RESEARCH REPORT

VTT-R-06126-12

Commission of the European Communities
Grant agreement No. RFSR-CT-2010-00026

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

Definition of test programme

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Confidentiality: Confidential until May 2014

Report's title	
SAFSS WP6: Definition of test programme	
Customer, contact person, address Commission of the European Communities	Order reference RFSR-CT-2010-00026
Project name Structural Applications of Ferritic Stainless Steels	Project number/Short name 39594/SAFSS
Author(s) Asko Talja	Pages 14 p.
Keywords stainless steel, ferritic, tests, screwed connections, bolted connections, Eurocodes	Report identification code VTT-R-06126-12

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 of WP6 compiles a programme of lap shear tests which are planned for various configurations of bolted and screwed connections.

Material of connections is ferritic stainless steel of grade 1.4509 (AISI 441) with thickness of 0.5–5.5 mm. Tested connections are planned for different failure types demonstrating net section, bearing and block tearing failures. Test programme for bolted connections comprises in all 40 tests, of which 24 are for thick plate connections 16 for thin plate connections. Test programme for screwed connections comprises 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. Tests are carried out for single lap specimens with varying material thicknesses and arrangements of screws in order to demonstrate different failure modes (shear failure, bearing failure, tilting failure).

The work of WP6 is made in co-operation of Institute of Metals and Technology (IMT) and Technical Research Centre of Finland (VTT). The tests are defined by VTT, while the tests and manufacturing of the specimens will be performed by IMT. The tests results and final information relating to the tests will be given in IMT's test report. Finally, VTT will make the comparison with Eurocodes and gives design recommendations.

Confidentiality	Confidential until May 2014

Espoo 17.9.2012

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Distribution (customer and VTT)

Project group	1 pdf copy in project workspace
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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. Work package WP6: Bolted and screwed connections, have bee planned for investigating the behaviour of stainless steel connections of thick and thin-walled structures. This report summarizes the test programme which will be carried out in WP6. It compiles a programme of lap shear tests for various configurations of bolted and screwed connections. The tested connections are planned for failure modes demonstrating net section, bearing and block tearing failures. Material of connections is ferritic stainless steel of grade 1.4509 (AISI 441) with thickness of 0.5–5.5 mm.

The work of WP6 is made in co-operation of Institute of Metals and Technology (IMT) and Technical Research Centre of Finland (VTT). The tests are defined by VTT, while the tests and manufacturing of the specimens will be performed by IMT. The tests results and final information relating to the tests will be given in IMT's test report. Finally, VTT will make the comparison with Eurocodes and gives design recommendations.

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Contents

1 Introduction

The objective of the work package WP 6 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 Package seeks to develop design guidelines for bolted and screwed connections in ferritic stainless steel members up to 6 mm thick. A programme of lap shear tests will be carried out on various configurations of bolted and screwed connections to study the various failure modes.

Austenitic stainless steel bolts (M10-M12) joining ferritic material up to 6 mm thick will be tested (it is understood that austenitic bolts are generally used to join ferritic material). The specimens are dimensioned such that the relevant failure modes are demonstrated. Net section failure, bearing failure (deformations of holes) and block shear ('pull into line') failures are studied. Also curling effects (out-of-plane deformations) are considered in double shear tests. The test programme concentrates on grade 1.4509 and the total number of tests is 94. In addition, standard material tension test (three repeats) will be carried out for the materials used in the tests. The specimens are subjected to monotonic loading.

Test programme for bolted connections comprises in all 40 tests, of which 24 are for thick plate connections 16 for thin plate connections. One bolt size of M12 (diameter d = 12 mm) with hole diameter of d_0 = 13 mm is used in all tests. Both single and double lap specimens are tested. In the case of thick-walled connections one ferritic stainless steel of grade 1.4509 with material thicknesses of 3, 4.5 and 5.5 mm is used. Specimens comprise four types of bolt groups which demonstrate net section, bearing and block tearing failure modes. In the case of thin-walled connections same type of failures is tested by single lap specimens for grade 1.4509 with thickness of 0.8, 1.2 and 2 mm.

