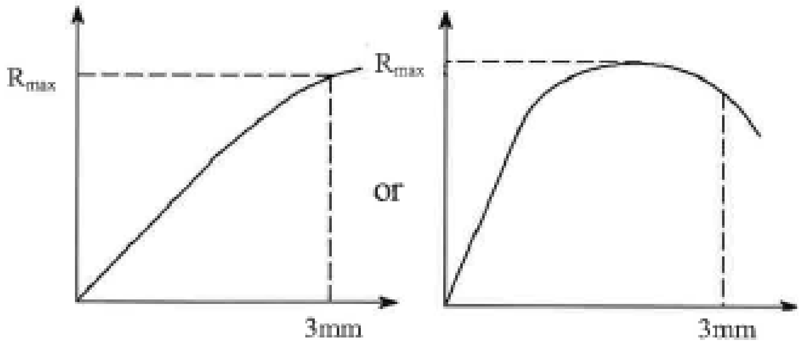

Figure 4. Failure limits for tests given in ref. [14].

5 Definition of test programme

Based on Eurocode design requirements, a programme of lap shear connection tests described in reference [1] was defined. Austenitic stainless steel bolts (M12) joining ferritic material with thickness of 0.8–5.5 mm were tested. The single and double shear specimens were dimensioned such that the relevant failure modes were demonstrated. Net section failure, bearing failure (deformations of holes) and block shear ('pull into line') failures were studied. In addition single lap specimens for self-drilling screws joining materials with thickness of 0.5–1.2 mm were tested. Tests were carried out in order to demonstrate the different failure modes (shear failure, bearing failure, tilting failure and pull-out failure).

5.1 Bolted connections

Types of bolt groups and the principle of testing are shown in Fig. 5. Types A–D are for single and double shear tests, and types E and F are for equal angle tests. One or two tests for each specimen configuration were carried out. The nominal dimensions of specimens (Fig. 6) and predicted failure modes are given in Tables 3 and 4. The spacing of holes is determined so that they agree with the minimum values given in Eurocodes.

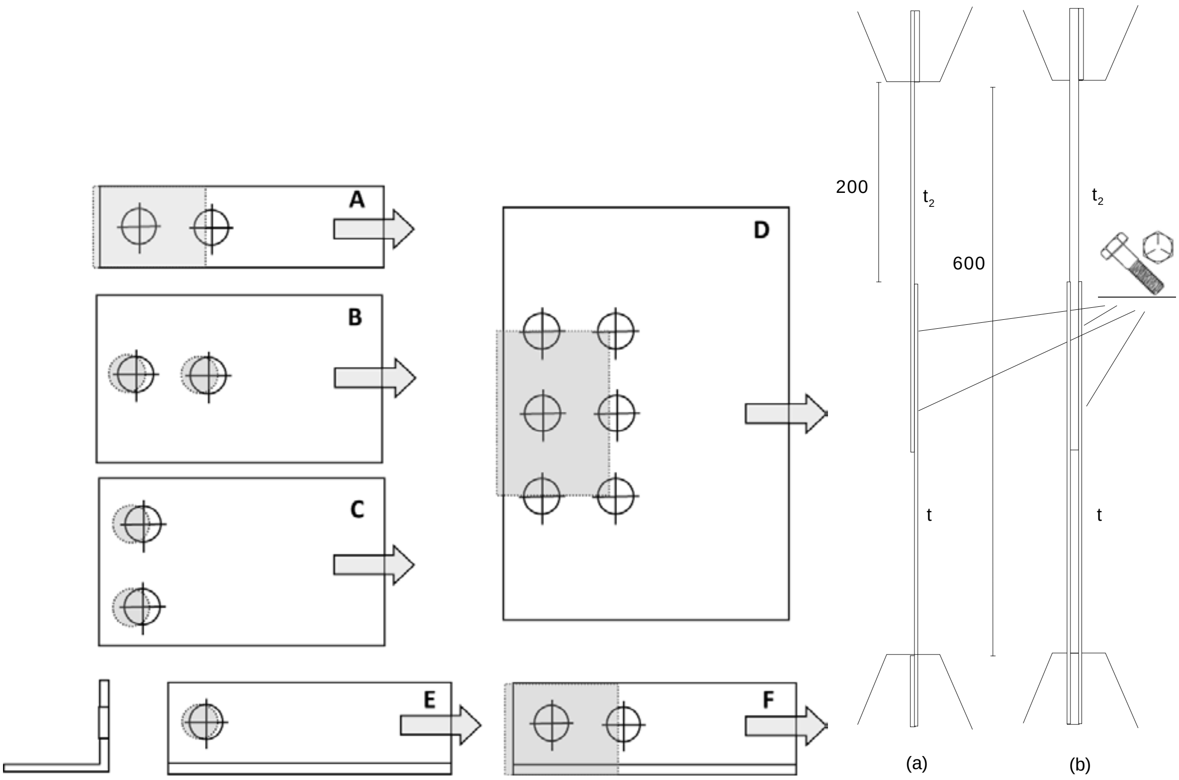

Figure 5. Connection types in shear lap tests (A–F). (a) Specimen for single shear tests. (b) Specimen for double shear test.

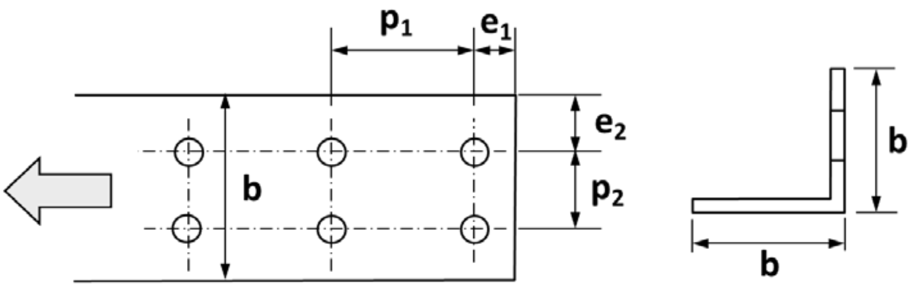

Figure 6. Symbols in Tables 3 and 4.

Table 3. Specimen dimensions as illustrated in Fig. 6 for single and double shear tests (Fig. 5, types A, B, C and D).

Final failure	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	-	32 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

Table 4. Specimen dimensions as illustrated in Fig. 6 for angle bar tests (Fig. 5, types E and F).

Final failure	Single shear	Double shear	Number of bolts	b	e_1	e_2	p_1
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

One bolt size of M12 (diameter d = 12 mm, DIN 933) with hole diameter 13 mm is used. Grade A2 austenitic stainless steel bolts to EN ISO 3506 property classes 70 with nominal values of f_{yb} = 450 N/mm^2 and f_{ub} = 700 N/mm^2 was used except of some comparative carbon steel specimens where normal class 8.8 bolts were employed. The bolts were fully threaded so that the same bolts could be used for all plate thicknesses. In the single shear tests with bolt in one row (types C1, E1) the bolts were provided with washers (M12, DIN 125) under both the head and the nut.

The tensile stress area of the bolts is 84.3 mm^2 which results in shear resistances of 34.1 kN in stainless and 38.9 kN in carbon bolts. The resistance is also reduced because of the thickness t_p of the connection, if the total thickness t_p > d/3 = 4 mm. The reduction factor β_p (3.6.1 (2) in EN 1993-1-8) is 0.82 for t_p = 12 mm and 0.69 for t_p = 20 mm.

The test material was cut so that the loading of the connection is always the rolling direction of the sheets. Holes were made by drilling with a drill of 13 mm diameter. The bolts are tightened so that the friction did not affect the results.

Based on the hole diameter d_0 = 13 mm, the specimen dimensions given in Tables 3 and 4 are: 1.6d_0 = 21 mm, 3.2 d_0 = 42 mm, 6.4 d_0 = 83 mm and 16 d_0 = 208 mm. The length of one connecting plate was 470 mm in all tests.

5.2 Screwed connections

Both one and single screw specimens are tested. The specimen dimensions and the principle of single shear testing are shown in Fig.7. The size of one connecting plate was 50 mm x 320 mm. The test pieces are taken so that the loading direction is always the rolling direction of the sheet. The specimen dimensions are based on ECCS guidance [14]. In addition of the recommended end distance e_1 = 30 mm, use of minimum value of e_1 = 3d = 16.5 mm given in EN1993-1-3 was tested by one screw specimens. The connected parts had equal or unequal thickness, but the thinnest sheet was always next to the head of the screw.

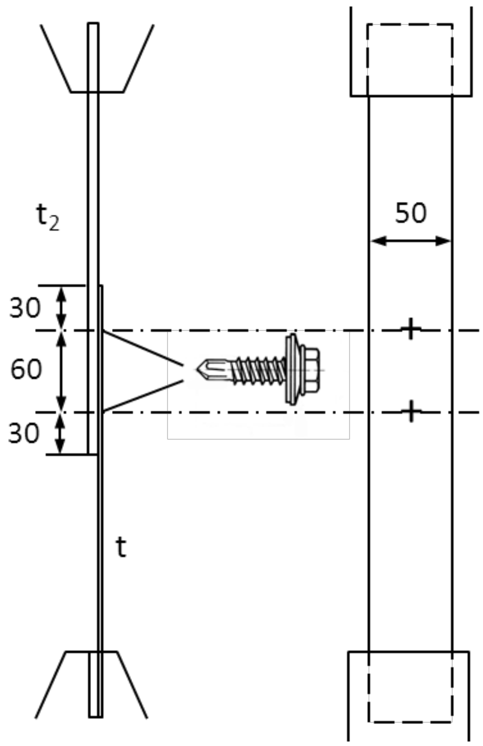

Figure 7. Specimen dimension for screwed connections (e_1 = 30 mm, p_1 = 60 mm).

Austenitic stainless steel stainless steel self-drilling screws with nominal diameter of d = 5.5 (corrosion class A2, DIN 7504K) were used in test specimens (EN ISO 1478: outer diameter 5.28–5.46 mm, inner diameter 3.99–4.17 mm, thread pitch 1.8 mm). Then the predicted failure mode in all tests was bearing failure (hole elongation, out of plane curling).

Self-drilling screws have an own drill point which forms the pilot hole. Because the drill point was not hard enough to drill all thicknesses properly, pre-drilled clearance holes with diameter of d_0 = 4.0 mm was utilized in all specimens.

5.3 Test programme

One ferritic stainless steel of grade 1.4509 was used in the case of all specimens except of the comparative carbon steel specimens where grade S355 was employed. Material thicknesses and test identification codes for bolted connections are presented in Table 5. Same information for screwed connections is given in Table 6. The test identification code indicates the type of specimen and the nominal thickness of the materials. One or two identical tests were carried for each bolted connection, and in the case of screwed connections the number of repeats was three.

The gauge length for measuring the elongation over the connection was 500 or 600 mm for bolted connections (Table 5) and 300 or 400 mm for screwed connections (Table 6).

Table 5. Materials and test identification codes of bolted connections (specimen types A - F are shown in Fig. 5).

Type of test	Test identification code	Material 1, thickness [mm] and grade	Material 2, thickness [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 $t \geq 3$ 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 $t \geq 3$ 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*	50 S355	10 S355
Angle bar test $t \geq 3$ 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 6. Materials and test identification codes of screwed connections (specimen type is shown in Fig. 7, distances e_1 and p_1 are shown in Fig. 6).

Plate thicknesses in test (t and t_2, see Fig. 7)						
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
Test identification codes						
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 $e_1 = 30$ mm $p_1 = 60$ 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.

6 Test results

6.1 Material properties

The properties of used materials are shown in Table 7. The values are mean values of three identical tests. The test pieces are taken in the rolling direction of the sheets, which is also the loading direction of the specimens. The tested proof strengths seem to be slightly lower than the values given in material certificates, but higher than nominal values. The nominal values of $R_{p0,2}$ and R_m are 230 and 430 MPa for grade 1.4509 (EN 10088-4:2009, cold rolled strip). For carbon grade S355 nominal values of $R_{p0,2}$ and R_m are 355 MPa and 470 MPa (EN 10025-2).

Table 7. Properties of test materials. The values in parentheses have been provided by the material supplier.

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

ID	Grade	t	a	$R_{p0.2}$	R_m	A_{LO}
S05	1.4509	0.5	0.52	276 (303)	457 (465)	32 (31)
S08	1.4509	0.8	0.80	327 (345)	478 (484)	30 (29)
S12	1.4509	1.2	1.20	311 (331)	456 (471)	33 (29)
S20	1.4509	2.0	1.97	334 (343)	463 (490)	34 (28)
M-3	1.4509	3.0	2.93	295 (322)	447 (501)	36 (37)
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

6.2 Bolted connections

Appendix A shows typical load-displacement curves and failure modes of test specimens. General comments on the results are as follows:

- Net section type of failure occurred in A1 type connections ($t < 3$ mm and $t \geq 3$ mm), as predicted.
- Bearing type of failure was dominating in B1 type connections, as predicted. Out-of-plane deformations were large in the case of $t < 3$ mm connections and they were also detectable to some extent in the case of $t \geq 3$ mm. In the case of $t = 4.5$ mm the final failure was bolt shear after large deformation of holes.
- Bearing type of failure occurred in type C1 connections, as predicted, but out-of-plane deformations were large in all tests ($t < 3$ mm and $t \geq 3$ mm).
- Block shear failure type failure occurred in D1 type connections, as predicted, but large out-of-plane deformations were large specially in the case of tests for $t < 3$ mm.

- Net section failure type of failure occurred in A2 type connections (t = 3/5.5 mm), as predicted.
- Bearing type of failure was dominating in B2 type connection for t = 3/5.5 mm, as predicted. In the case of B2-510S the final failure was bolt shear after large deformation of holes.
- Bearing type of failure was dominating in C2 type connection for t = 3/5.5 mm without significant out-of-plane deformations, as predicted. In the case of C2-510 and C2-510S the final failure was bolt shear after large deformation of holes.
- Block shear failure type failure was dominating in D2 type connection with t = 3/5.5 mm, as predicted. In the case of D2-510 and D2-510S the final failure was bolt shear after clearly visible deformation of holes.
- Bearing type of failure was dominating in E1 type connections (t = 3 mm and t = 4.5 mm), as predicted. In the case of t = 4.5 mm the final failure was bolt shear after large deformation of holes.
- Net section failure type of failure was dominating in F1 type connections (t = 3 mm and t = 4.5 mm), as predicted. In the case of t = 4,5 mm the final failure was bolt shear after large deformation of holes.

Figures 8–11 give a summary of the measured loads per screw and per shear plane. The values shown represent the results with 3 mm elongation, 6 mm elongation and maximum load. The numerical values of figures are given in Appendix C. The results are taken from test report [2], but some of results, which are based on deformations (marked by asterisk in the figures), are corrected. In those cases the deformations at the beginning of the experiment were unusually large before significant increase of the force.

The results shown by red colour in Figures 8–11 represent load at deformation of 3 mm in one connected part. Depending on the type of connection the deformation can correspond to either total elongation of 3 mm or 6 mm. The reason for that is that in the case where another plate is thick, the deformation concentrates only on one part.

The following paragraphs describe the general findings on different types of connections.

Findings concerning single shear tests with t < 3 mm (Fig.8):

- Total deformation at maximum load is 6–20 mm (Appendix A).
- B1 type connections have higher resistance per bolt than A1 type connections.
- C1 type connections have slightly higher resistance than B1 type connections except of test S2020-C1.
- D1 type connections have lower resistance per bolt than B1 and C1 type connections. Resistance per bolt of D1 type connections are most near the resistance of A1 type connections.
- Clear dependence on back plate thickness is not observable.

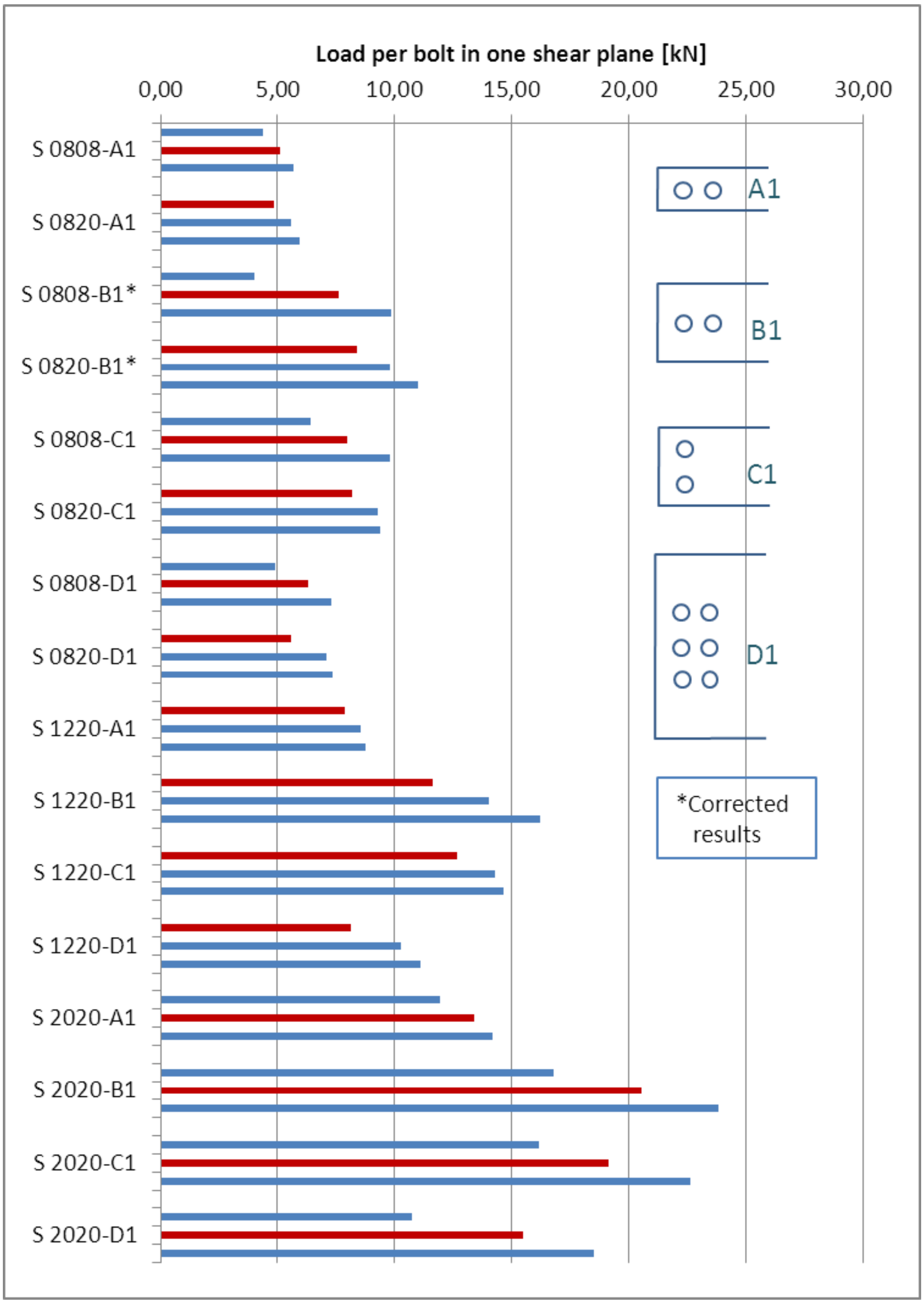

Figure 8. Results of bolted connections, single shear tests for t < 3 mm. The two first bars present loads at 3 and 6 mm elongation and the third corresponds to the maximum load.

Findings concerning single shear tests with t ≥ 3 mm (Fig. 9):

- Total deformation at maximum load is 12–24 mm (Appendix A).
- B1 type connections have higher resistance per bolt than A1 type connections.
- C1 type connections have about same resistance than B1 type connections.
- D1 type connections have lower resistance per bolt than B1 and C1 type connections.
- Resistance per bolt of D1 type connections are most near the resistance of A1 type connections.

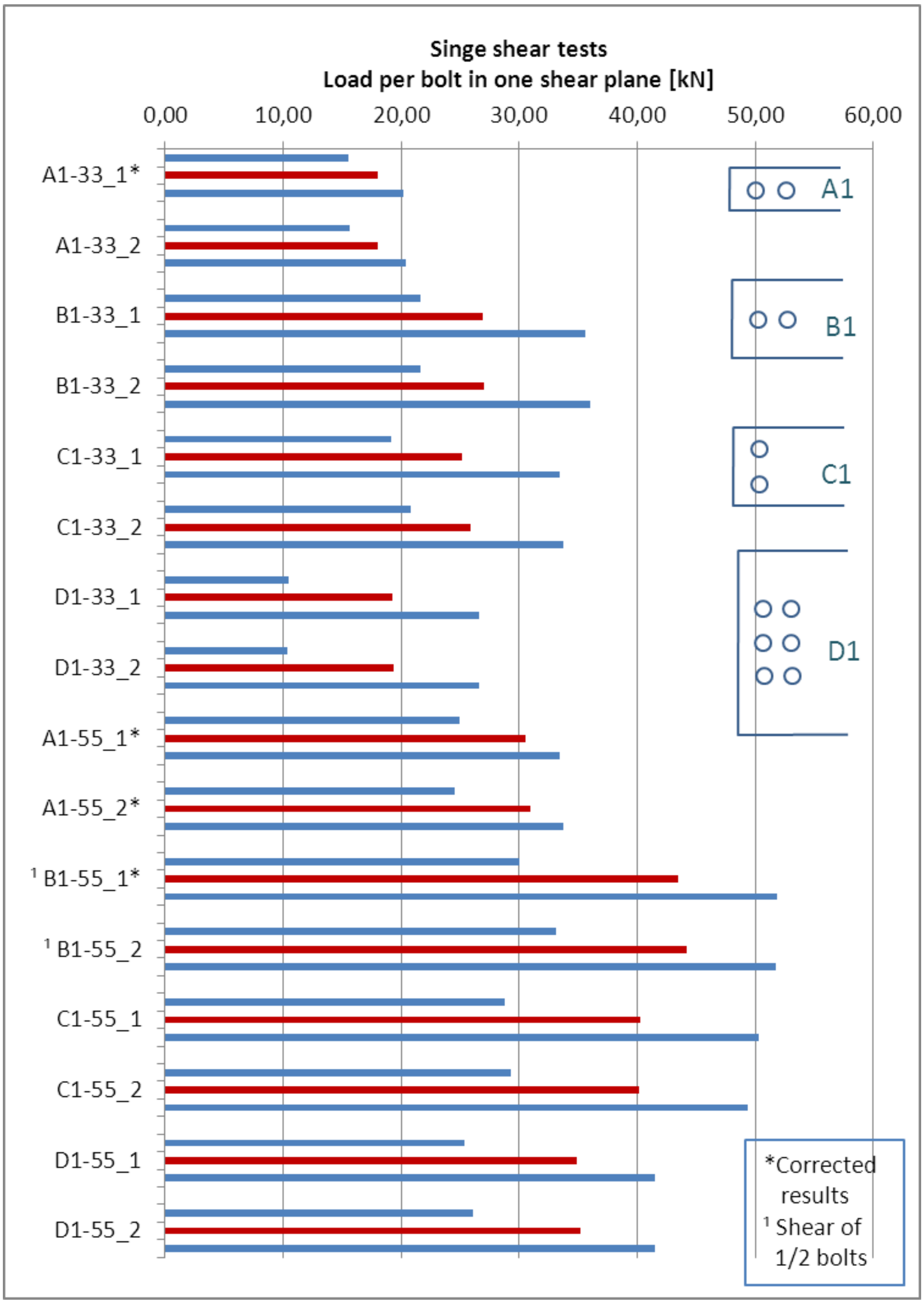

Figure 9. Results of bolted connections, single shear tests for t ≥ 3 mm. The two first bars present loads at 3 and 6 mm elongation and the third corresponds to the maximum load.

Findings concerning double shear tests with t ≥ 3 mm (Fig. 10):

- Total deformation at maximum load is 6–18 mm (Appendix A).
- B2 type connections have higher resistance than A2 type connections.
- C2 type connections have about same resistance than B2 type connections.
- D2 type connections have lower resistance than B2 and C2 type connections.
- Resistance of D2 type connections are slightly higher than the resistances of A2 type connections.

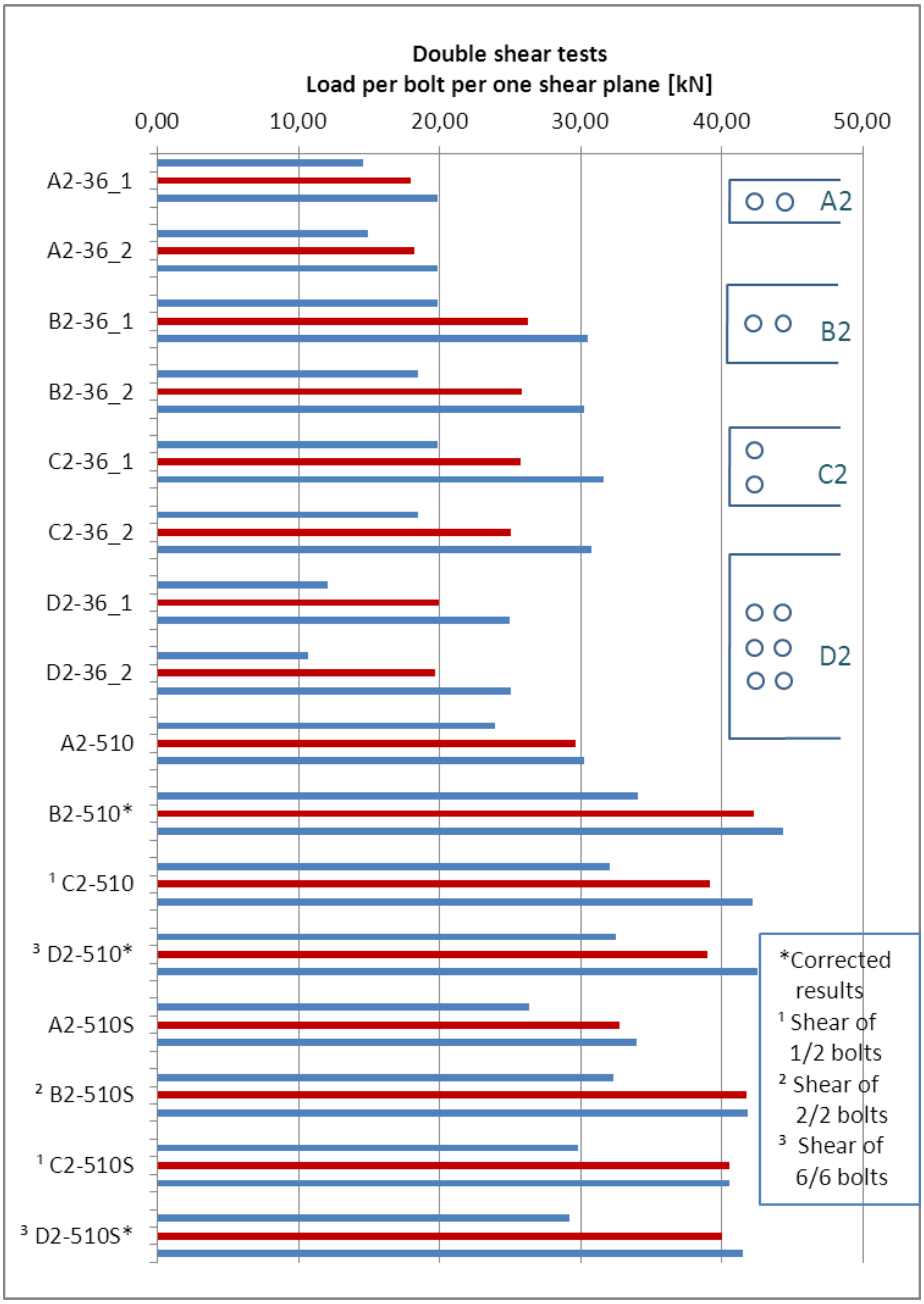

Figure 10. Results of bolted connections, double shear tests for t ≥ 3 mm. The two first bars present loads at 3 and 6 mm elongation and the third corresponds to the maximum load.

Fig. 11 compares the results of single shear tests with the results of double shear tests (t ≥ 3 mm). It shows that the resistances per one shear plane are roughly same in single and double shear tests. Therefore the test results could be studied in same group.

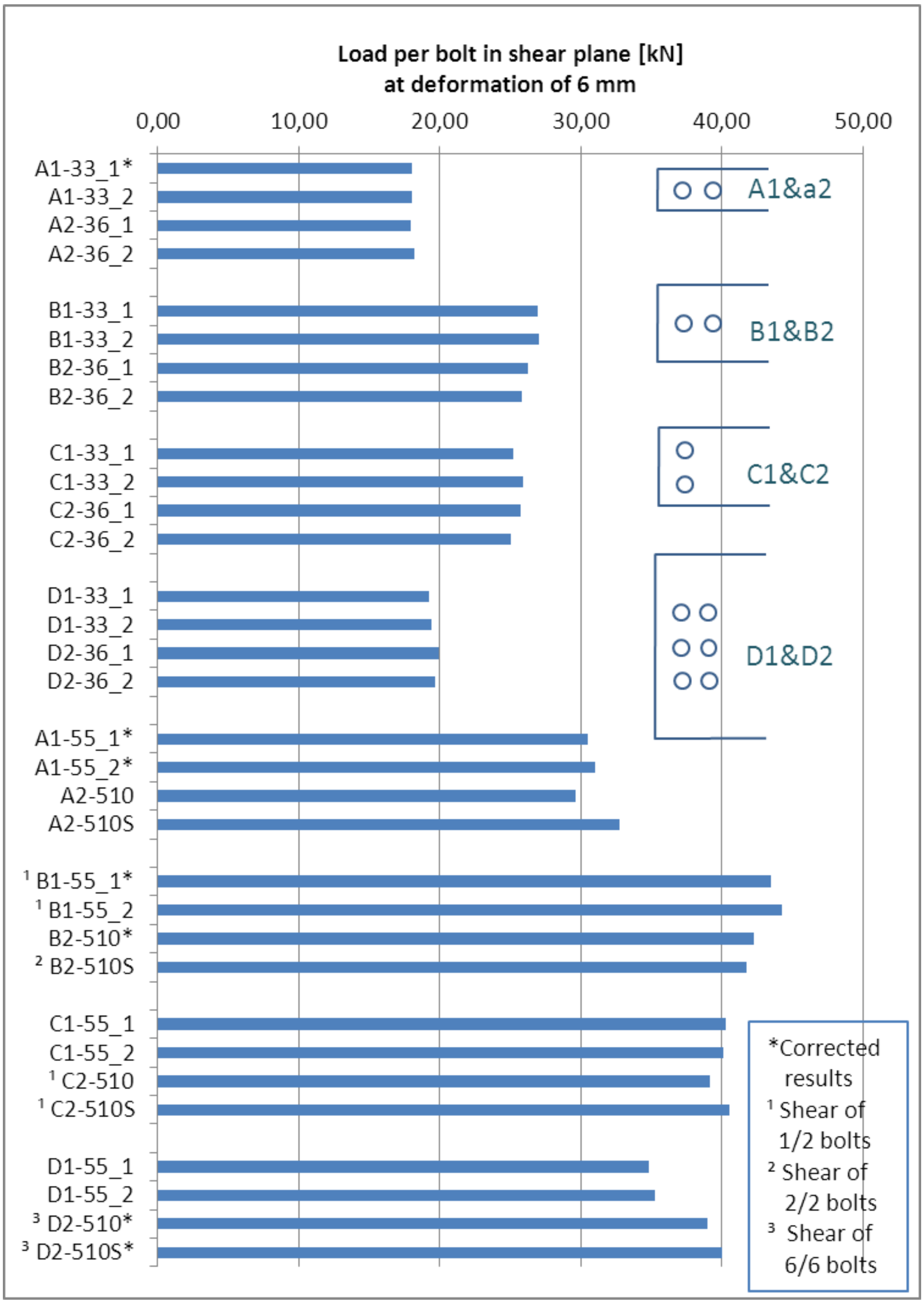

Figure 11. Results for bolt per shear plane, single and double shear tests for t ≥ 3 mm.

Findings concerning angle bar tests with t ≥3 mm (Fig.12):

– Total deformation at maximum load is 15–20 mm (Appendix A).
– Hole elongations were about 5 mm for both E1 and F1
– F1 type connections have lower resistances per bolt than E1 type connections.

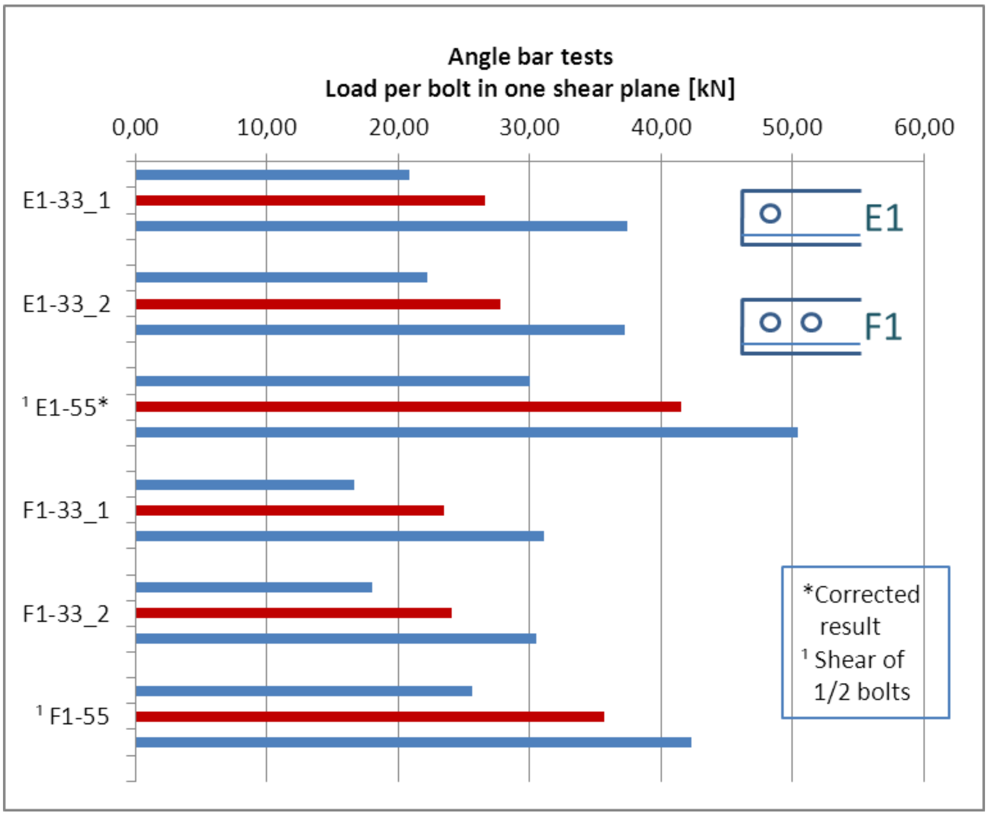

Figure 12. Results for bolt per shear plane, angle bar tests for t ≥ 3 mm. The two first bars present loads at 3 and 6 mm elongation and the third corresponds to the maximum load.

6.3 Screwed connections

Appendix C shows typical load-displacement curves and failure modes of test specimens. Findings concerning single shear tests on screwed connections t <3 mm are shown in Figs. 13 and 14. The numerical values of the figures are given in Appendix D. In most cases large out-of plane deformations and tilting of the screws was observed before the final failure. Other general findings are:

– Total deformation at maximum load is 2–16 mm (Appendix C).
– Maximum load was reached before elongation of 3 mm in S0505 tests.
– Final failure was always shear of screws in S1220-1a tests.
– Final failure was end failure in almost all S0820-1b and S1220-1b tests.
– There is no clear difference in ultimate loads between different types of connections, but the loads at elongation of 3 mm are slightly lower in S0820-2a and S1220-1b tests.
– In general the resistances of connections with equal plates are lower than resistances with thick back plate.

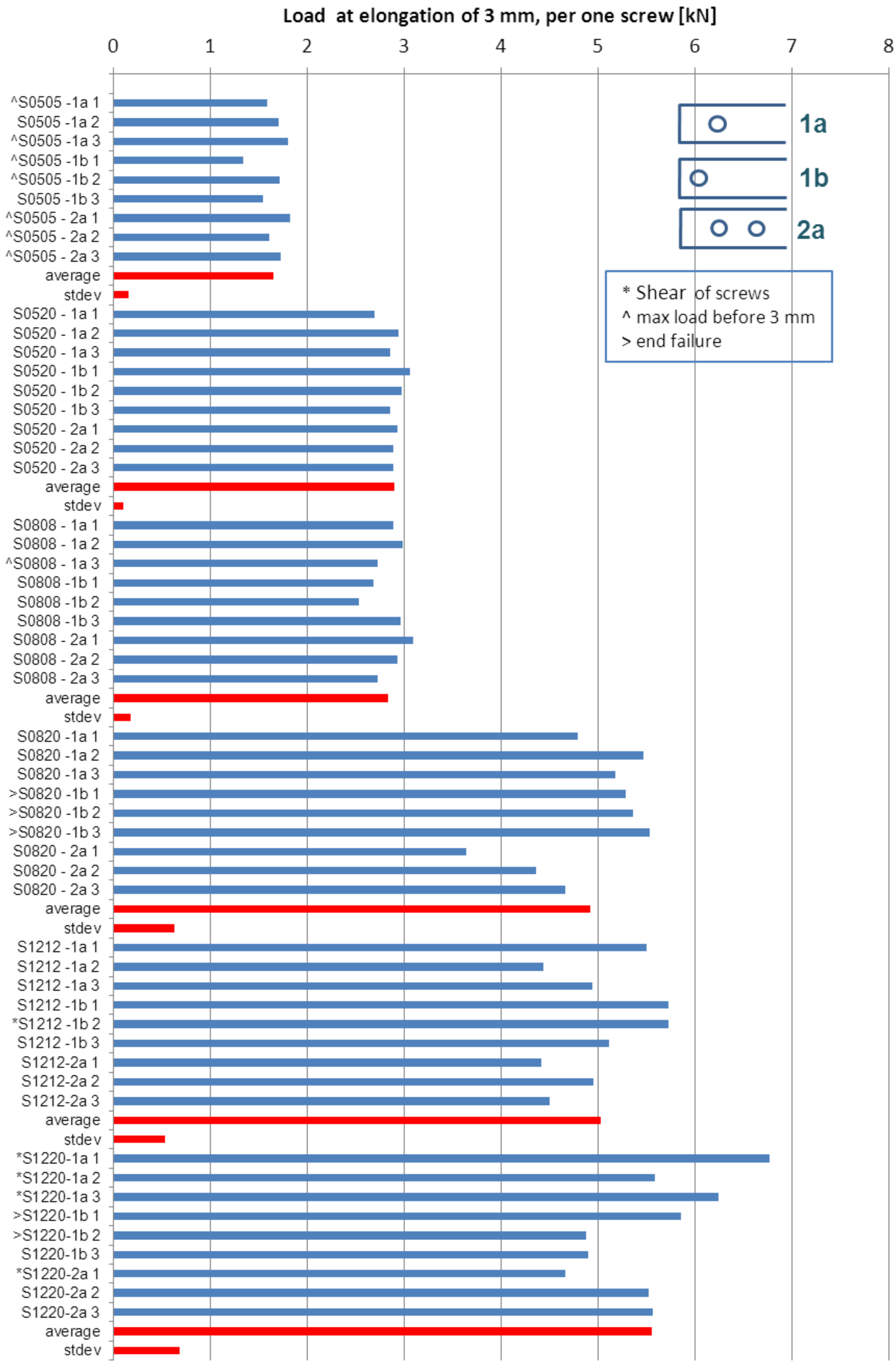

Figure 13. Results of screwed connections (t < 3 mm). Criterion: 3 mm elongation.

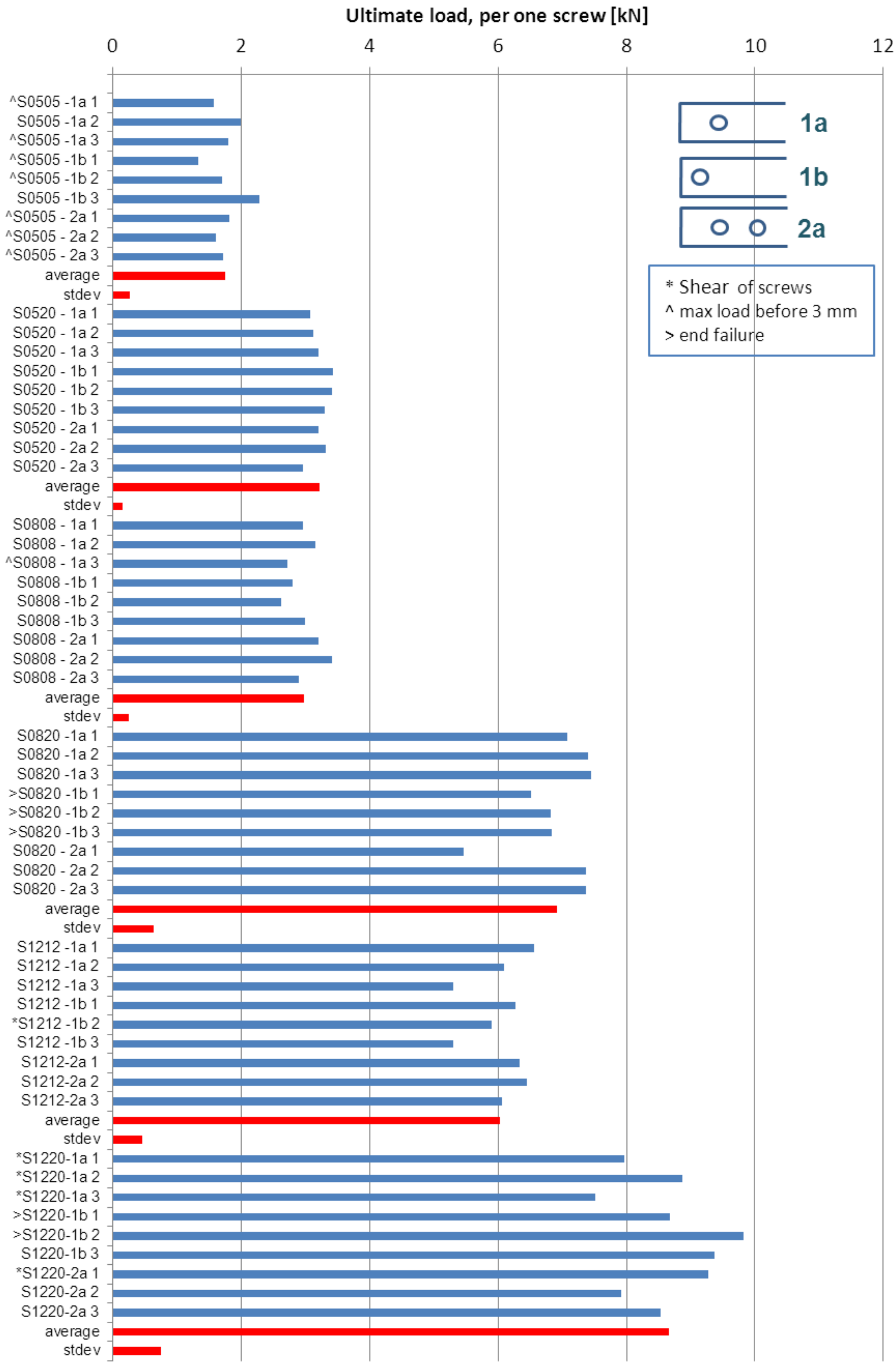

Figure 14. Results of screwed connections (t < 3 mm). Criterion: Ultimate load.

7 Comparison with Eurocode resistances

All resistances are calculated based on measured material properties, and γ_{M2} = 1.0 and γ_{M0} = 1.0. In addition measured values of t, f_y and f_u given in Table 7 are used in comparison. Numerical values of the figures in following comparisons are given in Appendix E.

7.1 Bolted connections

7.1.1 Net section failure

The resistances of test A1, A2 and F1 type failure are determined by the net section failure of the weakest material. The resistances are calculated according to the equations given in Chapter 2.2 using following approaches:

- EN 1993-1-1: Equations from EN 1993-1-1, angles EN 1993-1-8
- EN 1993-1-3: Equations from EN 1993-1-3 which are equal to EN 1993-1-4 and Design Manual
- Both comparison have been made based either f_u or $f_{u,red}$, although the existing design basis is only f_u.

Calculated net section areas of the connections are shown in Tables 8 and 9.

Table 8. Net section areas of type A1 and A2 specimens.

Connection type	EN 1993-1-1	EN 1993-1-3
A1 and A2	$0.9 \cdot 2.2 \cdot d_0 t = 1.98\ d_0 t$	$1.0 \cdot 2.2 \cdot d_0 t = 2.20\ d_0 t$
B1 and B2 *	$0.9 \cdot 5.4 \cdot d_0 t = 4.86\ d_0 t$	$0.784 \cdot 5.4 \cdot d_0 t = 4.23\ d_0 t$
C1 and C2 *	$0.9 \cdot 4.4 \cdot d_0 t = 3.96\ d_0 t$	$1.0 \cdot 4.4 \cdot d_0 t = 4.40\ d_0 t$
D1 and D2 *	$0.9 \cdot 13 \cdot d_0 t = 11.7 d_0 t$	$1.0 \cdot 13 \cdot d_0 t = 13.0\ d_0 t$
* Note: these values are not used, given only for information		

Table 9. Net section areas of type E1 specimens.

Connection type	EN 1993-1-8
E1*	$2.0 \cdot 1.1 \cdot d_0 t = 2.20\ d_0 t$
F1	$0.484 \cdot 5.4 \cdot d_0 t = 2.38\ d_0 t$
* Note: these values are not used, given only for information	

Comparison of the calculated resistances with test results is made based on two criteria, one condition is the ultimate load F_{max} and the second is limit elongation of the connection. In tests S0820-A1 and S1220-A1 (with thick back plates) the criterion for total displacement is 3 mm, in other tests criterion of 6 mm is used.

The comparisons based on f_u are shown in Figs. 15–16. The results show the following:

- No clear difference between tests for t < 3 mm and t ≥ 3 mm
- When the test criterion is F_{max}, EN 1993-1-1 is always on safe side and
- When the test criterion is F_{max}, EN 1993-1-3 is safe except of test A2-510.
- When the criterion is displacement, EN 1993-1-3 is usually unsafe, also EN1993-1 is quite safe in all cases.
- The result for one comparative carbon steel test is more unsafe than the result for A2-510 stainless steel test.
- EN 1993-1-1 is always safe in the case of F1-33 and F1-55 tests.

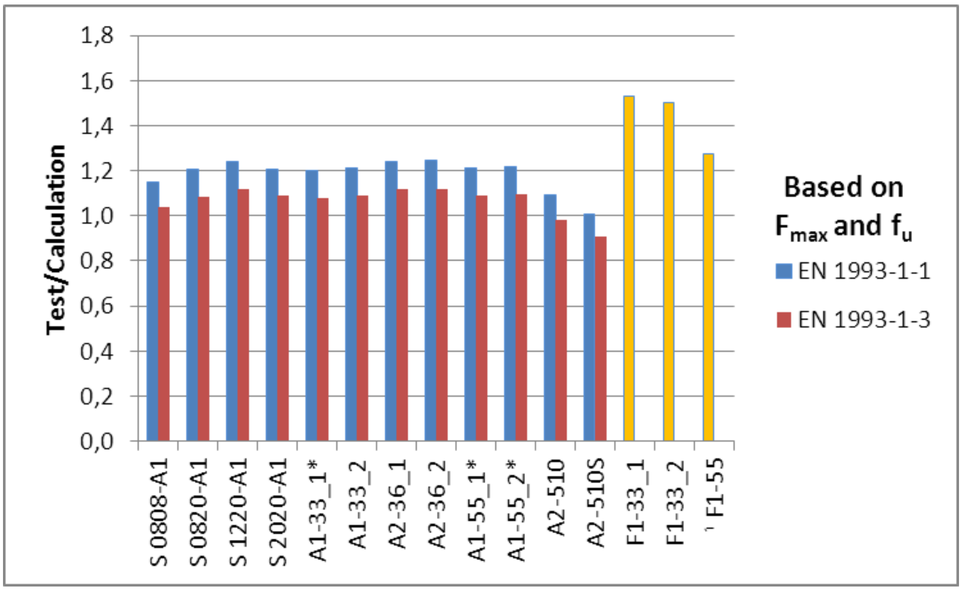

Figure 15. Test results v.s. calculated values: Criterion F_{max}, calculation by f_u.