Test programme for screwed connections comprises 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. Tests are carried out for single lap specimens with varying material thicknesses and arrangements of screws in order to demonstrate different failure modes (shear failure, bearing failure, tilting failure). One ferritic stainless steel grade 1.4509 is tested. Three tests are carried out for each configuration. The screws for the tests are chosen based on preliminary tests studying the thread cutting properties during installation.

2 Test programme for bolted plate connections

EN 1993-1-8 gives design equations for bolted connections with plate thickness larger than or equal to 3 mm, otherwise the rules for bolts in EN 1993-1-3 should be used.

Types of bolt groups and the principle of testing are shown in Fig. 1. Types A–D are for single and double shear tests, types E and F are for equal angle tests. One test for each specimen is carried out. The specimen dimensions (Fig. 2) and

predicted final failure modes for different types of tests are given in Tables 1 and 2. The given spacing of holes is slightly larger the than the minimum values given in Eurocodes (Appendix A, Fig. 5). Schematic presentation of failure modes is shown in Fig. 6 of Appendix A.

One bolt size of M12 (diameter d = 12 mm), which is the smallest nominal bolt size given in EN 1090-2), with hole diameter d_0 = 13 mm (nominal clearance of 1 mm specified in EN 1090-2) is used in all tests. Austenitic (or austenitic ferritic) stainless steel bolts to EN ISO 3506 property classes 80 with nominal values of f_{yb} = 600 N/mm^2 and f_{ub} = 800 N/mm^2 are used (Table 2.2 in EN 1993-1-4). In the case of comparative carbon steel specimens (4 tests) normal bolts of class 8.8 are used. The bolts are fully threaded so that the same bolts can be used for all plate thicknesses. In the single shear tests with bolt in one row (types C1, E1) the bolts are provided with washers under both the head and the nut.

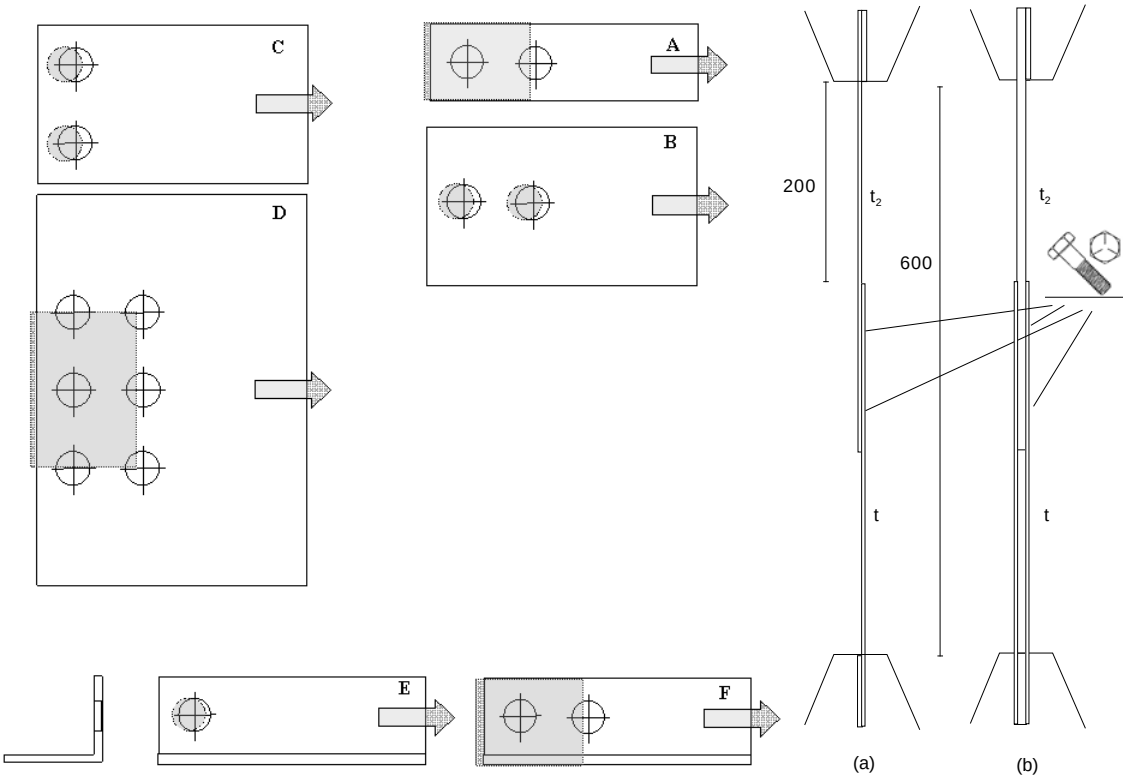

Figure 1. (A-F) Connection types. (a) Specimen for single shear tests. (b) Specimen for double shear test.

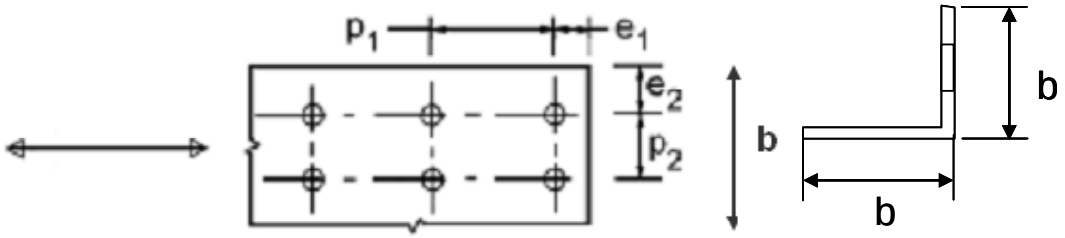

Figure 2. Symbols in Tables 1 and 2.

Table 1. Specimen dimensions for single and double shear tests (Fig. 1, types A, B, C and D).

Final failure	Single shear	Double shear	Number of bolts	b	e1	e2	p1	p2
Net section failure	A1	A2	2	3.2 d_0	1.6 d_0	1.6 d_0	3.2 d_0	-
Bearing failure	B1	B2	2	6.4 d_0	1.6 d_0	3.2 d_0	3.2 d_0	-
Bearing failure	C1	C2	2	6.4 d_0	1.6 d_0	1.6 d_0	-	3.2 d_0
Block tearing failure	D1	D2	6	16 d_0	1.6 d_0	4.8 d_0	3.2 d_0	3.2 d_0

Table 2. Specimen dimensions for angle bar tests (Fig. 1, types E and F).

Final failure	Single shear	Double shear	Number of bolts	b	e1	e2	p1	p2
Bearing failure	E1	-	1	3.2 d_0	1.6 d_0	1.6 d_0	3.2 d_0	-
Net section failure	F1	-	2	3.2 d_0	1.6 d_0	1.6 d_0	3.2 d_0	-

Table 3. Grade and thickness of the materials in bolted connections.

	Different type of tests and test identification codes for them	Material 1 t [mm]	Grade 1	Material 2 [mm]	Grade 2
Single shear tests (8 tests)	A1-33, B1-33, C1-33, D1-33 A1-55, B1-55, C1-55, D1-55	3 4.5	1.4509 1.4509	3 4.5	1.4509 1.4509
Double shear tests(12 tests)	A2-36, B2-36, C2-33, D2-36 A2-510, B2-510, C2-510, D2-510 A2-510S, B2-510S, C2-510S, D2-510S	3 4.5 4.5	1.4509 1.4509 S355	5.5 10 10	1.4509 S355 S355
Angle bar test (4 tests)	E1-33, F1-33 E1-55, F1-55	3 4.5	1.4509 1.4509	3 4.5	1.4509 1.4509
Material tests (3 repeats: a, b, c)	M-3a, M-3b, M-3c M-5a, M-5b, M-5c M-6a, M-6b, M-6c S-3a, M-3b, M-3c S-5a, M-5b, M-5c	3 4.5 5.5 4.5 10	1.4509 1.4509 1.4509 S355 S355		

Plate thickness of 3, and 4.5 mm (Table 3) are used in single shear tests. For double shear test the outer plate thickness (material 1) is 3.5 or 5 mm and the thickness of inner plate (material 2) is 5.5 or 10 mm.