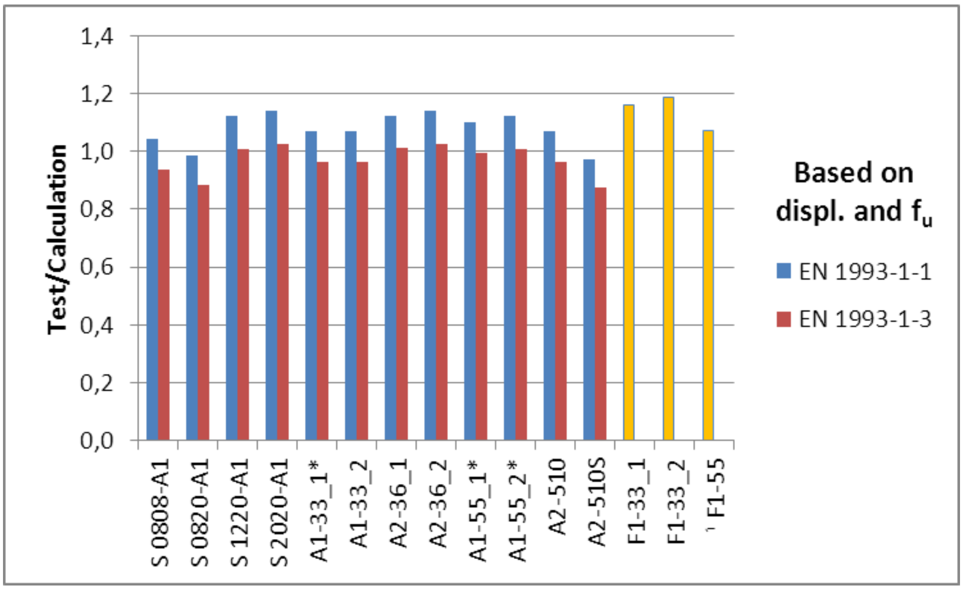

Figure 16. Test results v.s. calculated values: Criterion displacement, calculation by f_u.

The comparisons based on $f_{u,red}$ are shown in Figs. 17–18. The results show the following:

- When the test criterion is F_{max}, both EN 1993-1-1 and EN 1993-1-3 are safe except of comparative carbon steel test A2-510S.
- When the criterion is displacement, EN 1993-1-1 is safe, but EN1993-1-3 is in some tests slightly unsafe.
- Lower F_{max} value of F1-55 compared to F33 may be due to the break of one of the two bolts.

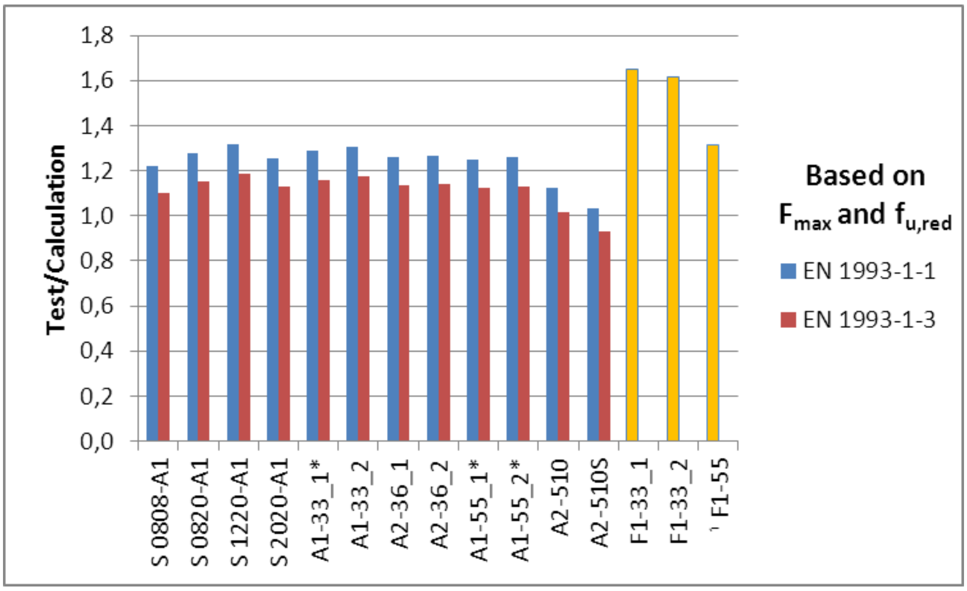

Figure 17. Test results v.s. calculated values: Criterion F_{max}, calculation by $f_{u.red}$.

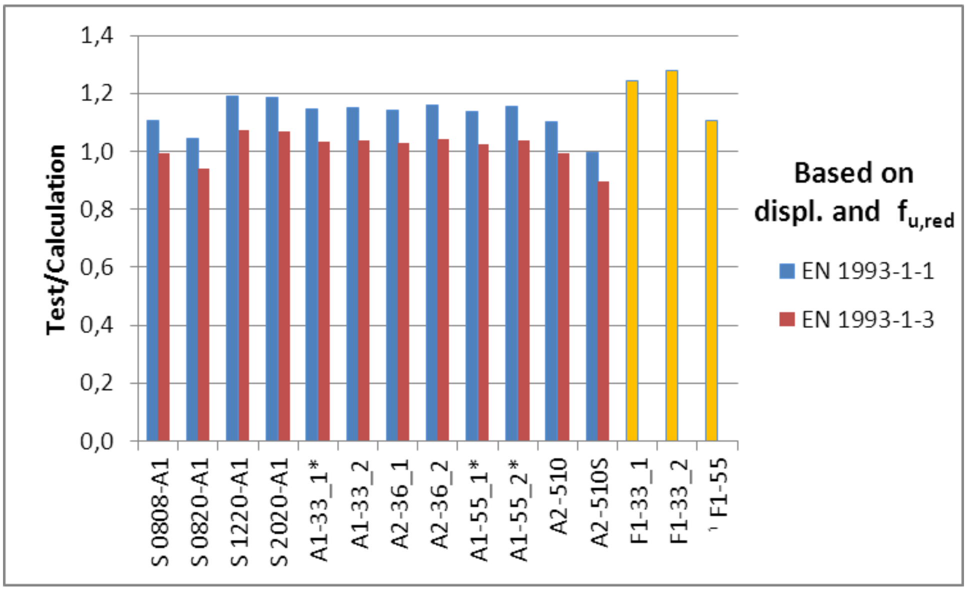

Figure 18. Test results v.s. calculated values: Criterion displacement, calculation by $f_{u.red}$.

Statistical values of the comparisons are shown in Tables 10–11. The characteristic value given in tables is based on Annex A of EN 1993-1-3 and it is calculated by (average – k x stdev). Value of k depends on the number of tests (N). The results in Table 10 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 $f_{u,red}$.

Table 10. Statistical values of test/calculation for S0808-A1… A2-510.

Tests without angles and test A2-510S								
N = 11 k = 1.90	EN 1993-1-1				EN 1993-1-3			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	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
Stdev	0.04	0.05	0.05	0.04	0.04	0.04	0.05	0.04
CoV	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Characteristic	1.12	1.00	1.16	1.06	1.01	0.90	1.04	0.95

In the case of three angle section tests (Table 11):

– 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.

Table 11. Statistical values of test test/calculation for type F1 angles.

Tests on angles (Series F1)				
N = 3 k = 3.37	EN 1993-1-8			
Calculation	f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.
Average	1.44	1.14	1.53	1.21
Stdev	0.14	0.06	0.19	0.09
CoV	0.10	0.05	0.12	0.08
Characteristic	0.96	0.94	0.90	0.90

7.1.2 Bearing type failure

Resistances of B1, B2, C1, C2 and E1 type bolted connections are based on bearing type failure of the weakest material. The resistances are calculated according to the equations given in Chapter 2.1 using following approaches:

– EN 1993-1-8: equations from EN 1993-1-8
– EN 1993-1-3: equations from EN 1993-1-3
– Both comparison have been made based either f_u (EN 1993-1-1, EN 1993-1-3) or $f_{u,red}$ (EN 1993-1-4).

Resistances are based on bearing resistance coefficient is $k_1 \cdot \alpha_b$ according to EN1993-1-8 and $2.5 \cdot \alpha_b \cdot k_t$ according to EN 1993-1-3. Calculated values of these coefficients are shown in Tables 12–15. It should be noted that the resistance of the connection is the sum of the resistances of weakest fasteners. Therefore in the case of B1 and B2 type connections the resistance can be based on two holes in one lap or on the end holes in separate laps.

Table 12. Coefficient $k_1 \cdot \alpha_b$ for two bolt connections according to EN1993-1-8.

Connection type	Screw 1	Screw 2	Sum
A1 and A2*	2.5·0.533 = 1.33	2.5·0.817 = 2.04	3.37
B1 and B2	2.5·0.533 = 1.33	2.5·0.817 = 2.04	3.37
C1 and C2	2.5·0.533 = 1.33**	2.5·0.533 = 1.33*	2.66
* Note: these values are not used, given only for information ** Note: values are leess than 1.5, which is the limit for single lap joint with only one bolt row			

Table 13. Coefficient $2.5 \cdot \alpha_b \cdot k_t$ for two bolt connections according to EN1993-1-3.

Connection type	Screw 1	Screw 2	Sum
B1 and B2, t = 0.8 mm	2.5·0.578· 0.856 = 1.24	2.5·1.0· 0.856 = 2.14	3.38
B1 and B2, t = 1.2 mm	2.5·0.578· 0.984 = 1.42	2.5·1.0· 0.984 = 2.46	3.88
B1 and B2, t > 1.25 mm	2.5·0.578·1.0 = 1.45	2.5·1.0· 1.0 = 2.50	3.95
C1 and C2, t = 0.8 mm	2.5·0.578· 0.856 = 1.24	2.5·0.578· 0.856 = 1.24	2.48
C1 and C2, t = 1.2 mm	2.5·0.578· 0.984 = 1.42	2.5·0.578· 0.984 = 1.42	2.84
C1 and C2, t > 1.25 mm	25·0.578·1.0 = 1,45	2.5·0.578·1.0 = 1.45	2.90

Table 14. Coefficient $k_1 \cdot \alpha_b$ for angle bar connections according to EN1993-1-8.

Connection type	Screw 1	Screw 2	Sum
E1	2.5·0.533 = 1.33		1.33**
F1 *	2.5·0.533 = 1.33	2.5·0.817 = 2.04	3.37
* Note: these values are not used, given only for information ** Note: value < 1,5, which is the limit for single lap joint with only one bolt row			

Table 15. Coefficient $k_1 \cdot \alpha_b$ for angle bar connections according to EN1993-1-3.

Connection type	Screw 1	Screw 2	Sum
E1, t > 1.25 mm	2.5·0.578·1.0 = 1.45		1.45
F1*, t > 1.25 mm	2.5·0.578·1.0 = 1.45	2.5·1.0·1.0 = 2.50	3.95
* Note: these values are not used, given only for information			

When the results are evaluated it must take into account that in design the shear resistance $F_{v,Rd}$ of the fastener should be greater than the design bearing resistance $F_{b,Rd}$. In the case of tests B1/C1-55, B2/C2-510, B2/C2-510S and E1-55 the measured ultimate loads are about 50% higher than the calculated shear resistance of the bolts. Therefore in these tests the shear resistance may limit the bearing resistance.

Comparison of the calculated resistances with test results is made based on two criteria, one condition is the ultimate load F_{max} and the second is limit elongation of the connection. In tests S 0820-B1 and S 1220-B1 (with thick back plates) the criterion for total displacement is 3 mm, in other tests criterion of 6 mm is used.

The comparisons of B1 and B2 type tests shown in Figs. 19–22. The results show the following:

- No clear difference between the tests for $t < 3$ mm and $t \geq 3$ mm.
- Double lap (B2) tests give slightly more unsafe results than single lap (B1) tests.
- When the failure criterion is F_{max}, regardless of whether f_u or $f_{u,red}$ is used in calculation, both EN 1993-1-8 and EN 1993-1-3 are safe except of test B2-510S.
- When the criterion is displacement, EN 1993-1-8 is always safe regardless of whether f_u or $f_{u,red}$ is used in calculation, also EN 1993-1-1 is in both cases safe except of tests S1220-B1 and B2-510S.

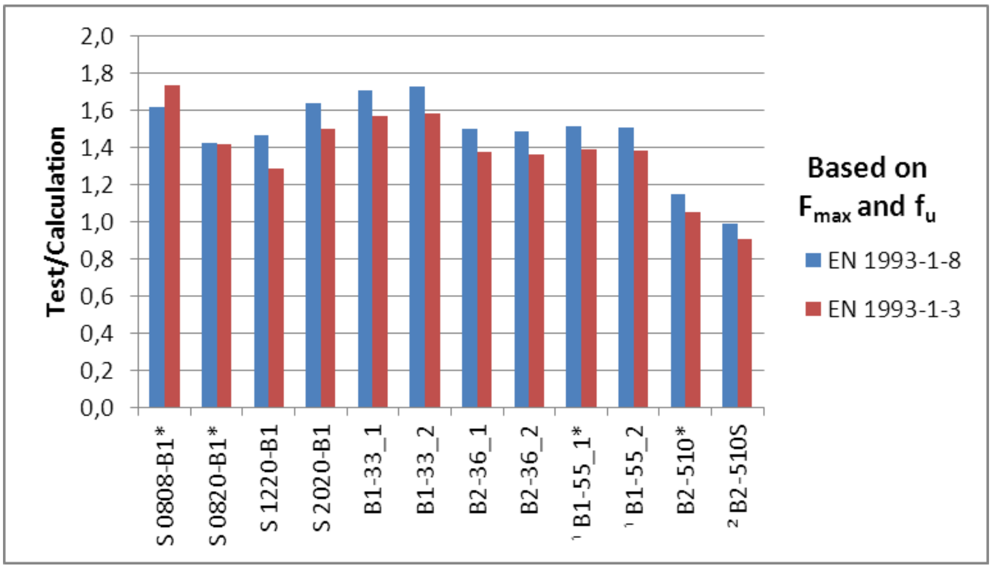

Figure 19. Test results v.s. calculated values: B1 and B2 type tests, criterion F_{max}, calculation by f_u.

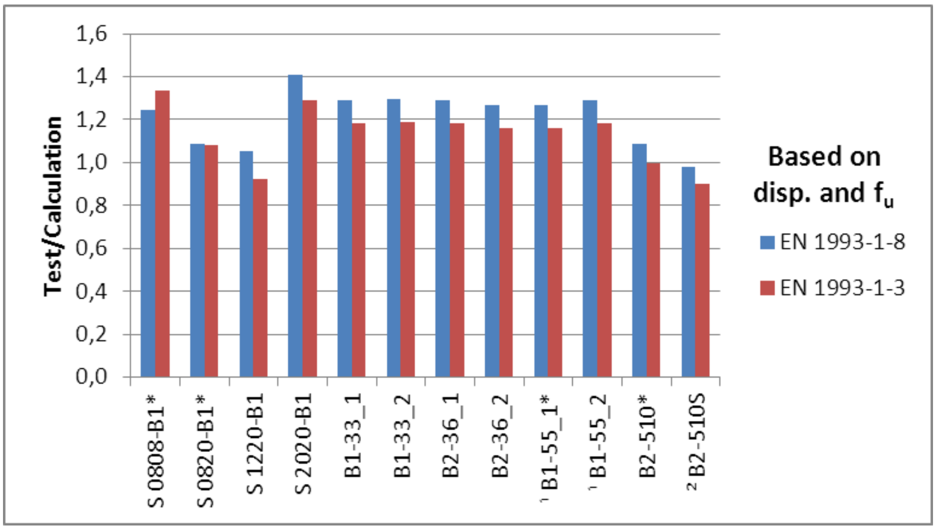

Figure 20. Test results v.s. calculated values: B1 and B2 type tests, criterion displacement, calculation by f_u.

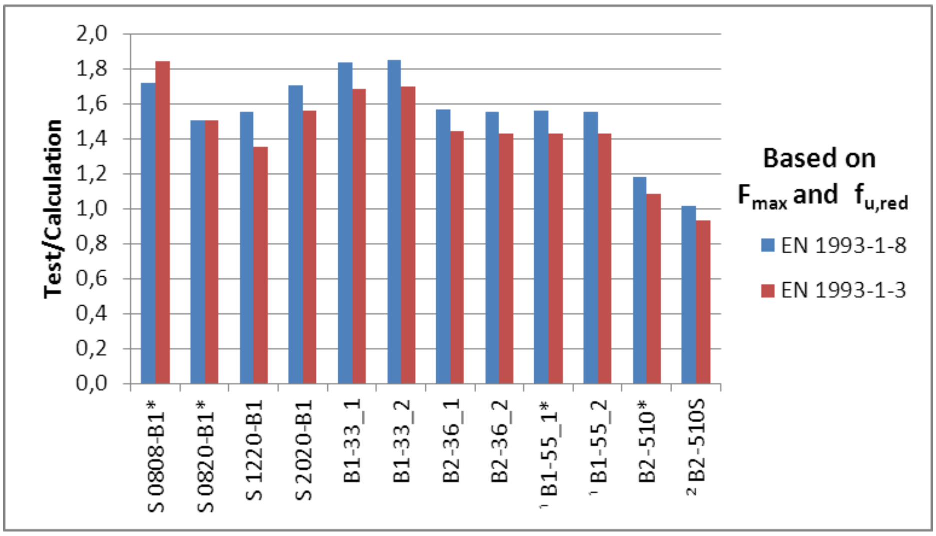

Figure 21. Test results v.s. calculated values: B1 and B2 type tests, criterion F_{max}, calculation by $f_{u,red}$.

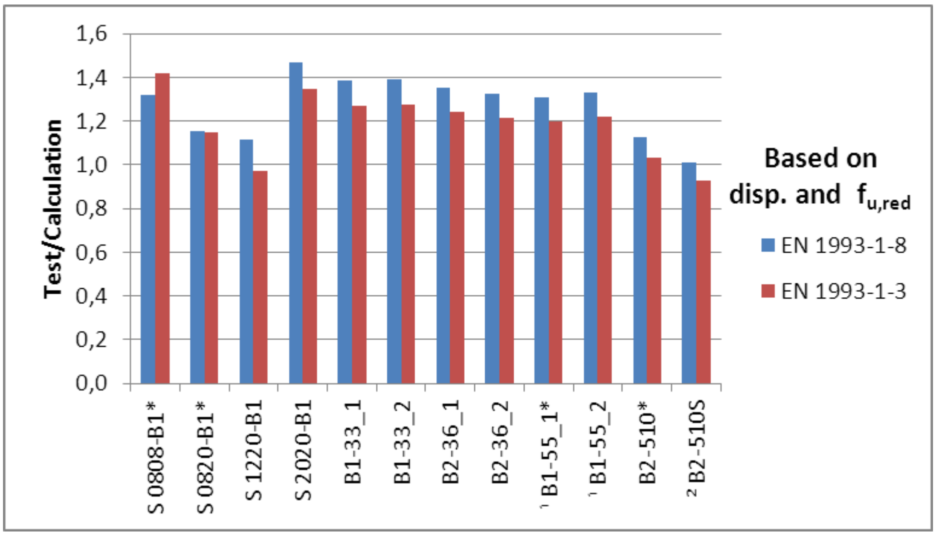

Figure 22. Test results v.s. calculated values: B1 and B2 type tests, criterion displacement, calculation by $f_{u,red}$.

Statistical values of the comparisons are shown in Table 16. The results show the following:

- Characteristic values based on either f_u or $f_{u,red}$ in EN 1993-1-8 are safe, regardless of whether the resistance is limited by deformations or not.
- Characteristic values based on either f_u or $f_{u,red}$ in EN 1993-1-3 are safe, except of case when criterion is deformation and calculation is based on f_u.
- EN 1993-1-3 with $f_{u,red}$ and EN 1993-1-8 with f_u gives the best characteristic values, if the if the resistance is limited by deformations.
- EN 1993-1-3 with f_u gives the best characteristic value, if the criterion is F_{max}.

Table 16. Statistical values of test/calculation for B1 and B2 type tests.

Tests without B2-510[*)] and B2-510S								
N = 10 k = 1.92	EN 1993-1-8				EN 1993-1-3			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.
Average	1.56	1.25	1.64	1.32	1.46	1.17	1.54	1.23
Stdev	0.11	0.11	0.13	0.11	0.13	0.11	0.16	0.12
CoV	0.07	0.08	0.08	0.08	0.09	0.10	0.10	0.10
Characteristic	1.36	1.05	1.40	1.11	1.20	0.96	1.24	1.00

[*)] Shear of bolts is not reported in reference [2], but based on the picture of the failure in Appendix A it is very likely that the ultimate load is affected by shear failure of the bolts as in test C2-510, in which the shear failure was observed.

The comparisons of C1, C2 and E1 type tests are shown in Figs. 23–26. The results show the following:

- Results of tests C2-510, C2-510S and E1-55 are affected by shear failure of the bolts.
- No clear difference between the tests for $t < 3$ mm and $t \geq 3$ mm.
- No clear difference between double (C2) and single lap (C1) tests.
- When the failure criterion is F_{max}, regardless of whether f_u or $f_{u,red}$ is used in calculation, both EN 1993-1-8 and EN 1993-1-3 are safe except of tests C2-510 and C2-510S.
- Also when the criterion is displacement, regardless of whether f_u or $f_{u,red}$ is used in calculation, both EN 1993-1-8 and EN 1993-1-3 are safe except of test C2-510S.

Statistical values of the comparisons C1 and C2 type tests are shown in Table 17. The results show the following:

- Characteristic values based on either f_u or $f_{u,red}$ in EN 1993-1-3 are unsafe, if the resistance is limited by deformations.
- EN 1993-1-8 with $f_{u,red}$ gives the best characteristic value, if the resistance is limited by deformations.
- EN 1993-1-8 with f_u gives the best characteristic value, if the criterion is ultimate load.

Table 17. Statistical values of test/calculation for C1 and C2 type tests.

Tests without C2-510 and C2-510S								
N = 10 k = 1.92	EN 1993-1-8				EN 1993-1-3			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.
Average	1.57	1.28	1.64	1.34	1.49	1.21	1.56	1.27
Stdev	0.07	0.09	0.10	0.10	0.13	0.14	0.16	0.15
CoV	0.05	0.07	0.06	0.07	0.09	0.11	0.10	0.12
Characteristic	1.43	1.11	1.45	1.15	1.24	0.95	1.26	0.98

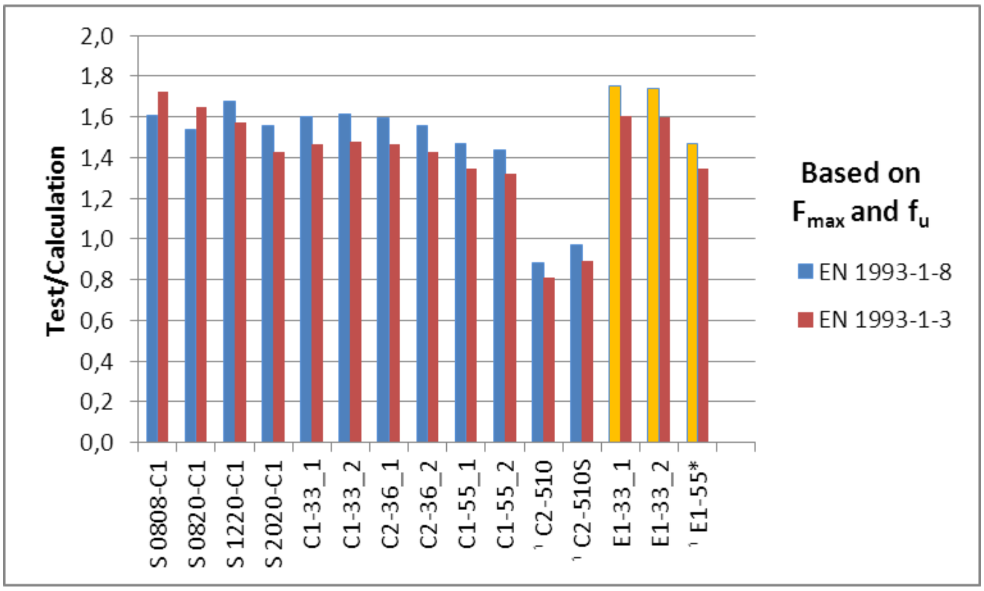

Figure 23. Test results v.s. calculated values: C1, C2 and E1 type tests, criterion F_{max}, calculation by f_u.

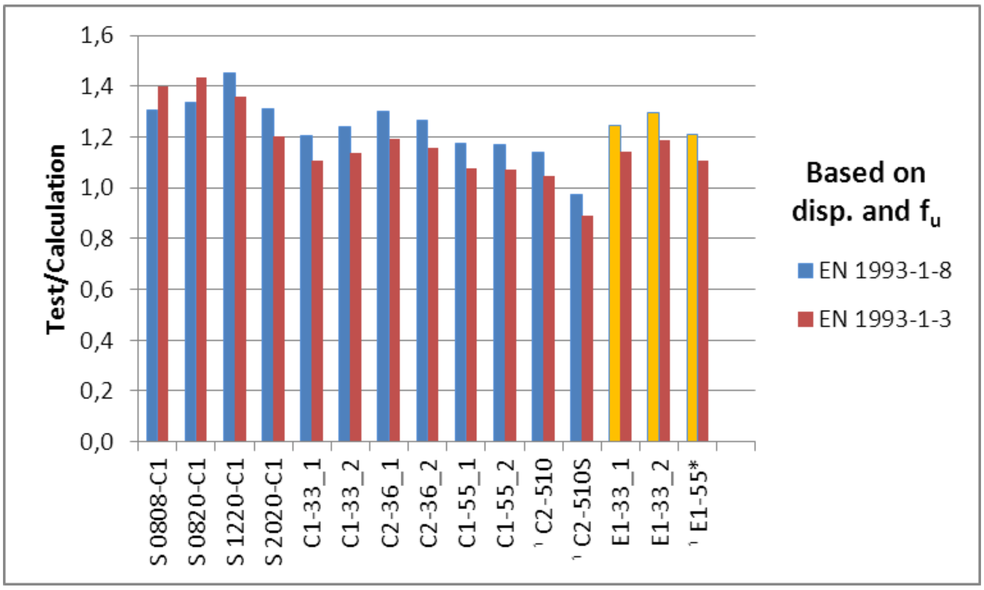

Figure 24. Test results v.s. calculated values: C1, C2 and E1 type tests, criterion displacement, calculation by f_u.

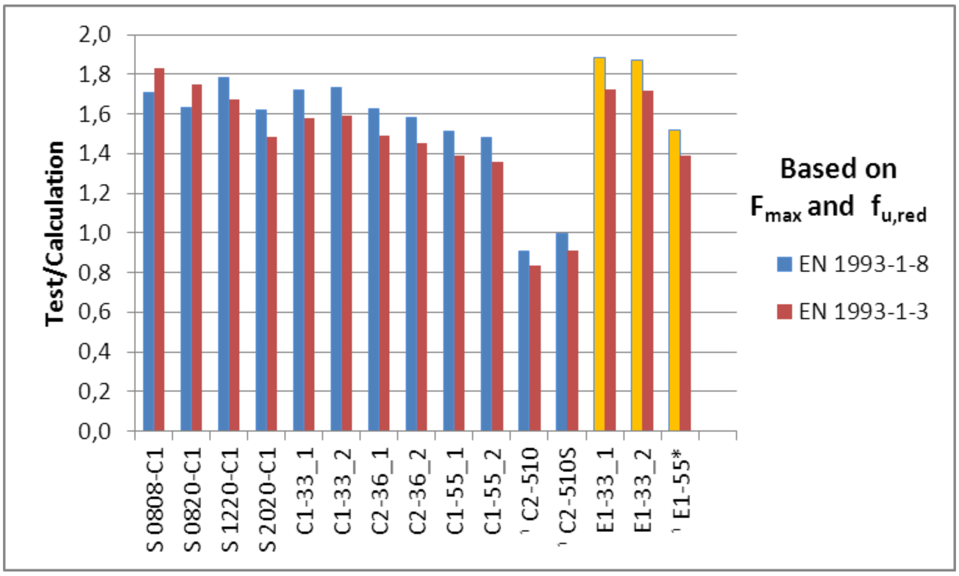

Figure 25. Test results v.s. calculated values: C1, C2 and E1 type tests, criterion F_{max}, calculation by $f_{u,red}$.

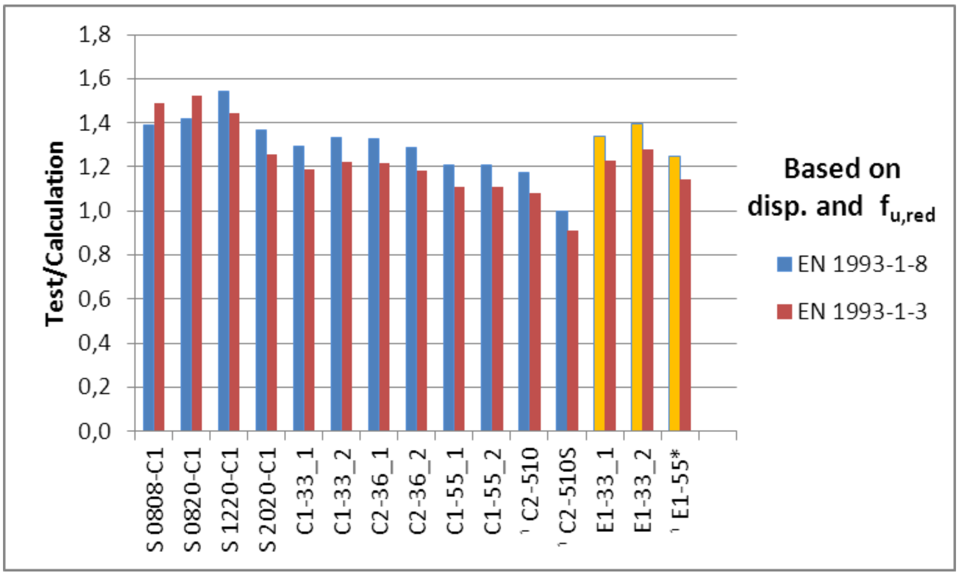

Figure 26. Test results v.s. calculated values: C1, C2 and E1 type tests, criterion displacement, calculation by $f_{u,red}$.

Statistical values for three angle section in Table 18 show the following:

- EN 1993-1-with both f_u and $f_{u,red}$ gives the best characteristic value, if the if the resistance is limited by deformations, EN 1993-1-8 results to more safety.
- Small amount tests makes it difficult to draw wider conclusions.

Table 18. Statistical values of test test/calculation for type E1 angles.

N = 3 k = 3.37	EN 1993-1-8				EN 1993-1-3			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.	F_{max}	Displ.
Average	1.653	1.249	1.756	1.326	1.516	1.146	1.611	1.216
Stdev	0.159	0.044	0.208	0.074	0.146	0.040	0.191	0.068
Characteristic	1.116	1.101	1.054	1.077	1.024	1.010	0.967	0.988

Statistical values of all bearing type tests used in previous comparison are shown in Table 19. 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.

Table 19. Statistical values of bolted connections, bearing resistance, all tests (series B1, B2 and E).

	Bearing tests without tests B2-510, B2-510S, C2-510, C2-510S; N = 23, k = 1.75							
	EN 1993-1-8				EN 1993-1-3			
Calculation	f_u		$f_{u,red}$		f_u		$f_{u,red}$	
Criterion	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
StDev	0.10	0.09	0.13	0.10	0.13	0.12	0.15	0.13
CoV	0.06	0.07	0.08	0.07	0.09	0.10	0.10	0.10
Characteristic	1.40	1.11	1.43	1.16	1.25	0.98	1.29	1.02

7.1.3 Block shear failure

Resistances of type D1 and D2 bolted connections are based on block tearing type failure of the weakest material. The resistance is calculated according to the equations from EN 1993-1-8 given in chapter 2.3. Comparison have been made based on f_u (EN 1993-1-1, EN 1993-1-3, EN 1993-1-4) and $f_{u,red}$.

Table 20. Areas subjected to tension and shear (EN1993-1-8).

Connection type	Tension area, subjected to f_u	Shear area, subjected to $f_y/\sqrt{3}$
D1 and D2	$2 \cdot 2.2 \cdot d_0 t = 4.40\ d_0 t$	$2 \cdot (1.1+2.2) \cdot d_0 t = 6.60\ d_0 t$

When the results are evaluated it must take into account that in the shear resistance of the bolt group should be greater than the block tearing resistance. However, in the case of tests D1-55, D2-510and D2-510S the measured ultimate loads are about 50% higher than the calculated shear resistance of the bolts. Therefore in these tests the shear resistance may limit the block tearing resistance.

Comparison of the calculated resistances with test results is made based on two criteria, one condition is the ultimate load F_{max} and the second is limit elongation of the connection. In tests S 0820-D1 and S 1220-D1 (with thick back plates) the criterion for total displacement is 3 mm, in other tests criterion of 6 mm is used.

The comparisons of D1 and D2 type tests shown in Figs. 27–28. The results show the following:

- No clear difference between the tests for $t < 3$ mm and $t \geq 3$ mm.
- When the failure criterion is F_{max}, regardless of whether f_u or $f_{u,red}$ is used in calculation, EN 1993-1-8 is always safe.
- When the criterion is displacement, EN 1993-1-8 is safe, when $f_{u,red}$ is used in calculation. If f_u is used, some result is slightly unsafe.
- In D2-510 the ultimate load is limited by shear failure of the bolts.

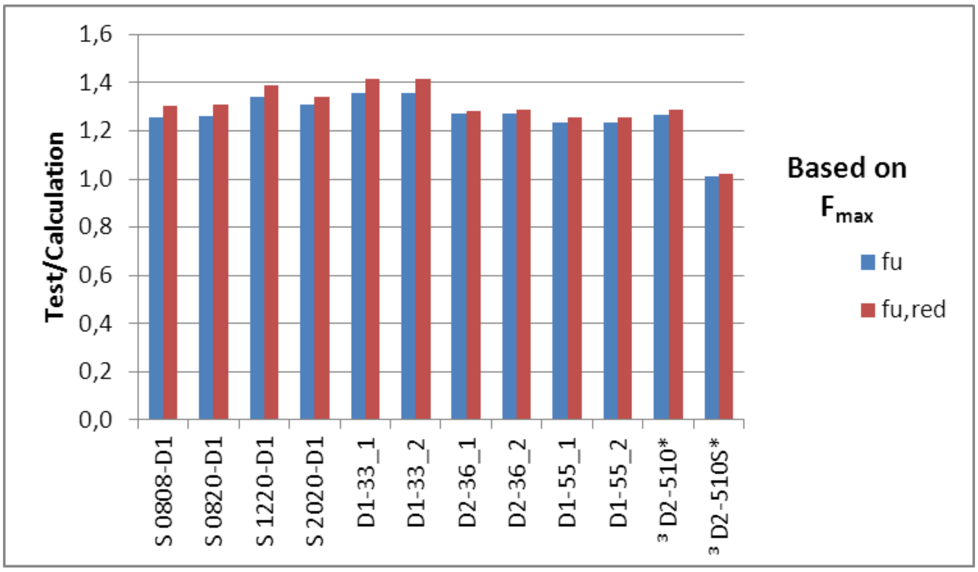

Figure 27. Test results v.s. calculated values: D1 and D2 type tests, criterion F_{max}.

Figure 28. Test results v.s. calculated values: D1 and D2 type tests, criterion displacement.

Statistical values of the comparisons of D1 and D2 type tests are shown in Table 21. 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.

Table 21. Statistical values of test/calculation for D1 and D2 type tests.

Tests without D2-510S				
N = 11 k = 1.92	EN 1993-1-8			
Calculation	f_u		$f_{u,red}$	
Criterion	F_{max}	Displ.	F_{max}	Displ.
Average	1.29	1.03	1.32	1.06
Stdev	0.05	0.06	0.06	0.06
CoV	0.04	0.06	0.05	0.06
Characteristic	1.20	0.91	1.21	0.95

8 Screwed connections

All resistances are calculated based on measured material properties, and γ_{M2} = 1.0. In addition measured values of t, f_y and f_u given in Table 7 are used in comparison. Numerical values of the figures in following comparisons are given in Appendix F.

Resistances of screwed connections are calculated according to the equations given in Chapter 3. Resistances of EN1993-1-3 are based on bearing resistance coefficient α (Table 22). Average thread diameter of d = 5.37 mm (EN ISO 1478) is used in calculation. Comparison have been made based on f_u (EN 1993-1-3, EN 1993-1-4) and $f_{u,red}$. The values given in parentheses are not taking into account the extra criterion for t < 1.0 mm given in EN 1993-1-3.

When the results are evaluated it must take into account that in the shear resistance of screws should be greater than the bearing resistance. However, only in the case of test series S1220 shear of screws was observed in final failure. In these tests the shear resistance may be limited due to shear failure.

Table 22. 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 (210)
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

Comparison of the calculated resistances with test results is made based on two criteria, one condition is the ultimate load F_{max} and the second is limit is total elongation of 3 mm.

The comparisons of results are shown in Figs. 29–30. The results based on F_{max} (Fig. 29) show the following:

- No clear difference between the types of connections 1 a, 1b and 2a.
- Design is safe in all tests regardless of whether f_u or $f_{u,red}$ is used in calculation
- Test series S0520 and S0820 with thick back plate without taking into account the extra criterion for t < 10 mm given in EN 1993-1-3 agree well with other results.

The results based on displacement criterion (Fig. 30) show the following:

- No clear difference between the types of connections 1 a, 1b and 2a except test series S0820, in which results for connection with two screws (S0820-2a) are less safe than results for connections with one screw.
- If $f_{u,red}$ is used in calculation, design is safe in all tests except of two tests in series S0820 and S1220. If f_u is used in calculation, design is unsafe in four cases.

– The results of connections with thick back plate are unsafe in some cases of test series S0820 and S1220.

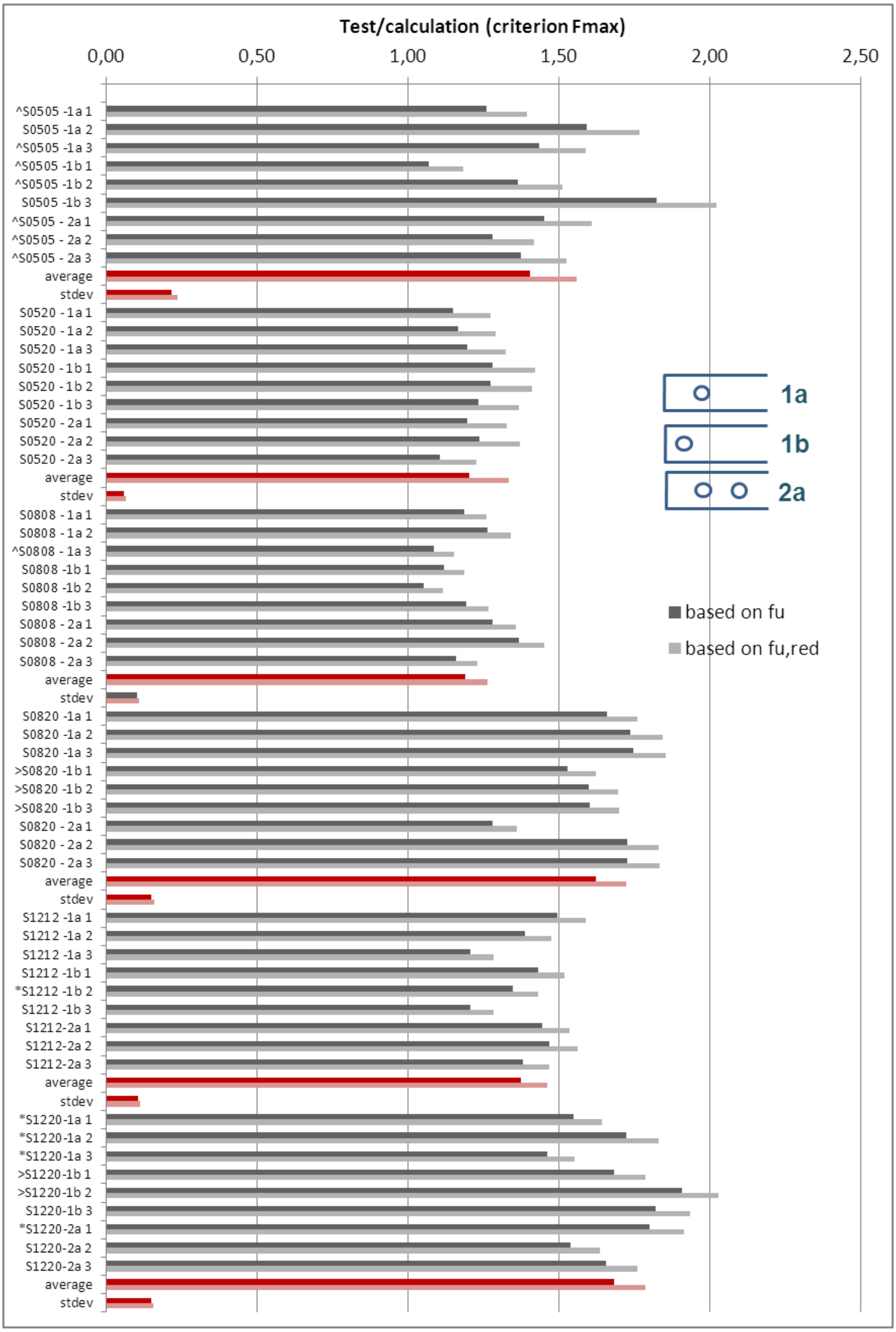

Figure 29. Test results v.s. calculated values for screwed connections, failure criterion is F_{max}. Criterion t < 1.0 mm is not taken into account in S0520 and S0820 series.

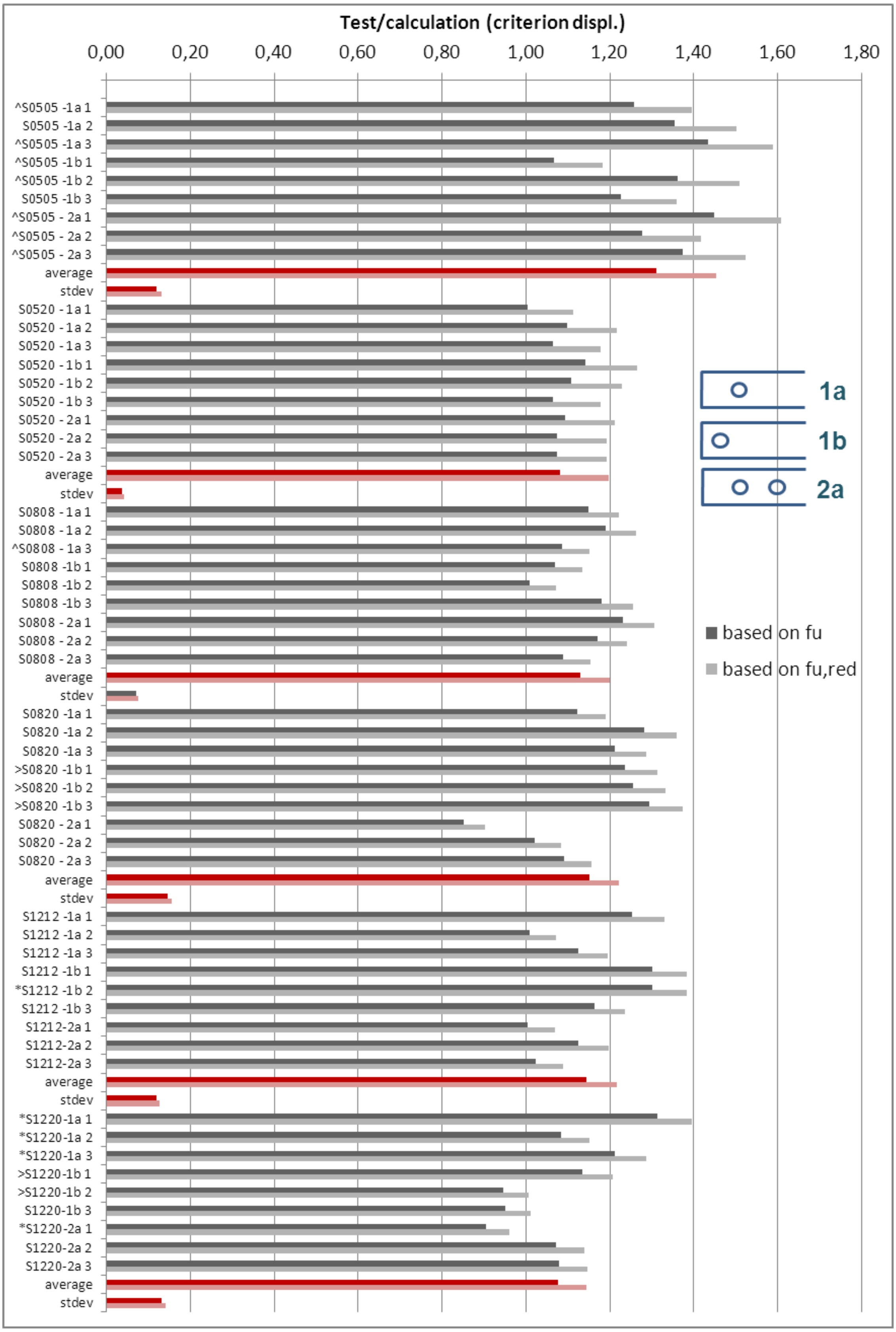

Figure 30. Test results v.s. calculated values for screwed connections, failure criterion is elongation of 3 mm. Criterion t < 1.0 mm is not taken into account in S0520 and S0820 series.

Statistical values of the tests are shown in Table 23 Results show the following:

- If the characteristic values are based on $f_{u,red}$ and the resistance is limited by deformation, EN 1993-1-3 is safe except of series S1212 and S1220.
- If the characteristic values are based on $f_{u,red}$ and the resistance is taken as F_{max}, EN 1993-1-3 is safe in all cases.
- If the extra criterion for t < 1.0 mm given in EN 1993-1-3 (values in parentheses), is taken into account the underestimation in design is large in the case of test series S0520 and S0820. The capacity is significantly underestimated in the case of test series S0520.

Table 23. Statistical values of test/calculation for screwed connections (N = 9, k = 1.96).

	Displ. criterion 3 mm				Displ. criterion F_{max}			
Test	Based on f_u		Based on $f_{u.red}$		Based on f_u		Based on $f_{u,red}$	
	Average	Char.	Average	Char.	Average	Char.	Average	Char.
S0505	1.31	1.08	1.45	1.20	1.40	0.98	1.56	1.09
S0520	2.31 (1.08)	2.15 (1.01)	2.56 (1.20)	2.38 (1.12)	2.57 (1.20)	2.33 (1.09)	2.85 (1.33)	2.58 (1.21)
S0808	1.13	0.99	1.20	1.05	1.19	0.99	1.26	1.05
S0820	1.96 (1.15)	1.47 (0.86)	2.08 (1.22)	1.57 (0.92)	2.76 (1.62)	2.27 (1.33)	2.93 (1.72)	2.41 (1.41)
S1212	1.15	0.91	1.22	0.97	1.37	1.17	1.46	1.24
S1220	1.08	0.82	1.14	0.87	1.68	1.39	1.79	1.48

Statistical values of all screwed connections in previous comparisons are shown in Table 24. The extra criterion for t < 1.0 mm given in EN 1993-1-3 is not used in this comparison. 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.

Table 24. Statistical values of all test for screwd connections (N = 54, k = 1.70).

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

9 Summary and conclusions

9.1 Failure criteria

Figure 31 shows the importance of the selection of the considered criterion. The figure is based on the bearing design equations for bolted connections proposed in Table 2, where separate equations are given for ultimate and service limits states. The criterion for service limit load is hole elongation of 1 mm. The figure shows that the serviceability limit is not often determining, if the edge distances e_1 and e_2 are large. This is due to the fact that usually the load safety factor multiplied by material safety factor does not exceed the value of 1.6.

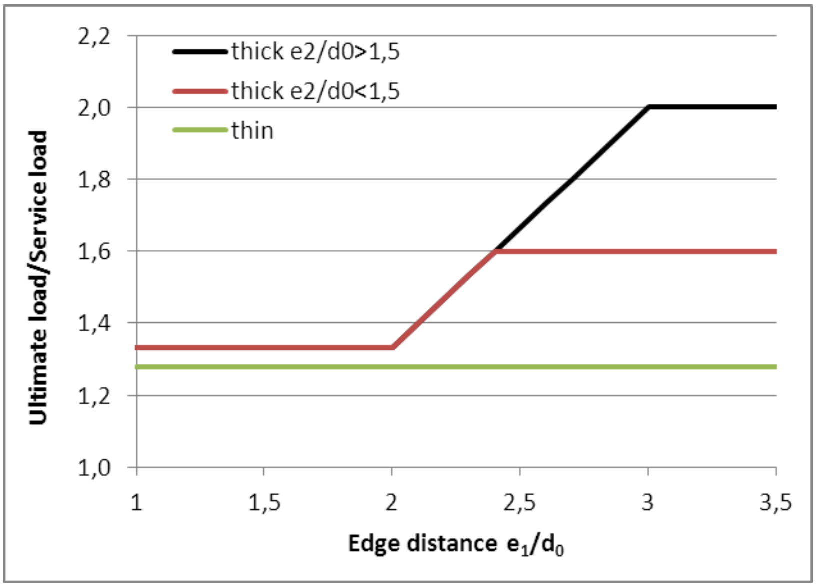

Figure 31. Calculated ratio of the loads corresponding the ultimate limit state and serviceability limit (edge distances e_1 and e_2 are shown in Fig. 6)

On the other hand, another question is, how correct is it to use the ultimate limit load as a design criterion when the deformations are very large. In this study the 12 mm bolts with 13 mm hole size were used and then maxim loads were reached at total deformations of

- 6–20 mm, in single shear tests with t < 3 mm
- 12–24 mm, in single shear tests with t ≥ 3 mm
- 6–18 mm, in double shear tests with t ≥ 3 mm
- 15–20 mm, in angle bar tests with t ≥ 3 mm.