One ferritic stainless steel of grade 1.4509 is used in all specimens except of comparative carbon steel specimens (4 tests), in which carbon steel grade S355 is used (Table 3). The minimum nominal value of 0.2 %-proof strength $R_{p0,2}$ and tensile strength R_m are 230 and 430 MPa for grade 1.4509 (EN 10088-4:2009, cold rolled strip). These are less than nominal minimum values of $R_{p0,2}$ = 355 MPa and R_m = 470 MPa for carbon grade S355 (EN 10025-2). The given maximum value for R_m is 650 MPa for 1.4509 and 630 MPa for S355.

Based on the hole diameter d_0 = 13 mm, the specimen dimensions given in Tables 1 and 2 are: $1.6d_0$ = 21 mm, $3.2d_0$ = 42 mm, $6.4d_0$ = 83 mm and $16d_0$ = 208 mm.

3 Test programme for sheeting connections

3.1 Screwed connections

Specimen dimensions and the principle of single shear testing are shown in Fig. 3. Both one and single screw specimens are tested. The specimen dimensions are based on ECCS guidance [1]. In addition to the recommended end distance e_1 = 30 mm, use of minimum value of e_1 = 3d = 16.5 mm given in EN1993-1-3 is tested on test specimens with only one screw. The plate thickness combinations and test identification codes are shown in Table 4. The thinnest sheet is always next to the head of the screw. One ferritic stainless steel of grade 1.4509 is used in the case of all specimens. Three test repeats are performed for all each test combination.

Austenitic stainless steel stainless steel (corrosion class A2, 1.4301, AISI 304) self-drilling screws with nominal diameter of d = 5.5 mm are used in test specimens. Self-drilling screws have an own drill point which forms the pilot hole. The drilling and thread-cutting properties depend on the shape and hardness of the drill point. The screws for the tests will be chosen based on preliminary tests studying the thread cutting properties. If the self-drilling screws are not hard enough to drill ferritic stainless steel properly, they are installed through pre-drilled clearance holes (see reference [2]).

The predicted final failure mode is bearing failure (hole elongation, out of plane curling) except of combination of t = 1.2 mm and t_2 = 2 mm, where predicted failure mode is shear failure of the fastener. Schematic presentation of different failure modes is illustrated in Fig. 7 of Appendix A.