Results of the bearing tests show that the average ratio of loads corresponding to hole deformation of 3 mm and F_{max} criterion is 0.8. In addition, Figure 31 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 for 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 deformation criterion is used, no additional equations for SLS are necessary.

The used deformation limit of 3 mm per connected part is reasonable for bolted connections. If the hole clearance is already 1 mm (bolts M12-M14) or 2 mm

(M16–M24), total deformation of 3 mm per connected part sounds to be reasonable. This selection is also in line with previous practices described in Chapter 4.1.1. In addition, if this criterion is used as design criterion, then the deformations at service limit state need not to be checked separately and equations for that purpose are not needed in normal case.

For the screwed connections, the failure load of by using elongation criterion of 3 mm over the connection as described in Chapter 4.1.2, is reasonable because of smaller diameter of the fasteners.

9.2 Summary of results

The test programme consist lap shear tests for both bolted and screwed ferritic stainless steel connections. 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 joints are connected by a single or two self-tapping screws with a nominal diameter of 5.5 mm. The steel grade of EN 1.4509 (ASTM 441) is used in all tests.

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 comparison of test results with calculated resistances of bolted connections is shown in Figure 33 for criterion F_{max} and in Figure 32 for displacement criterion. Some tests with shear failure of bolts and comparative tests for carbon steel are excluded from the comparison. The comparison of test results with calculated resistances of screwed connections is shown in Figure 34. The extra criterion for t < 1.0 mm given in EN 1993-1-3 is not used in this comparison, because it gives too conservative results.

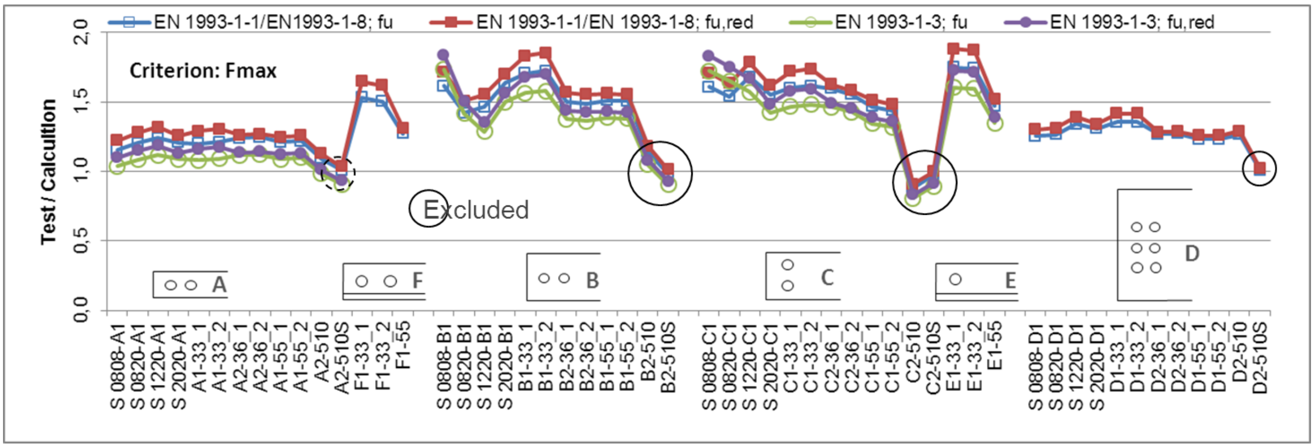

Figure 32. Experimental results of bolted connections compared to calculated resistances, failure criterion is F_{max}.

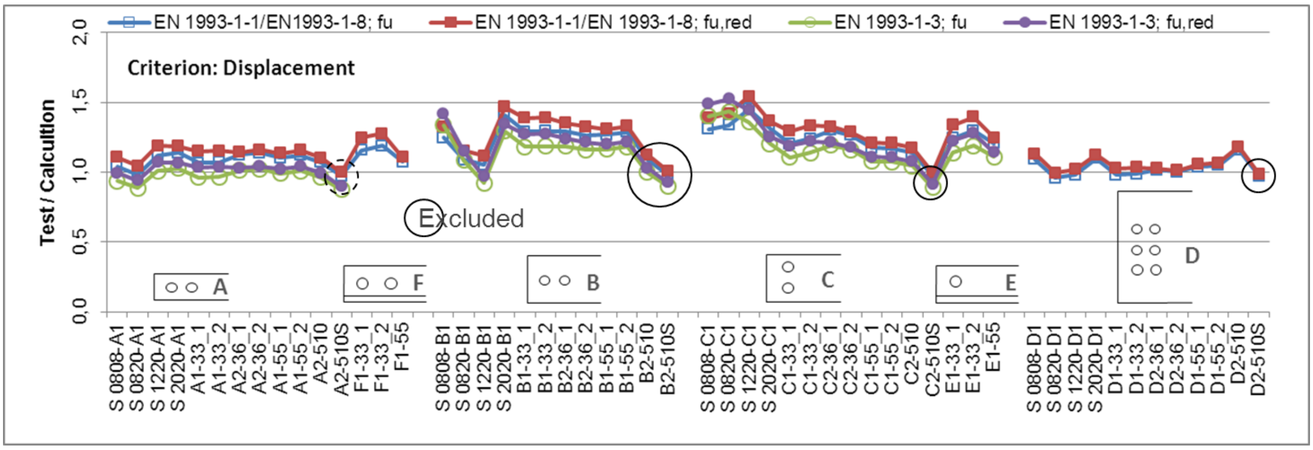

Figure 33. Experimental results of bolted connections compared to calculated resistances, failure criterion is displacement.

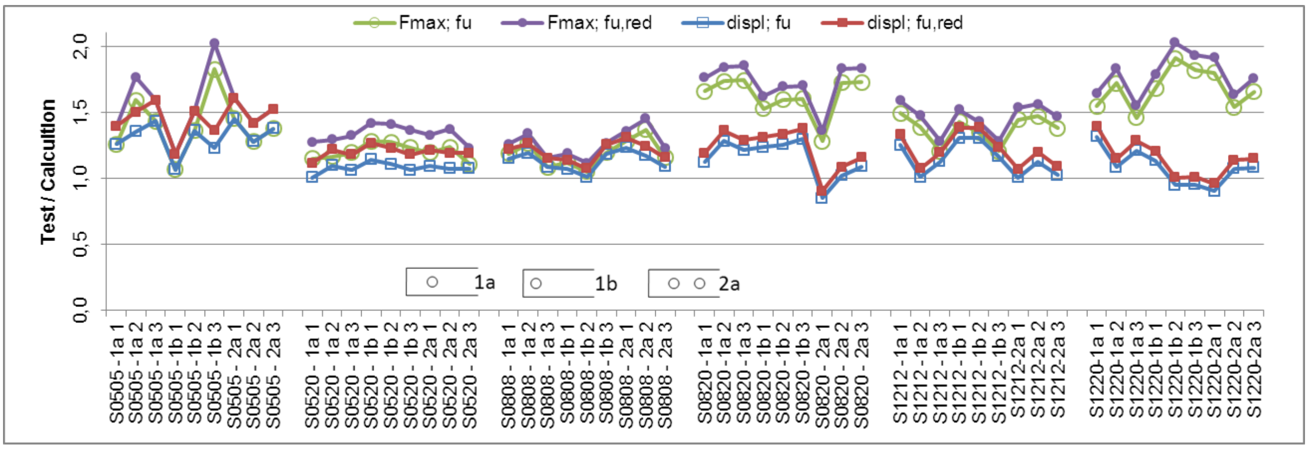

Figure 34. Experimental results of screwed connections compared to calculated resistances. Failure criteria F_{max} and displacement.

9.3 Conclusions

9.3.1 Net section resistance of bolted connections

In the case of net section resistance of flats (tests A1 and A2), both EN 1993-1-1 with modification of k_r = 1.0 instead of k_r = 0.9 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 1993-1-1 with reduction factor k_r=0.9 as it is in the existing EN 1993-1-1.

In the case of net sections resistance of angle sections (tests F1) the conclusion is that, 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.

9.3.2 Bearing resistance of bolted connections

In the case of bearing resistance (tests B1, B2, C1, C2 and E1), 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. When 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 1993-1-3.

9.3.3 Block tearing resistance of bolted connections

In the case of block tearing resistance (tests D1 and D2), 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.

9.3.4 Bearing resistance of screwed connnections

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.

10 Recommendations

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. In addition the results indicate that the deformations should also be taken into account in the design of net section failure and block shear failure, not only in the case of bearing failure.

In the case of bearing resistance of bolted connections, 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. The three test results for net section resistance of angle sections are also 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 results of screwed connections also indicate that the extra criterion given in EN 1993-1-3 for $t < 1.0$ mm would not be necessary.

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 results 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 in normal calculation. Because more favourable results may be achieved, if statistical determination of resistance models according to Annex D of EN-1990 is used, the study is recommended to be done. It 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 could be studied by finite element calculations.

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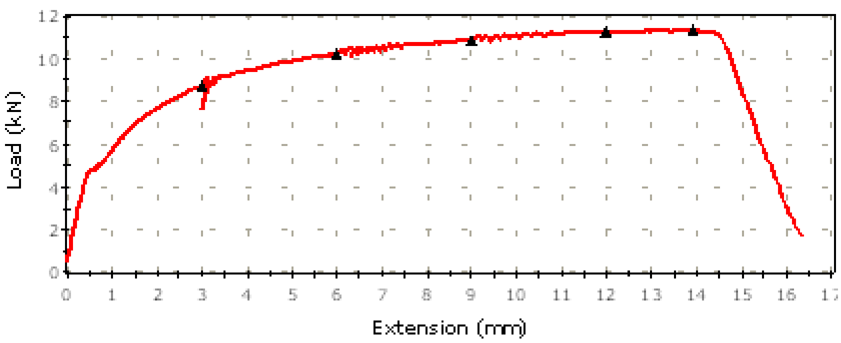
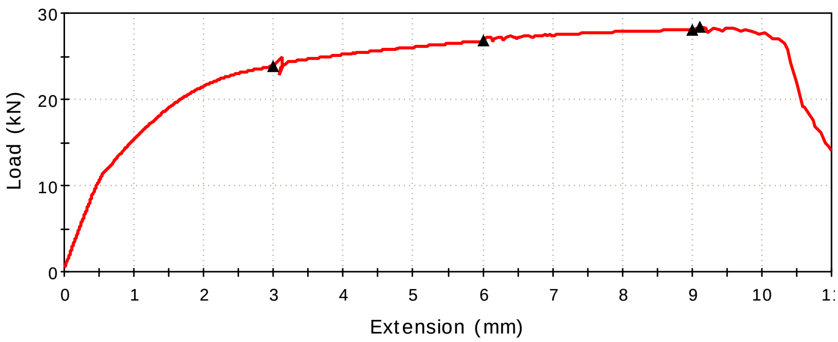
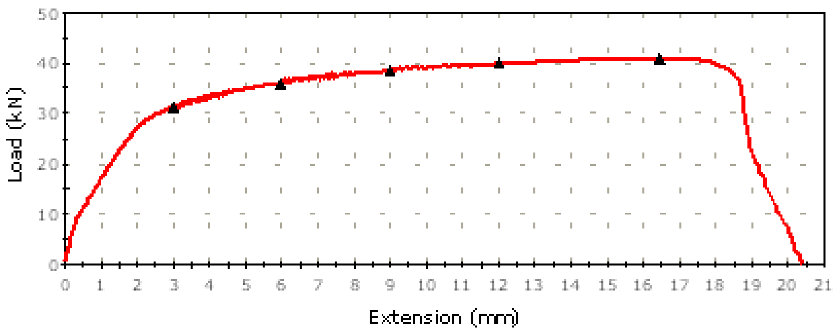
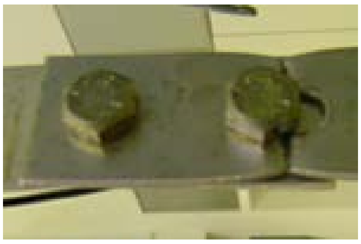
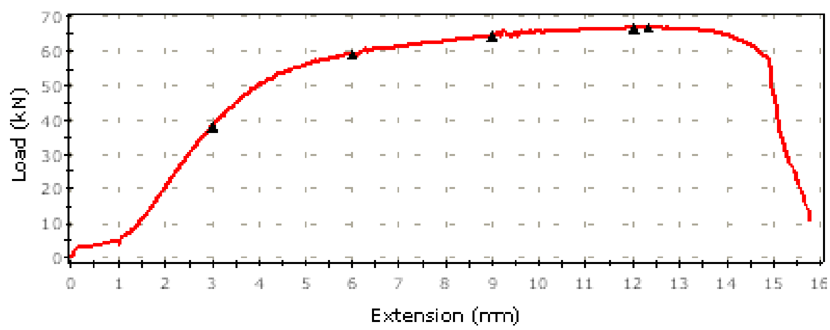
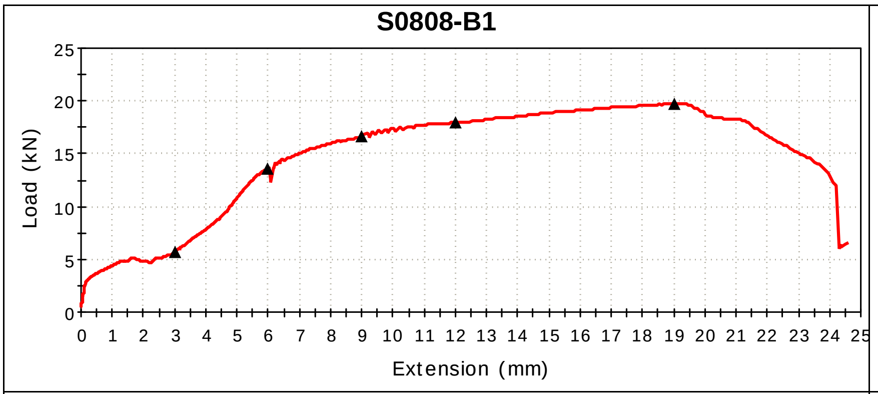
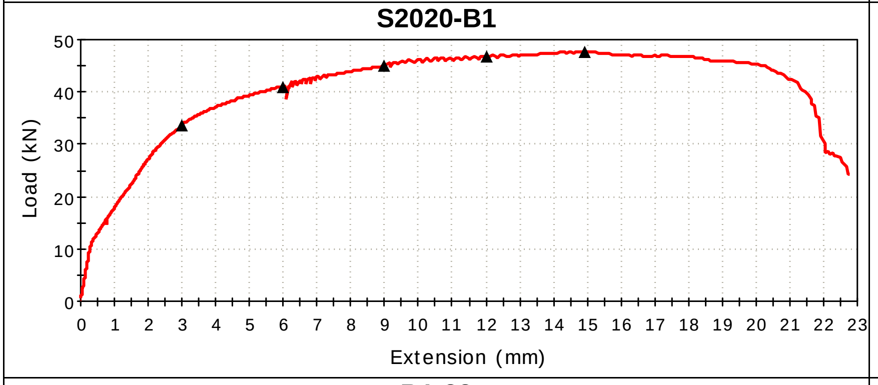
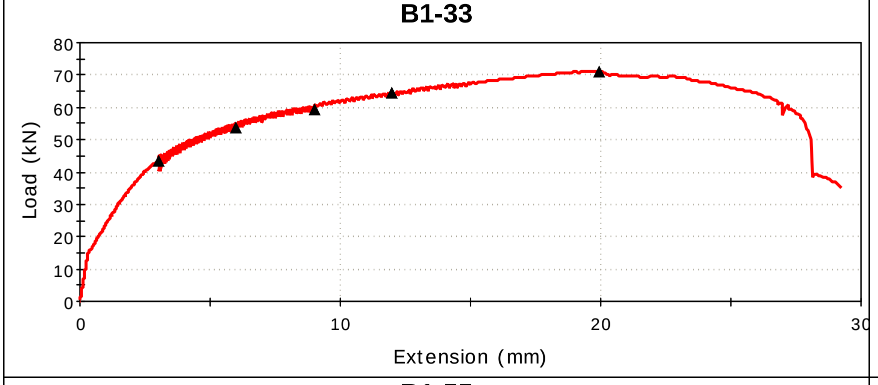
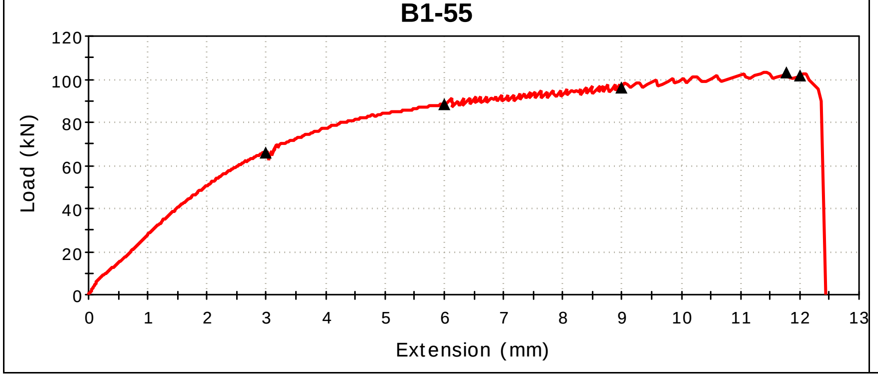
Appendix A. Bolted connections – Samples from test data

S0808-A1  	
S2020-A1  	
A1-33  	
A1-55  	

 S0808-B1 Load (kN) Extension (mm)	
 S2020-B1 Load (kN) Extension (mm)	
 B1-33 Load (kN) Extension (mm)	
 B1-55 Load (kN) Extension (mm)	

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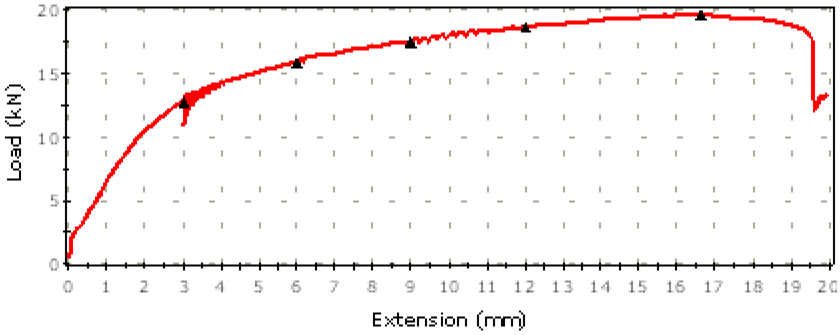

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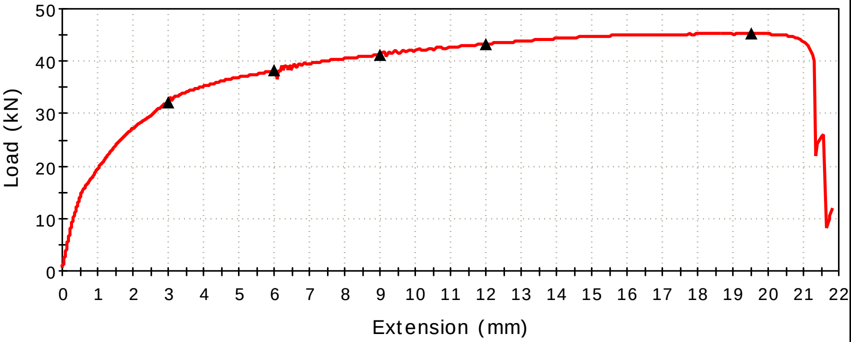

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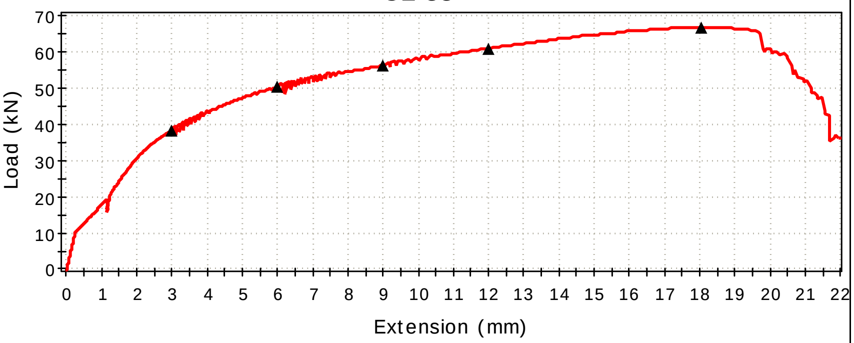

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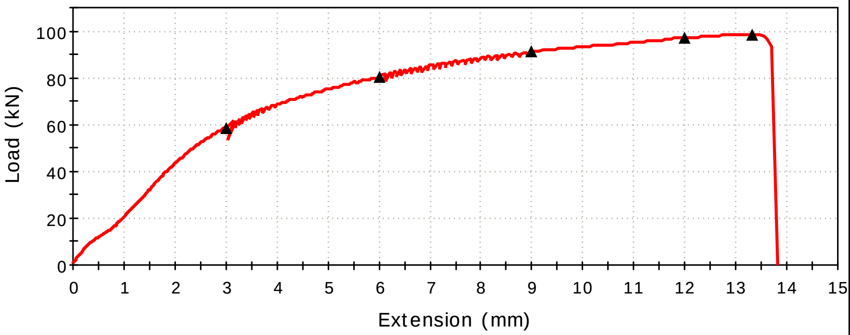

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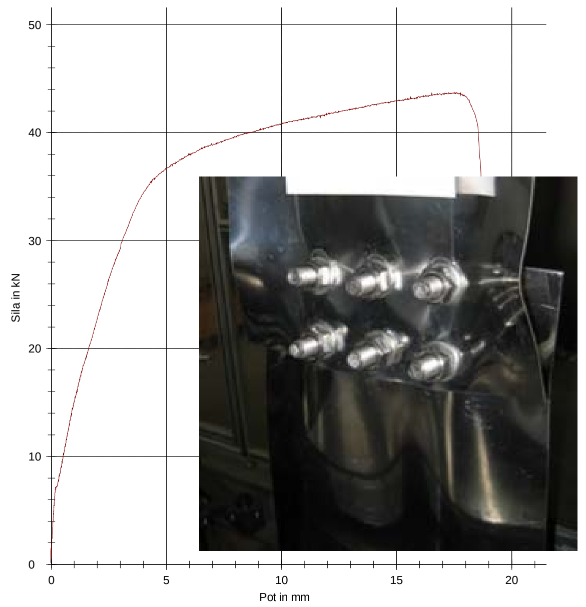

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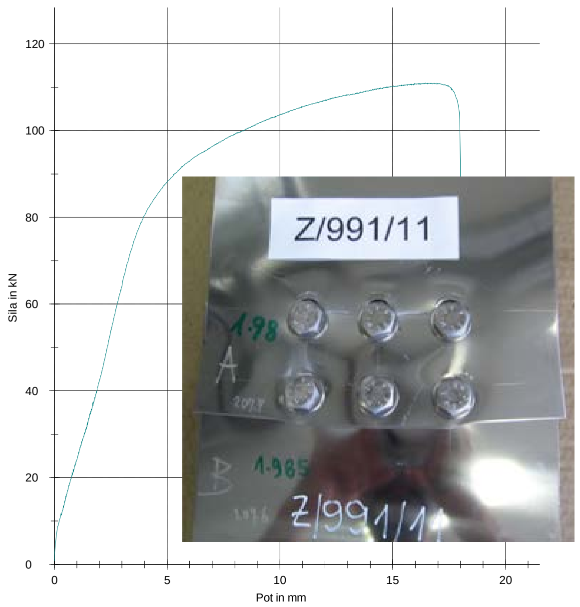

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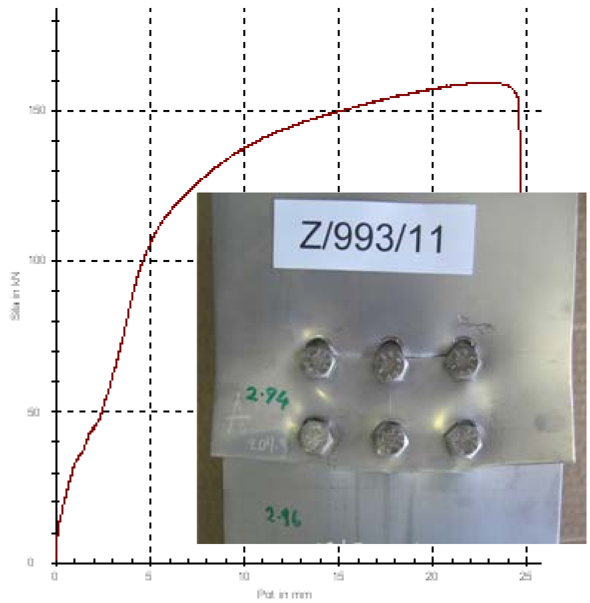

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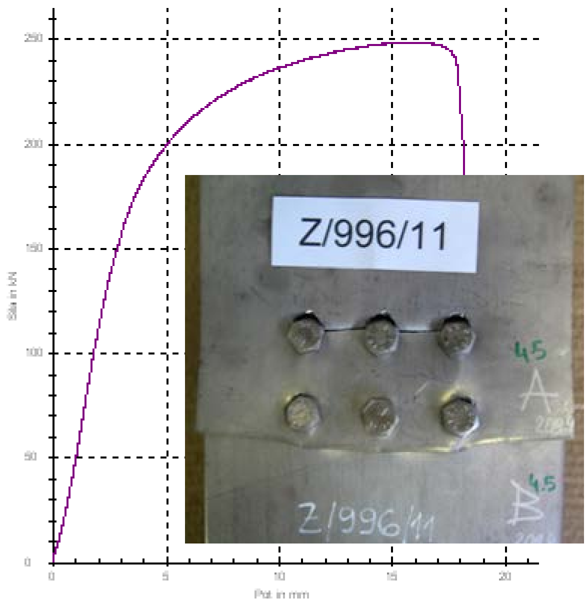

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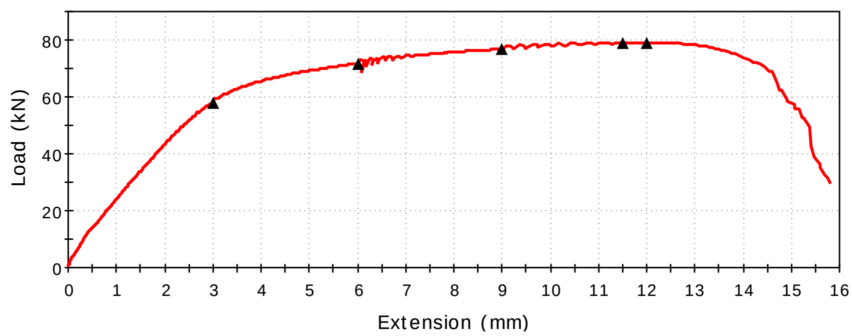

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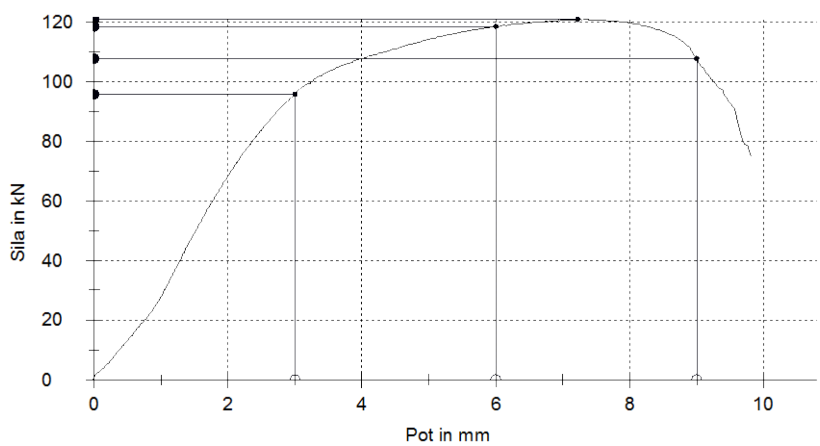

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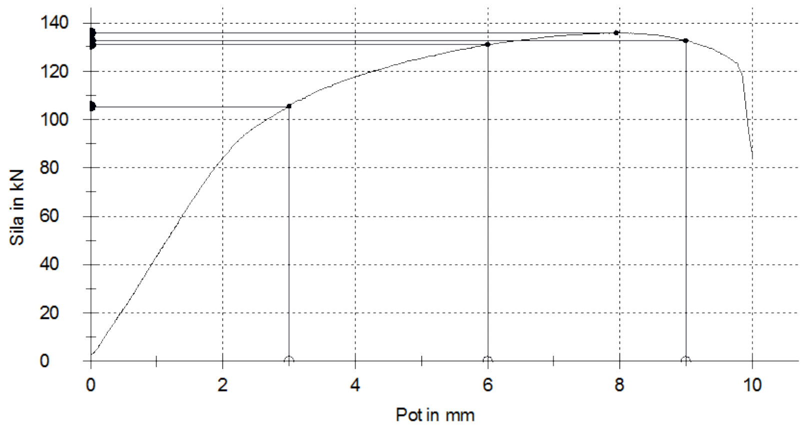
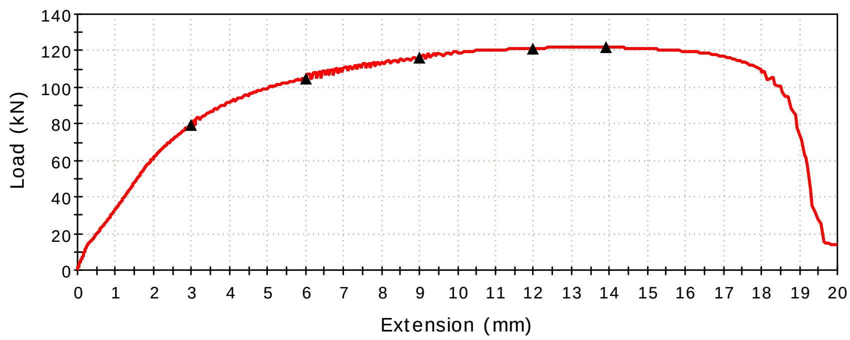
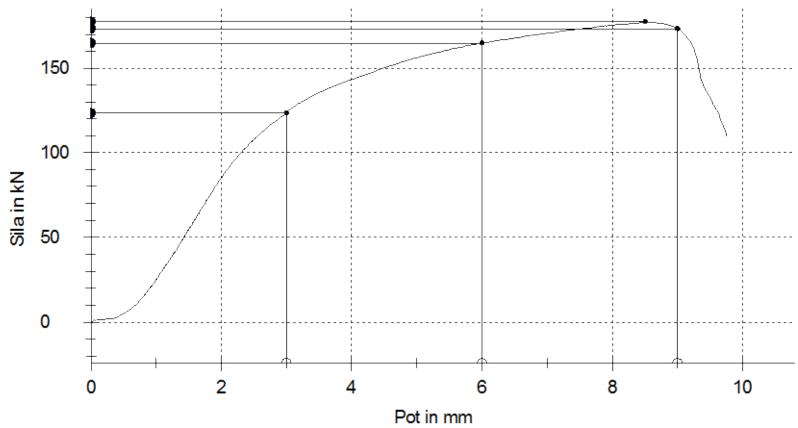
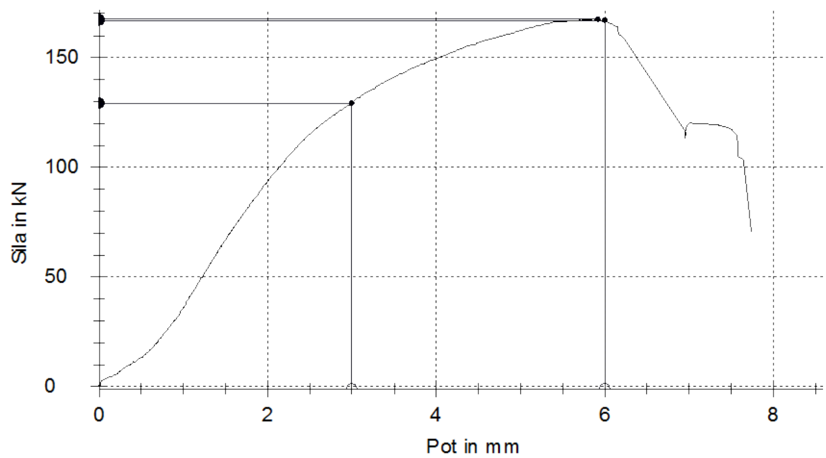
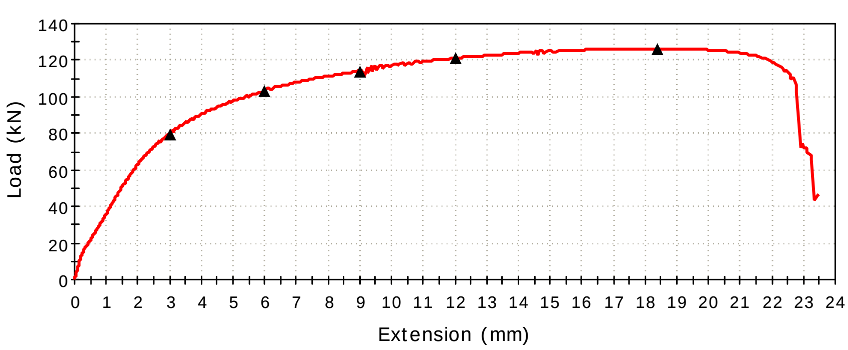
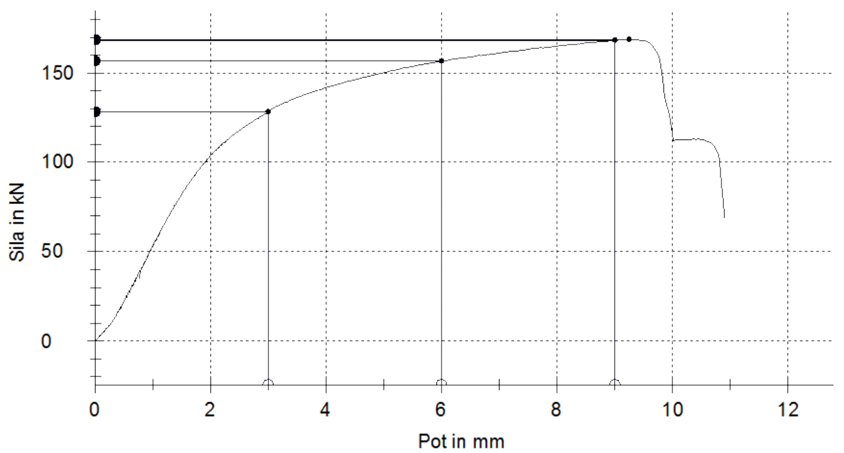
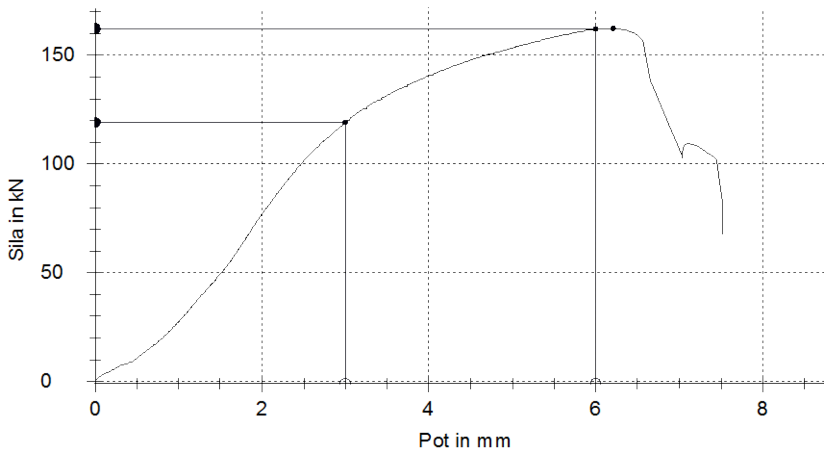
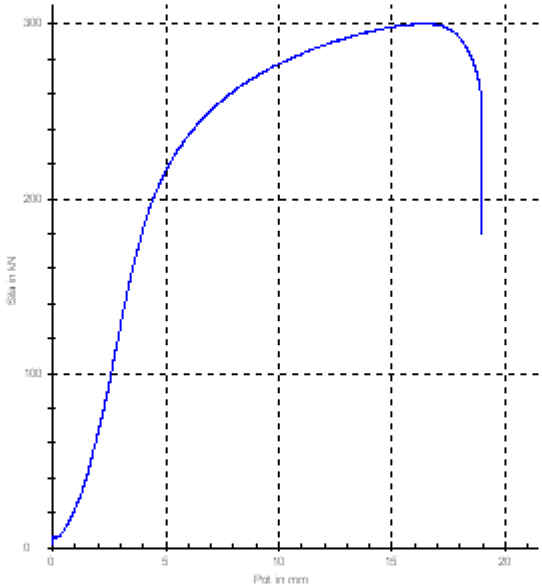
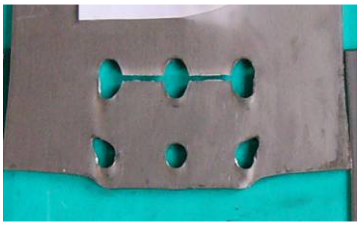
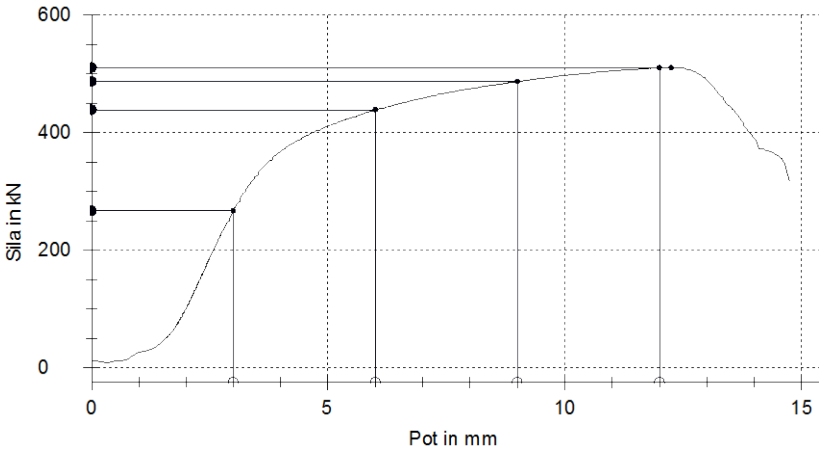
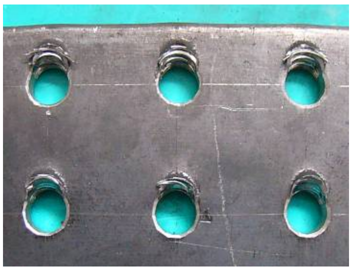
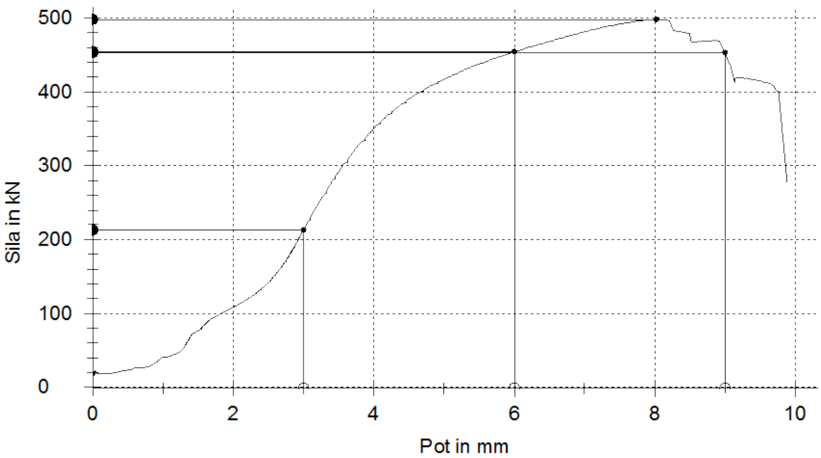
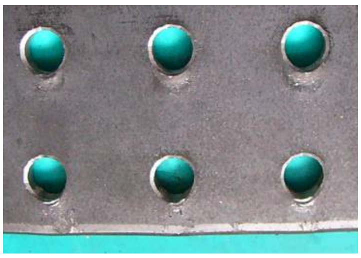


B2-36 	
B2-510 	
B2-510S 	

C2-36 	
C2-510 	
C2-510S 	

D2-36 	 
D2-510 	 
D2-510S 	 

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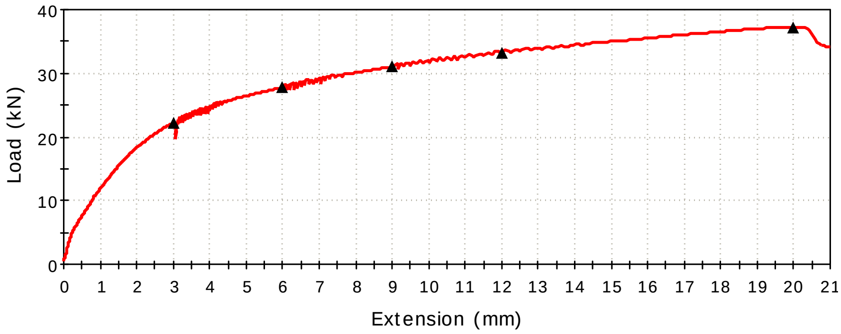

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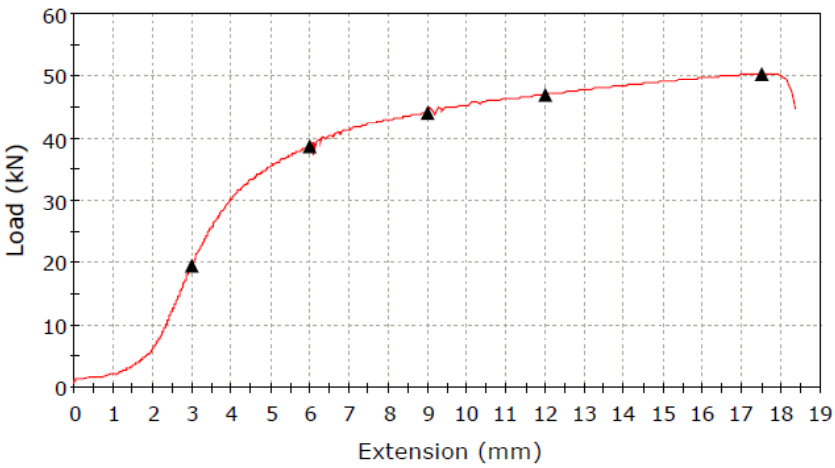

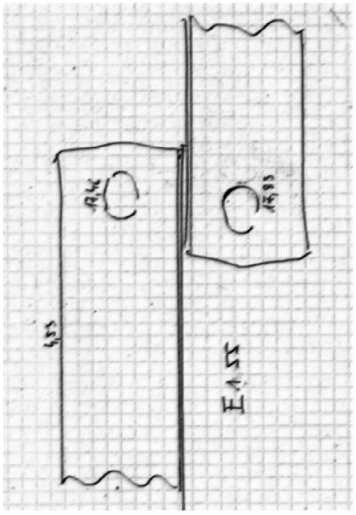

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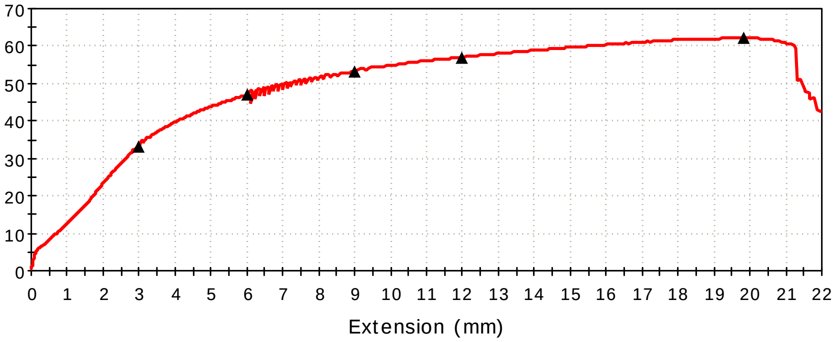

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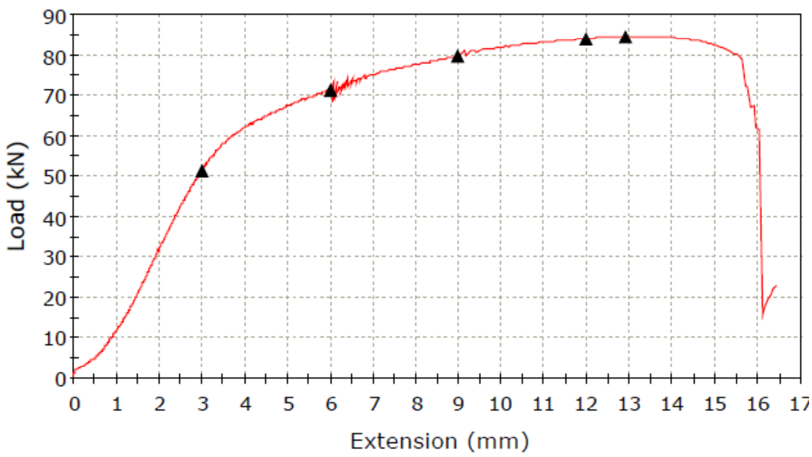
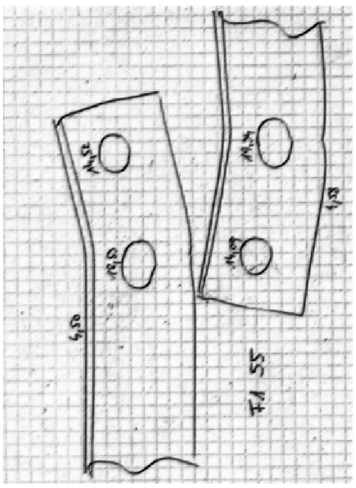




Appendix B. Bolted connections – Test results

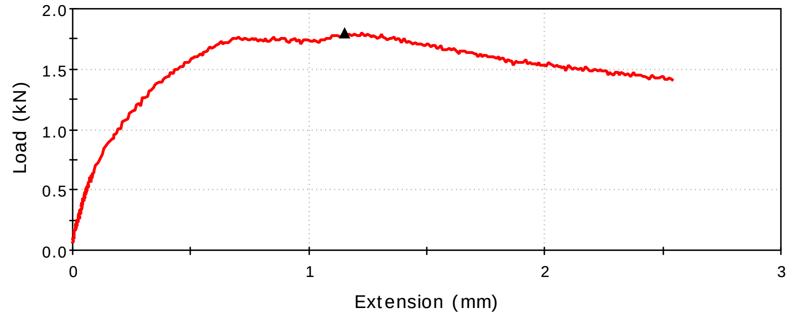
SINGLE SHEAR, t < 3mm			
Test	Elongation	Force	Per bolt
S 0808-A1	3 mm 6 mm max	8.71 10.24 11.34	4.36 5.12 5.67
S 0820-A1	3 mm 6 mm max	9.68 11.18 11.86	4.84 5.59 5.93
S 0808-B1*	3 mm 6 mm max	8.00 15.20 19.73	4.00 7.60 9.87
S 0820-B1*	3 mm 6 mm max	16.80 19.60 21.96	8.40 9.80 10.98
S 0808-C1	3 mm 6 mm max	12.79 15.95 19.63	6.40 7.98 9.82
S 0820-C1	3 mm 6 mm max	16.33 18.56 18.77	8.17 9.28 9.39
S 0808-D1	3 mm 6 mm max	29.30 38.00 43.70	4.88 6.33 7.28
S 0820-D1	3 mm 6 mm max	33.40 42.50 44.00	5.57 7.08 7.33
S 1220-A1	3 mm 6 mm max	15.78 17.10 17.48	7.89 8.55 8.74
S 1220-B1	3 mm 6 mm max	23.26 28.05 32.38	11.63 14.03 16.19
S 1220-C1	3 mm 6 mm max	25.34 28.59 29.32	12.67 14.30 14.66
S 1220-D1	3 mm 6 mm max	48.80 61.60 66.70	8.13 10.27 11.12
S 2020-A1	3 mm 6 mm max	23.87 26.77 28.36	11.94 13.39 14.18
S 2020-B1	3 mm 6 mm max	33.56 41.04 47.64	16.78 20.52 23.82
S 2020-C1	3 mm 6 mm max	32.28 38.23 45.24	16.14 19.12 22.62
S 2020-D1	3 mm 6 mm max	64.30 93.00 111.00	10.72 15.50 18.50

SINGLE SHEAR, t ≥ 3mm			
Test	Elongation	Force	per bolt
A1-33_1*	3 mm 6 mm max	31.00 36.00 40.44	15.50 18.00 20.22
A1-33_2	3 mm 6 mm max	31.26 36.10 40.86	15.63 18.05 20.43
B1-33_1	3 mm 6 mm max	43.39 53.91 71.24	21.70 26.96 35.62
B1-33_2	3 mm 6 mm max	43.36 54.11 72.01	21.68 27.06 36.01
C1-33_1	3 mm 6 mm max	38.27 50.34 66.87	19.14 25.17 33.44
C1-33_2	3 mm 6 mm max	41.65 51.84 67.50	20.83 25.92 33.75
D1-33_1	3 mm 6 mm max	62.70 115.40 159.50	10.45 19.23 26.58
D1-33_2	3 mm 6 mm max	62.30 116.40 159.50	10.38 19.40 26.58
A1-55_1*	3 mm 6 mm max	50.00 61.00 66.96	25.00 30.50 33.48
A1-55_2*	3 mm 6 mm max	49.00 62.00 67.50	24.50 31.00 33.75
[1] B1-55_1*	3 mm 6 mm max	60.00 87.00 103.81	30.00 43.50 51.91
[1] B1-55_2	3 mm 6 mm max	66.23 88.43 103.42	33.12 44.22 51.71
C1-55_1	3 mm 6 mm max	57.55 80.54 100.64	28.78 40.27 50.32
C1-55_2	3 mm 6 mm max	58.63 80.27 98.68	29.32 40.14 49.34
D1-55_1	3 mm 6 mm max	152.00 209.10 248.80	25.33 34.85 41.47
D1-55_2	3 mm 6 mm max	156.60 211.30 248.90	26.10 35.22 41.48

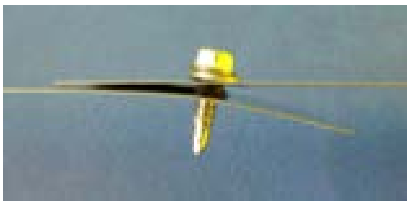
DOUBLE SHEAR, t ≥ 3mm			
Test	Elongation	Force	per bolt per shear plane
A2-36_1	3 mm 6 mm max	58.13 71.74 79.17	14.53 17.94 19.79
A2-36_2	3 mm 6 mm max	59.48 72.68 79.50	14.87 18.17 19.88
B2-36_1	3 mm 6 mm max	79.39 105.12 122.09	19.85 26.28 30.52
B2-36_2	3 mm 6 mm max	73.86 103.08 120.93	18.47 25.77 30.23
C2-36_1	3 mm 6 mm max	79.46 103.06 126.45	19.87 25.77 31.61
C2-36_2	3 mm 6 mm max	73.89 100.08 123.13	18.47 25.02 30.78
D2-36_1	3 mm 6 mm max	144.60 239.30 299.60	12.05 19.94 24.97
D2-36_2	3 mm 6 mm max	127.40 236.10 300.40	10.62 19.68 25.03
A2-510	3 mm 6 mm max	95.70 118.50 120.90	23.93 29.63 30.23
B2-510*	3 mm 6 mm max	136.00 169.00 177.40	34.00 42.25 44.35
[1] C2-510	3 mm 6 mm max	128.10 156.50 168.70	32.03 39.13 42.18
[3] D2-510*	3 mm 6 mm max	390.00 468.00 510.20	32.50 39.00 42.52
A2-510S	3 mm 6 mm max	105.40 130.90 135.90	26.35 32.73 33.98
[2] B2-510S	3 mm 6 mm max	129.0 166.90 167.40	32.33 41.73 41.85
[1] C2-510S	3 mm 6 mm max	119.10 162.10 162.20	29.78 40.53 40.55
[3] D2-510S*	3 mm 6 mm max	350.00 480.00 497.90	29.17 40.00 41.49

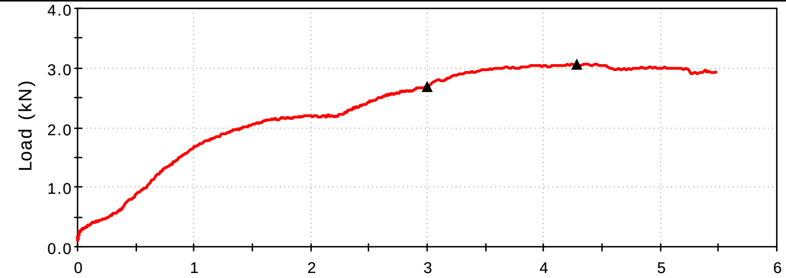
ANGLE SECTIONS, SINGLE SHEAR, t ≥ 3mm			
Test	Elongation	Force	Per bolt
E1-33_1	3 mm 6 mm max	20.86 26.60 37.45	20.86 26.60 37.45
E1-33_2	3 mm 6 mm max	22.18 27.74 37.25	22.18 27.74 37.25
[1] E1-55*	3 mm 6 mm max	30.00 41.50 50.44	30.00 41.50 50.44
F1-33_1	3 mm 6 mm max	33.34 46.92 62.13	16.67 23.46 31.07
F1-33_2	3 mm 6 mm max	36.08 48.13 60.93	18.04 24.07 30.47
[1] F1-55	3 mm 6 mm max	51.22 71.36 84.69	25.61 35.68 42.35

Appendix C. Screwed connections – Samples from test data

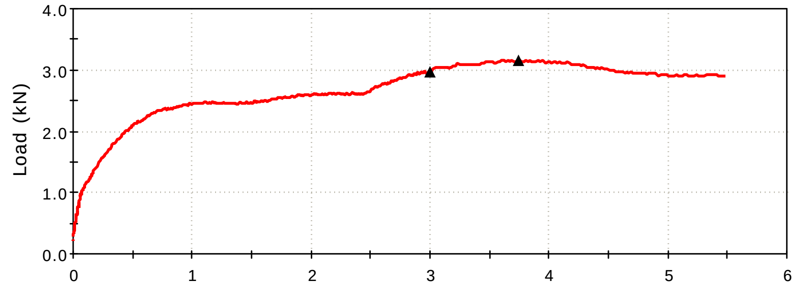


S0505-1a

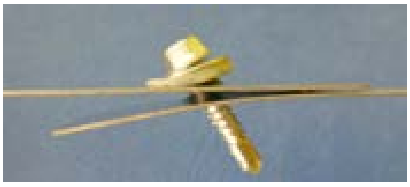


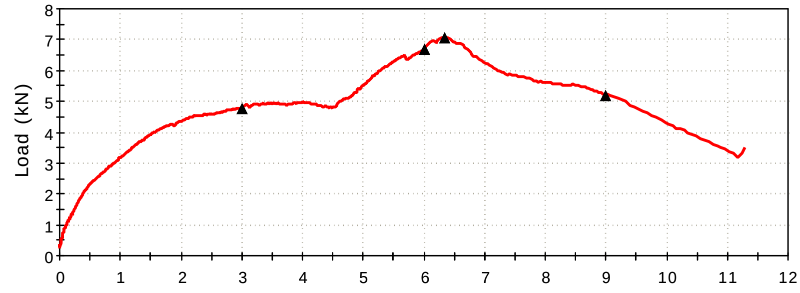


S0520-1a

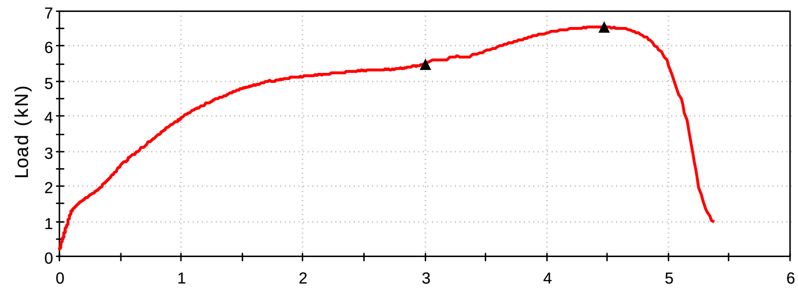


S0808-1a

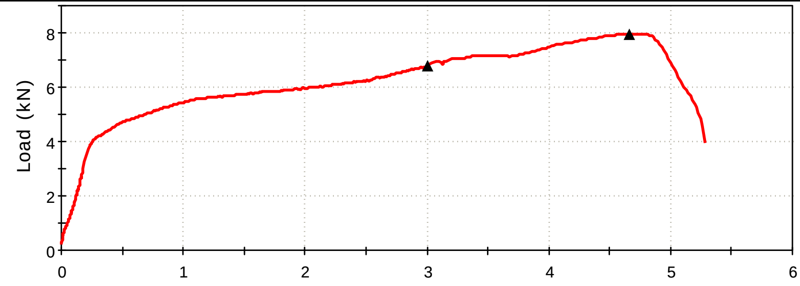




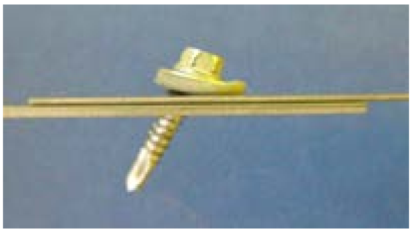
S0820-1a

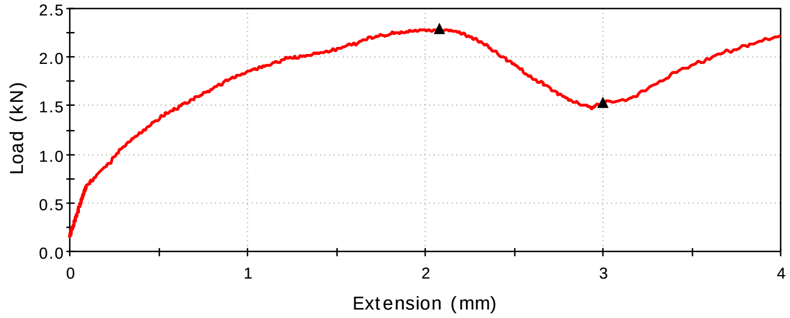


S1212-1a

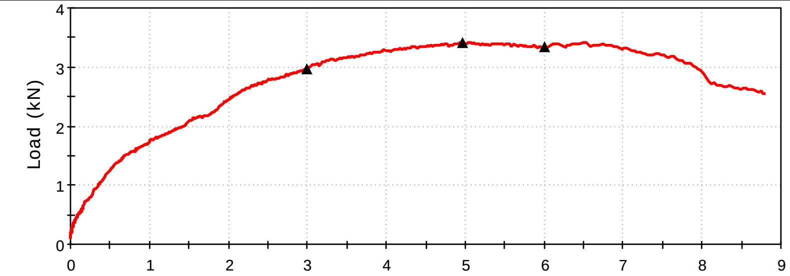


S1220-1a

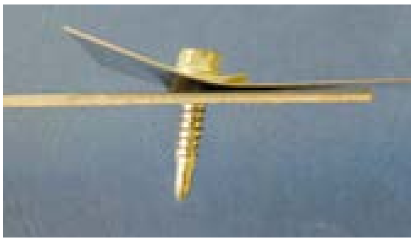


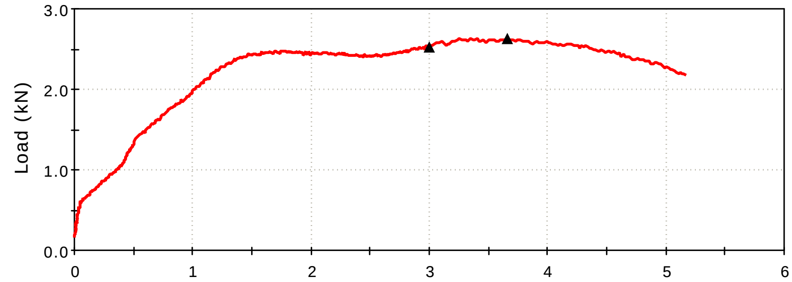


S0505-1b

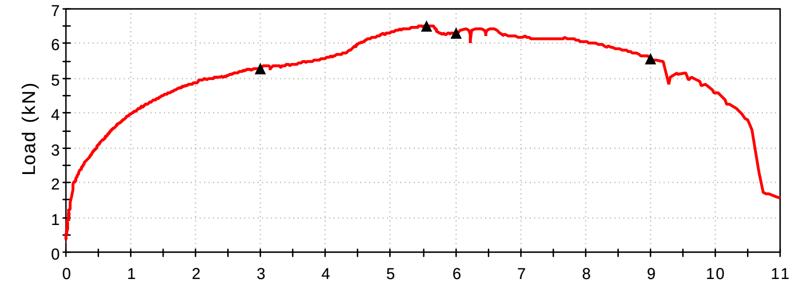


S0520-1b

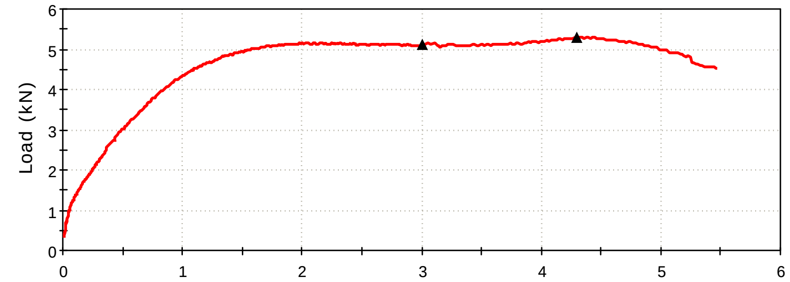




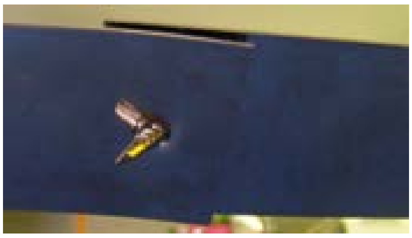
S0808-1b

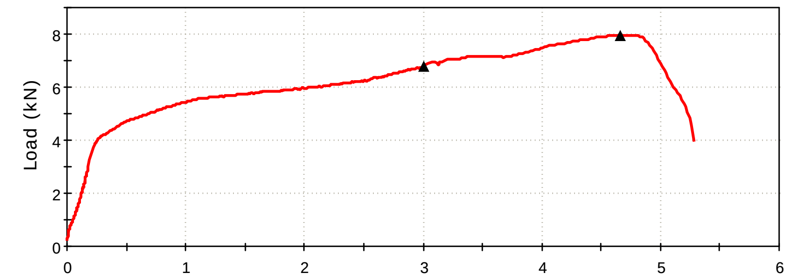


S0820-1b

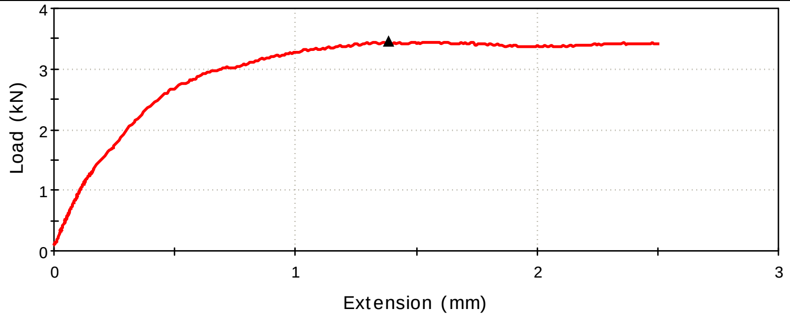


S1212-1b

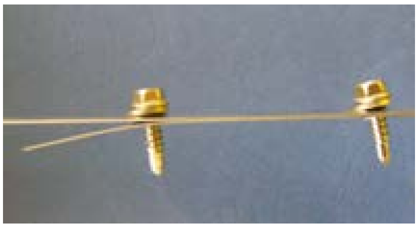


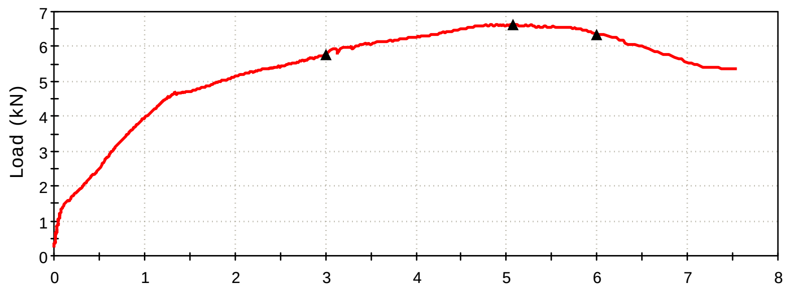


S1220-1b

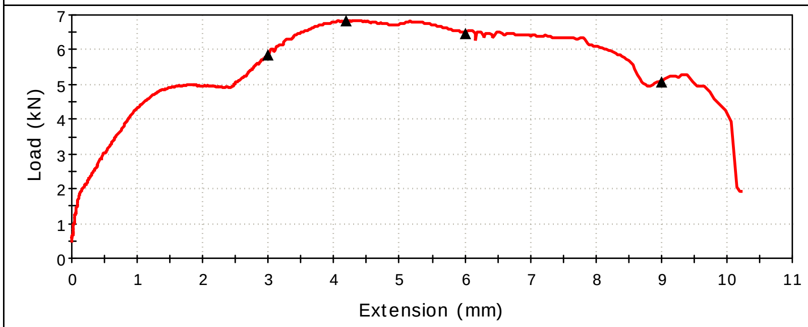


S0505-2a

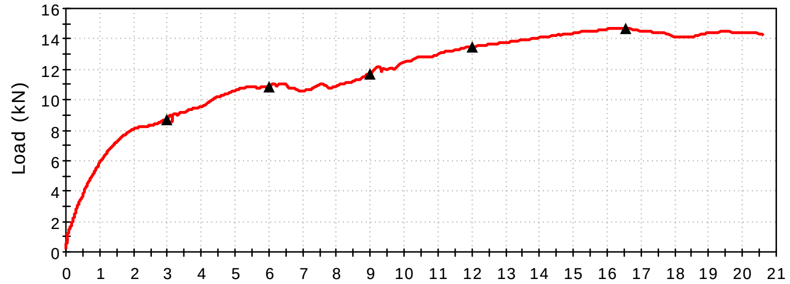




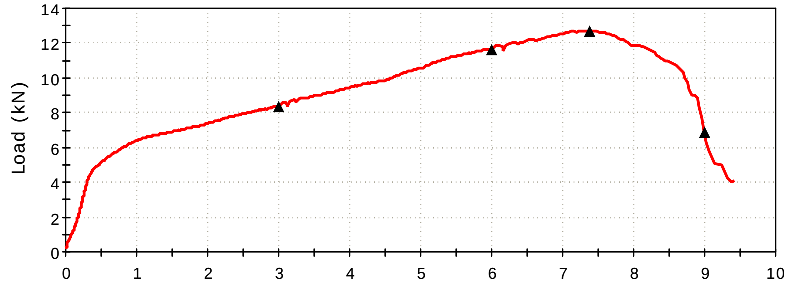
S0520-2a



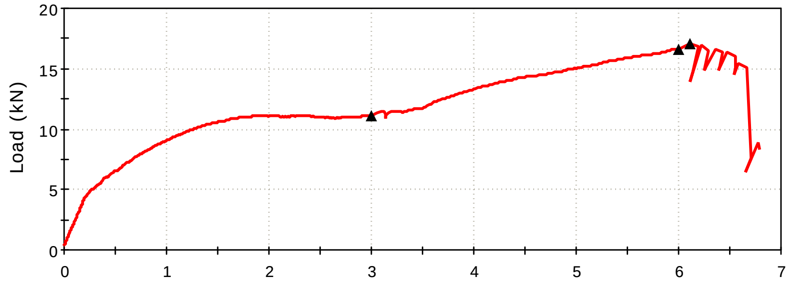
S0808-2a



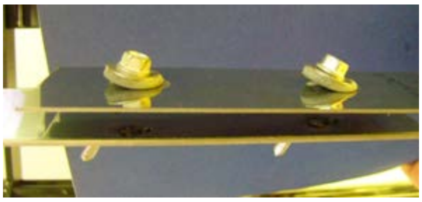
S0820-2a



S1212-2a



S1220-2a



Appendix D. Screwed connections – Test results

	Criterion: Elongation of 3 mm		*Criterion: Ultimete load*	
Test	Load	per screw	Load	per screw
^S0505 -1a 1	1.58	1.58	1.58	1.58
S0505 -1a 2	1.70	1.70	2.00	2.00
^S0505 -1a 3	1.80	1.80	1.80	1.80
^S0505 -1b 1	1.34	1.34	1.34	1.34
^S0505 -1b 2	1.71	1.71	1.71	1.71
S0505 -1b 3	1.54	1.54	2.29	2.29
^S0505 - 2a 1	3.64	1.82	3.64	1.82
^S0505 - 2a 2	3.21	1.61	3.21	1.61
^S0505 - 2a 3	3.45	1.73	3.45	1.73
average		1.65		1.76
stdev		0.15		0.27
S0520 - 1a 1	2.69	2.69	3.08	3.08
S0520 - 1a 2	2.94	2.94	3.12	3.12
S0520 - 1a 3	2.85	2.85	3.20	3.20
S0520 - 1b 1	3.06	3.06	3.43	3.43
S0520 - 1b 2	2.97	2.97	3.41	3.41
S0520 - 1b 3	2.85	2.85	3.30	3.30
S0520 - 2a 1	5.86	2.93	6.41	3.21
S0520 - 2a 2	5.76	2.88	6.63	3.32
S0520 - 2a 3	5.76	2.88	5.93	2.97
average		2.89		3.23
stdev		0.10		0.15
S0808 - 1a 1	2.88	2.88	2.97	2.97
S0808 - 1a 2	2.98	2.98	3.16	3.16
^S0808 - 1a 3	2.72	2.72	2.72	2.72
S0808 -1b 1	2.68	2.68	2.80	2.80
S0808 -1b 2	2.53	2.53	2.63	2.63
S0808 -1b 3	2.96	2.96	2.99	2.99
S0808 - 2a 1	6.17	3.09	6.41	3.21
S0808 - 2a 2	5.86	2.93	6.85	3.43
S0808 - 2a 3	5.45	2.73	5.80	2.90
average		2.83		2.98
stdev		0.18		0.25
S0820 -1a 1	4.79	4.79	7.08	7.08
S0820 -1a 2	5.47	5.47	7.41	7.41
S0820 -1a 3	5.18	5.18	7.45	7.45
>S0820 -1b 1	5.28	5.28	6.52	6.52
>S0820 -1b 2	5.36	5.36	6.82	6.82
>S0820 -1b 3	5.53	5.53	6.84	6.84
S0820 - 2a 1	7.27	3.64	10.94	5.47
S0820 - 2a 2	8.72	4.36	14.73	7.37
S0820 - 2a 3	9.31	4.66	14.75	7.38
average		4.92		6.93
stdev		0.62		0.64

S1212 -1a 1	5.50	5.50	6.56	6.56
S1212 -1a 2	4.43	4.43	6.09	6.09
S1212 -1a 3	4.94	4.94	5.30	5.30
S1212 -1b 1	5.72	5.72	6.28	6.28
*S1212 -1b 2	5.72	5.72	5.91	5.91
S1212 -1b 3	5.11	5.11	5.30	5.30
S1212-2a 1	8.83	4.42	12.68	6.34
S1212-2a 2	9.89	4.95	12.90	6.45
S1212-2a 3	8.99	4.50	12.13	6.07
average		5.03		6.03
stdev		0.53		0.46
*S1220-1a 1	6.77	6.77	7.97	7.97
*S1220-1a 2	5.58	5.58	8.87	8.87
*S1220-1a 3	6.24	6.24	7.52	7.52
>S1220-1b 1	5.85	5.85	8.67	8.67
>S1220-1b 2	4.88	4.88	9.83	9.83
S1220-1b 3	4.90	4.90	9.37	9.37
*S1220-2a 1	9.32	4.66	18.55	9.28
S1220-2a 2	11.05	5.53	15.85	7.93
S1220-2a 3	11.13	5.57	17.06	8.53
average		5.55		8.66
stdev		0.68		0.76

Appendix E. Numerical values of comparisons, bolted connections

Net section failure

Criterion Fmax, calculation by f_u.

	Test	*t*	f_y	f_u	$f_{u,red}$	$A_{net}/d_o/t/n$		*n*	*Calculated*		*test/calculated*	
EN						1-1	1-3		1-1	1-3	1-1	1-3
S 0808-A1	11.34	0.80	327	478	450.3	1.98	2.20	1	9.84	10.94	1.15	1.04
S 0820-A1	11.86	0.80	327	478	450.3	1.98	2.20	1	9.84	10.94	1.20	1.08
S 1220-A1	17.48	1.20	311	456	429.1	1.98	2.20	1	14.08	15.65	1.24	1.12
S 2020-A1	28.36	1.97	334	463	444.8	1.98	2.20	1	23.48	26.09	1.21	1.09
A1-33_1*	40.44	2.93	295	447	415.7	1.98	2.20	1	33.71	37.46	1.20	1.08
A1-33_2	40.86	2.93	295	447	415.7	1.98	2.20	1	33.71	37.46	1.21	1.09
A2-36_1	79.17	5.50	345	451	443.1	1.98	2.20	1	63.85	70.94	1.24	1.12
A2-36_2	79.5	5.50	345	451	443.1	1.98	2.20	1	63.85	70.94	1.25	1.12
A1-55_1*	66.96	4.50	353	478	463.3	1.98	2.20	1	55.37	61.52	1.21	1.09
A1-55_2*	67.5	4.50	353	478	463.3	1.98	2.20	1	55.37	61.52	1.22	1.10
A2-510	120.9	4.50	353	478	463.3	1.98	2.20	2	110.73	123.04	1.09	0.98
A2-510S	135.9	4.97	395	526	513.1	1.98	2.20	2	134.58	149.53	1.01	0.91
F1-33_1	62.13	2.93	295	447	415.7	2.38		1	40.52		1.53	
F1-33_2	60.93	2.93	295	447	415.7	2.38		1	40.52		1.50	
[1] F1-55	84.69	4.50	353	478	463.3	2.38		1	66.55		1.27	

Criterion displacement, calculation by f_u.

	Test	*t*	f_y	f_u	$f_{u,red}$	$A_{net}/d_o/t/n$		*n*	*Calculated*		*test/calculated*	
EN						1-1	1-3		1-1	1-3	1-1	1-3
S 0808-A1	10.24	0.80	327	478	450.3	1.98	2.20	1	9.84	10.94	1.040	0.936
S 0820-A1	9.68	0.80	327	478	450.3	1.98	2.20	1	9.84	10.94	0.983	0.885
S 1220-A1	15.78	1.20	311	456	429.1	1.98	2.20	1	14.08	15.65	1.120	1.008
S 2020-A1	26.77	1.97	334	463	444.8	1.98	2.20	1	23.48	26.09	1.140	1.026
A1-33_1*	36.00	2.93	295	447	415.7	1.98	2.20	1	33.71	37.46	1.068	0.961
A1-33_2	36.10	2.93	295	447	415.7	1.98	2.20	1	33.71	37.46	1.071	0.964
A2-36_1	71.74	5.50	345	451	443.1	1.98	2.20	1	63.85	70.94	1.124	1.011
A2-36_2	72.68	5.50	345	451	443.1	1.98	2.20	1	63.85	70.94	1.138	1.024
A1-55_1*	61.00	4.50	353	478	463.3	1.98	2.20	1	55.37	61.52	1.102	0.992
A1-55_2*	62.00	4.50	353	478	463.3	1.98	2.20	1	55.37	61.52	1.120	1.008
A2-510	118.5	4.50	353	478	463.3	1.98	2.20	2	110.73	123.04	1.070	0.963
A2-510S	130.9	4.97	395	526	513.1	1.98	2.20	2	134.58	149.53	0.973	0.875
F1-33_1	46.92	2.93	295	447	415.7	2.38		1	40.52		1.158	
F1-33_2	48.13	2.93	295	447	415.7	2.38		1	40.52		1.188	
[1] F1-55	71.36	4.50	353	478	463.3	2.38		1	66.55		1.072	

Criterion F_{max}, calculation by $f_{u.red}$.

	Test	*t*	f_y	f_u	$f_{u,red}$	$A_{net}/d_o/t/n$		*n*	*Calculated*		*test/calculated*	
EN						1-1	1-3		1-1	1-3	1-1	1-3
S 0808-A1	11.34	0.80	327	478	450.3	1.98	2.20	1	9.27	10.30	1.22	1.10
S 0820-A1	11.86	0.80	327	478	450.3	1.98	2.20	1	9.27	10.30	1.28	1.15
S 1220-A1	17.48	1.20	311	456	429.1	1.98	2.20	1	13.25	14.73	1.32	1.19
S 2020-A1	28.36	1.97	334	463	444.8	1.98	2.20	1	22.55	25.06	1.26	1.13
A1-33_1*	40.44	2.93	295	447	415.7	1.98	2.20	1	31.35	34.83	1.29	1.16
A1-33_2	40.86	2.93	295	447	415.7	1.98	2.20	1	31.35	34.83	1.30	1.17
A2-36_1	79.17	5.50	345	451	443.1	1.98	2.20	1	62.73	69.70	1.26	1.14
A2-36_2	79.5	5.50	345	451	443.1	1.98	2.20	1	62.73	69.70	1.27	1.14
A1-55_1*	66.96	4.50	353	478	463.3	1.98	2.20	1	53.66	59.63	1.25	1.12
A1-55_2*	67.5	4.50	353	478	463.3	1.98	2.20	1	53.66	59.63	1.26	1.13
A2-510	120.9	4.50	353	478	463.3	1.98	2.20	2	107.33	119.25	1.13	1.01
A2-510S	135.9	4.97	395	526	513.1	1.98	2.20	2	131.28	145.87	1.04	0.93
F1-33_1	62.13	2.93	295	447	415.7	2.38		1	37.68		1.65	
F1-33_2	60.93	2.93	295	447	415.7	2.38		1	37.68		1.62	
[1] F1-55	84.69	4.50	353	478	463.3	2.38		1	64.51		1.31	

Criterion displacement, calculation by $f_{u.red}$.

	Test	*t*	f_y	f_u	$f_{u,red}$	$A_{net}/d_o/t/n$		*n*	*Calculated*		*test/calculated*	
EN						1-1	1-3		1-1	1-3	1-1	1-3
S 0808-A1	10.24	0.80	327	478	450.3	1.98	2.20	1	9.27	10.30	1.104	0.994
S 0820-A1	9.68	0.80	327	478	450.3	1.98	2.20	1	9.27	10.30	1.044	0.940
S 1220-A1	15.78	1.20	311	456	429.1	1.98	2.20	1	13.25	14.73	1.191	1.072
S 2020-A1	26.77	1.97	334	463	444.8	1.98	2.20	1	22.55	25.06	1.187	1.068
A1-33_1*	36.00	2.93	295	447	415.7	1.98	2.20	1	31.35	34.83	1.148	1.033
A1-33_2	36.10	2.93	295	447	415.7	1.98	2.20	1	31.35	34.83	1.151	1.036
A2-36_1	71.74	5.50	345	451	443.1	1.98	2.20	1	62.73	69.70	1.144	1.029
A2-36_2	72.68	5.50	345	451	443.1	1.98	2.20	1	62.73	69.70	1.159	1.043
A1-55_1*	61.00	4.50	353	478	463.3	1.98	2.20	1	53.66	59.63	1.137	1.023
A1-55_2*	62.00	4.50	353	478	463.3	1.98	2.20	1	53.66	59.63	1.155	1.040
A2-510	118.5	4.50	353	478	463.3	1.98	2.20	2	107.33	119.25	1.104	0.994
A2-510S	130.9	4.97	395	526	513.1	1.98	2.20	2	131.28	145.87	0.997	0.897
F1-33_1	46.92	2.93	295	447	415.7	2.38		1	37.68		1.245	
F1-33_2	48.13	2.93	295	447	415.7	2.38		1	37.68		1.277	
[1] F1-55	71.36	4.50	353	478	463.3	2.38		1	64.51		1.106	

Bearing type failure

B1 and B2 type tests, criterion F_{max}, calculation by f_u and $f_{u,red}$

	Test	Calculation by fu				Calculation by fu,red			
		Calculated		Test/Calculated		Calculated		Test/Calculated	
		1-8	1-3	1-8	1-3	1-8	1-3	1-8	1-3
S 0808-B1*	19.73	12.21	11.38	1.616	1.734	11.50	10.72	1.716	1.840
S 0820-B1*	21.96	15.46	15.51	1.420	1.416	14.57	14.61	1.507	1.503
S 1220-B1	32.38	22.13	25.20	1.463	1.285	20.82	23.97	1.555	1.351
S 2020-B1	47.64	29.11	31.74	1.636	1.501	27.97	30.49	1.703	1.562
B1-33_1	71.24	41.81	45.58	1.704	1.563	38.88	42.39	1.832	1.681
B1-33_2	72.01	41.81	45.58	1.722	1.580	38.88	42.39	1.852	1.699
B2-36_1	122.09	81.39	88.74	1.500	1.376	77.77	84.79	1.570	1.440
B2-36_2	120.93	81.39	88.74	1.486	1.363	77.77	84.79	1.555	1.426
[1] B1-55_1*	103.81	68.66	74.85	1.512	1.387	66.55	72.55	1.560	1.431
[1] B1-55_2	103.42	68.66	74.85	1.506	1.382	66.55	72.55	1.554	1.425
B2-510*	177.4	155.29	169.31	1.142	1.048	150.32	163.88	1.180	1.082
[2] B2-510S	167.4	170.08	185.43	0.984	0.903	165.17	180.07	1.013	0.930

B1 and B2 type tests, criterion displacement, calculation by f_u and $f_{u,red}$

	Test	Calculation by fu				Calculation by fu,red			
		Calculated		Test/Calculated		Calculated		Test/Calculated	
		1-8	1-3	1-8	1-3	1-8	1-3	1-8	1-3
S 0808-B1*	15.2	12.21	11.38	1.245	1.336	11.50	10.72	1.322	1.418
S 0820-B1*	16.8	15.46	15.51	1.086	1.083	14.57	14.61	1.153	1.150
S 1220-B1	23.26	22.13	25.20	1.051	0.923	20.82	23.97	1.117	0.970
S 2020-B1	41.04	29.11	31.74	1.410	1.293	27.97	30.49	1.467	1.346
B1-33_1	53.91	41.81	45.58	1.290	1.183	38.88	42.39	1.387	1.272
B1-33_2	54.11	41.81	45.58	1.294	1.187	38.88	42.39	1.392	1.277
B2-36_1	105.12	81.39	88.74	1.291	1.185	77.77	84.79	1.352	1.240
B2-36_2	103.08	81.39	88.74	1.266	1.162	77.77	84.79	1.325	1.216
[1] B1-55_1*	87	68.66	74.85	1.267	1.162	66.55	72.55	1.307	1.199
[1] B1-55_2	88.43	68.66	74.85	1.288	1.181	66.55	72.55	1.329	1.219
B2-510*	169	155.29	169.31	1.088	0.998	150.32	163.88	1.124	1.031
[2] B2-510S	166.9	170.08	185.43	0.981	0.900	165.17	180.07	1.010	0.927

C1, C2 and E1 type tests, criterion F_{max}, calculation by f_u and $f_{u,red}$

	Test	*Calculation by f_u*				*Calculation by $f_{u,red}$*			
		Calculated		Test/Calculated		Calculated		Test/Calculated	
		1-8	1-3	1-8	1-3	1-8	1-3	1-8	1-3
S 0808-C1	19.63	12.21	11.38	1.608	1.725	11.50	10.72	1.707	1.831
S 0820-C1	18.77	12.21	11.38	1.538	1.649	11.50	10.72	1.632	1.751
S 1220-C1	29.32	17.47	18.65	1.679	1.572	16.44	17.55	1.784	1.671
S 2020-C1	45.24	29.11	31.74	1.554	1.425	27.97	30.49	1.617	1.484
C1-33_1	66.87	41.81	45.58	1.600	1.467	38.88	42.39	1.720	1.578
C1-33_2	67.50	41.81	45.58	1.615	1.481	38.88	42.39	1.736	1.592
C2-36_1	126.45	79.18	86.32	1.597	1.465	77.79	84.81	1.626	1.491
C2-36_2	123.13	79.18	86.32	1.555	1.426	77.79	84.81	1.583	1.452
C1-55_1	100.64	68.66	74.85	1.466	1.344	66.55	72.55	1.512	1.387
C1-55_2	98.68	68.66	74.85	1.437	1.318	66.55	72.55	1.483	1.360
[1] C2-510	120.90	137.32	149.71	0.880	0.808	133.10	145.11	0.908	0.833
[1] C2-510S	162.20	166.89	181.95	0.972	0.891	162.80	177.49	0.996	0.914
E1-33_1	37.45	21.40	23.33	1.750	1.605	19.90	21.70	1.882	1.726
E1-33_2	37.25	21.40	23.33	1.740	1.596	19.90	21.70	1.872	1.717
[1] E1-55*	50.44	34.33	37.43	1.469	1.348	33.27	36.28	1.516	1.390

C1, C2 and E1 type tests, criterion displacement, calculation by f_u and $f_{u,red}$

	Test	*Calculation by f_u*				*Calculation by $f_{u,red}$*			
		Calculated		Test/Calculated		Calculated		Test/Calculated	
		1-8	1-3	1-8	1-3	1-8	1-3	1-8	1-3
S 0808-C1	15.95	12.21	11.38	1.307	1.402	11.50	10.72	1.387	1.488
S 0820-C1	16.33	12.21	11.38	1.338	1.435	11.50	10.72	1.420	1.523
S 1220-C1	25.34	17.47	18.65	1.451	1.359	16.44	17.55	1.542	1.444
S 2020-C1	38.23	29.11	31.74	1.313	1.204	27.97	30.49	1.367	1.254
C1-33_1	50.34	41.81	45.58	1.204	1.104	38.88	42.39	1.295	1.188
C1-33_2	51.84	41.81	45.58	1.240	1.137	38.88	42.39	1.333	1.223
C2-36_1	103.06	79.18	86.32	1.302	1.194	77.79	84.81	1.325	1.215
C2-36_2	100.08	79.18	86.32	1.264	1.159	77.79	84.81	1.287	1.180
C1-55_1	80.54	68.66	74.85	1.173	1.076	66.55	72.55	1.210	1.110
C1-55_2	80.27	68.66	74.85	1.169	1.072	66.55	72.55	1.206	1.106
[1] C2-510	156.5	137.32	149.71	1.140	1.045	133.10	145.11	1.176	1.079
[1] C2-510S	162.1	166.89	181.95	0.971	0.891	162.80	177.49	0.996	0.913
E1-33_1	26.6	21.40	23.33	1.243	1.140	19.90	21.70	1.336	1.226
E1-33_2	27.74	21.40	23.33	1.296	1.189	19.90	21.70	1.394	1.278
[1] E1-55*	41.5	34.33	37.43	1.209	1.109	33.27	36.28	1.247	1.144

D1 and D2 type tests, criterion F_{max}.

	Test	*t*	f_y	f_u	$f_{u,red}$	*Area*		*n*	*based on* f_u		*based on* $f_{u,red}$	
						Tension	Shear		Calc.	test/calc.	Calc.	test/calc.
S 0808-D1	43.7	0.80	327	478	450	4.40	6.60	1	34.83	1.255	33.56	1.302
S 0820-D1	44	0.80	327	478	450	4.40	6.60	1	34.83	1.263	33.56	1.311
S 1220-D1	66.7	1.20	311	456	429	4.40	6.60	1	49.79	1.340	47.94	1.391
S 2020-D1	111	1.97	334	463	445	4.40	6.60	1	84.77	1.309	82.72	1.342
D1-33_1	159.5	2.93	295	447	416	4.40	6.60	1	117.73	1.355	112.49	1.418
D1-33_2	159.5	2.93	295	447	416	4.40	6.60	1	117.73	1.355	112.49	1.418
D2-36_1	299.6	5.50	345	451	443	4.40	6.60	1	235.88	1.270	233.40	1.284
D2-36_2	300.4	5.50	345	451	443	4.40	6.60	1	235.88	1.274	233.40	1.287
D1-55_1	248.8	4.50	353	478	463	4.40	6.60	1	201.73	1.233	197.94	1.257
D1-55_2	248.9	4.50	353	478	463	4.40	6.60	1	201.73	1.234	197.94	1.257
[3] D2-510*	510.2	4.50	353	478	463	4.40	6.60	2	403.45	1.265	395.88	1.289
[3] D2-510S*	497.9	4.97	395	526	513	4.40	6.60	2	493.56	1.009	486.23	1.024

D1 and D2 type tests, criterion displacement.

	Test	*t*	f_y	f_u	$f_{u,red}$	*Area*		*n*	*based on* f_u		*based on* $f_{u,red}$	
						Tension	Shear		Calc.	test/calc.	Calc.	test/calc.
S 0808-D1	38.0	0.80	327	478	450	4.40	6.60	1	34.83	1.091	33.56	1.132
S 0820-D1	33.4	0.80	327	478	450	4.40	6.60	1	34.83	0.959	33.56	0.995
S 1220-D1	48.8	1.20	311	456	429	4.40	6.60	1	49.79	0.980	47.94	1.018
S 2020-D1	93	1.97	334	463	445	4.40	6.60	1	84.77	1.097	82.72	1.124
D1-33_1	115.4	2.93	295	447	416	4.40	6.60	1	117.73	0.980	112.49	1.026
D1-33_2	116.4	2.93	295	447	416	4.40	6.60	1	117.73	0.989	112.49	1.035
D2-36_1	239.3	5.50	345	451	443	4.40	6.60	1	235.88	1.014	233.40	1.025
D2-36_2	236.1	5.50	345	451	443	4.40	6.60	1	235.88	1.001	233.40	1.012
D1-55_1	209.1	4.50	353	478	463	4.40	6.60	1	201.73	1.037	197.94	1.056
D1-55_2	211.3	4.50	353	478	463	4.40	6.60	1	201.73	1.047	197.94	1.067
[3] D2-510*	468	4.50	353	478	463	4.40	6.60	2	403.45	1.160	395.88	1.182
[3] D2-510S*	480	4.97	395	526	513	4.40	6.60	2	493.56	0.973	486.23	0.987

Appendix F.Numerical values of comparisons, screwed connections

Test	*Test per screw*		*Calculated*		*Test/calculated*			
Criterion	3 mm	F_{max}			3 mm		F_{max}	
Calculation			f_u	$f_{u,red}$	f_u	$f_{u,red}$	f_u	$f_{u,red}$
^S0505 -1a 1	1.58	1.58	1.286	1.160	1.26	1.40	1.26	1.40
S0505 -1a 2	1.70	2.00	1.286	1.160	1.35	1.50	1.59	1.77
^S0505 -1a 3	1.80	1.80	1.286	1.160	1.43	1.59	1.43	1.59
^S0505 -1b 1	1.34	1.34	1.286	1.160	1.07	1.18	1.07	1.18
^S0505 -1b 2	1.71	1.71	1.286	1.160	1.36	1.51	1.36	1.51
S0505 -1b 3	1.54	2.29	1.286	1.160	1.23	1.36	1.82	2.02
^S0505 - 2a 1	1.82	1.82	1.286	1.160	1.45	1.61	1.45	1.61
^S0505 - 2a 2	1.61	1.61	1.286	1.160	1.28	1.42	1.28	1.42
^S0505 - 2a 3	1.73	1.73	1.286	1.160	1.37	1.52	1.37	1.52
average	1.65	1.76			1.31	1.45	1.40	1.56
stdev	0.15	0.27			0.12	0.13	0.21	0.24
S0520 - 1a 1	2.69	3.08	1.286	1.160	1.00	1.11	1.15	1.27
S0520 - 1a 2	2.94	3.12	1.286	1.160	1.10	1.22	1.16	1.29
S0520 - 1a 3	2.85	3.20	1.286	1.160	1.06	1.18	1.19	1.32
S0520 - 1b 1	3.06	3.43	1.286	1.160	1.14	1.27	1.28	1.42
S0520 - 1b 2	2.97	3.41	1.286	1.160	1.11	1.23	1.27	1.41
S0520 - 1b 3	2.85	3.30	1.286	1.160	1.06	1.18	1.23	1.37
S0520 - 2a 1	2.93	3.21	1.286	1.160	1.09	1.21	1.20	1.33
S0520 - 2a 2	2.88	3.32	1.286	1.160	1.07	1.19	1.24	1.37
S0520 - 2a 3	2.88	2.97	1.286	1.160	1.07	1.19	1.11	1.23
average	2.89	3.23			1.08	1.20	1.20	1.33
stdev	0.10	0.15			0.04	0.04	0.06	0.06
S0808 - 1a 1	2.88	2.97	2.566	2.417	1.15	1.22	1.19	1.26
S0808 - 1a 2	2.98	3.16	2.566	2.417	1.19	1.26	1.26	1.34
^S0808 - 1a 3	2.72	2.72	2.566	2.417	1.09	1.15	1.09	1.15
S0808 -1b 1	2.68	2.80	2.566	2.417	1.07	1.14	1.12	1.19
S0808 -1b 2	2.53	2.63	2.566	2.417	1.01	1.07	1.05	1.11
S0808 -1b 3	2.96	2.99	2.566	2.417	1.18	1.25	1.19	1.27
S0808 - 2a 1	3.09	3.21	2.566	2.417	1.23	1.31	1.28	1.36
S0808 - 2a 2	2.93	3.43	2.566	2.417	1.17	1.24	1.37	1.45
S0808 - 2a 3	2.73	2.90	2.566	2.417	1.09	1.15	1.16	1.23
average	2.83	2.98			1.13	1.20	1.19	1.26
stdev	0.18	0.25			0.07	0.08	0.10	0.11
S0820 -1a 1	4.79	7.08	2.566	2.417	1.12	1.19	1.66	1.76
S0820 -1a 2	5.47	7.41	2.566	2.417	1.28	1.36	1.73	1.84
S0820 -1a 3	5.18	7.45	2.566	2.417	1.21	1.29	1.74	1.85
>S0820 -1b 1	5.28	6.52	2.566	2.417	1.24	1.31	1.53	1.62
>S0820 -1b 2	5.36	6.82	2.566	2.417	1.25	1.33	1.60	1.69
>S0820 -1b 3	5.53	6.84	2.566	2.417	1.29	1.37	1.60	1.70
S0820 - 2a 1	3.64	5.47	2.566	2.417	0.85	0.90	1.28	1.36
S0820 - 2a 2	4.36	7.37	2.566	2.417	1.02	1.08	1.72	1.83
S0820 - 2a 3	4.66	7.38	2.566	2.417	1.09	1.16	1.73	1.83
average	4.92	6.93			1.15	1.22	1.62	1.72
stdev	0.62	0.64			0.15	0.16	0.15	0.16

Test	*Test per screw*		*Calculated*		*Test/calculated*			
Criterion	3 mm	F_{max}			3 mm		F_{max}	
Calculation			f_u	$f_{u,red}$	f_u	$f_{u,red}$	f_u	$f_{u,red}$
S1212 -1a 1	5.50	6.56	4.499	4.234	1.25	1.33	1.49	1.59
S1212 -1a 2	4.43	6.09	4.499	4.234	1.01	1.07	1.39	1.47
S1212 -1a 3	4.94	5.30	4.499	4.234	1.12	1.20	1.21	1.28
S1212 -1b 1	5.72	6.28	4.499	4.234	1.30	1.38	1.43	1.52
*S1212 -1b 2	5.72	5.91	4.499	4.234	1.30	1.38	1.35	1.43
S1212 -1b 3	5.11	5.30	4.499	4.234	1.16	1.24	1.21	1.28
S1212-2a 1	4.42	6.34	4.499	4.234	1.01	1.07	1.44	1.53
S1212-2a 2	4.95	6.45	4.499	4.234	1.13	1.20	1.47	1.56
S1212-2a 3	4.50	6.07	4.499	4.234	1.02	1.09	1.38	1.47
average	5.03	6.03			1.15	1.22	1.37	1.46
stdev	0.53	0.46			0.12	0.13	0.10	0.11
*S1220-1a 1	6.77	7.97	5.279	4.967	1.31	1.40	1.55	1.64
*S1220-1a 2	5.58	8.87	5.279	4.967	1.08	1.15	1.72	1.83
*S1220-1a 3	6.24	7.52	5.279	4.967	1.21	1.29	1.46	1.55
>S1220-1b 1	5.85	8.67	5.279	4.967	1.14	1.21	1.68	1.79
>S1220-1b 2	4.88	9.83	5.279	4.967	0.95	1.01	1.91	2.03
S1220-1b 3	4.90	9.37	5.279	4.967	0.95	1.01	1.82	1.93
*S1220-2a 1	4.66	9.28	5.279	4.967	0.90	0.96	1.80	1.91
S1220-2a 2	5.53	7.93	5.279	4.967	1.07	1.14	1.54	1.63
S1220-2a 3	5.57	8.53	5.279	4.967	1.08	1.15	1.66	1.76
average	5.55	8.66			1.08	1.14	1.68	1.79
stdev	0.68	0.76			0.13	0.14	0.15	0.16