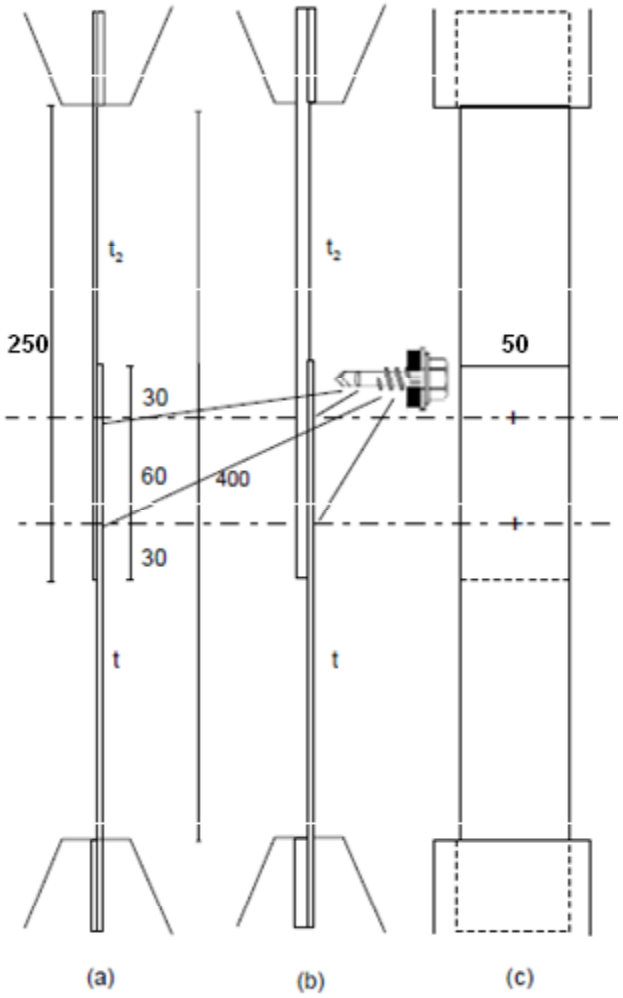

Figure 3. Connection types and specimen dimension for screwed connections (e_1 = 30 mm, d_1 = 60 mm).

Table 4. Plate thicknesses in screwed connections.

Plate thicknesses in test (see Fig 3)						
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 code						
1 screw, e_1 = 30 mm (3x6 =18 tests)	S0505-1a	S0520-1a	S0808-1a	S0820-1a	S1212-1a	S1220-1a
1 screw, e_1 = 3d = 16.5 mm (3x16 = 18 tests)	S0505-1b	S0520-1b	S0808-1b	S0820-1b	S1212-1b	S1220-1b
2 screws e_1 = 30 mm, d_1 = 60 mm (3x6 = 18 tests)	S0505-2a	S0520-2a	S0808-2a	S0820-2a	S1212-2a	S1220-2a
material tests (three repeats for every thickness)	S05-1 S05-2 S05-3		S08-1 S08-2 S08-3		S12-1 S12-2 S12-3	S20-1 S20-2 S20-3

3.2 Bolted connections

EN 1993-1-3 gives design equations for screwed and bolted connections with t = 0.45–3 mm and the equations are different from EN 1993-1-1. Therefore the bolt groups A, B, C and D in Fig. 1 are also tested using thin-walled materials. The material thicknesses of specimens of the tests are shown in Table 5. The specimen dimensions are same as given in Table 1. Also the bolt and hole sizes are same as in Chapter 2. However, the bolts in all types of connections are provided with washers under both the head and the nut. One test for each specimen is carried out.

Because of curling effects (out-of-plane deformations), failure in net section is predicted to be determinative in all of the tests.

Table 5. Grade and thickness of the materials in bolted sheeting connections.

	Test identification code	Material 1 t [mm]	Grade 1	Material 2 t_2 [mm]	Grade 2
Single shear tests (4x4 = 16 tests)	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

4 Tests

4.1 Manufacturing of the specimens

The test specimens and material test pieces are always taken in the rolling direction of the sheets. Holes are made by drilling. The bolts are tightened only to a little bit more than finger tight so that the friction does not affect to results, but the plates are in good contact. Washers are used as specified in the previous chapters.

4.2 Checking the dimensions

Dimension of the specimens should be checked before tests. If the dimensions (edge distances, bolt distances) differ more than 1 mm from the nominal dimensions, the values shall be reported. The major diameter (outer thread diameter), minor diameter (diameter of the thread groove) are measured from the self-drilling screws (average diameter and range of variation). If screws usual for side laps are used (Fig. 3), which have thread-free zone under the fastener head, the diameter of the thread-free zone shall be measured.

4.3 Connection tests

The load-displacement behaviour of the connections is determined by tensile tests. The deformation of the connection (Fig. 4) is measured and recorded for further use. Loading rate is 10% of the predicted ultimate load per minute up to 50% of the predicted ultimate load (about 5 min). Thereafter the displacement rate is 0.5 mm/min up to deformation of 3 mm (about 6 min). After that the strain rate can be doubled at deformations of 6, 9 and 12 mm up to final failure. The predicted maximum loads are given in Appendix B.

The tests are carried out with machine under strain control. All data from load cells and displacements are recorded at 1 second intervals. Photographs of failures and the force-displacement curves are presented as shown in Appendix B of reference [3]. The strength of test specimens at different deformations is presented as in Table 3.3 of reference [3].

Figure 4. An example of measuring the displacements over the connection.

4.4 Material tests

The material tests are performed according to EN 10002-1. From each material thickness three samples are taken along the rolling direction. The samples are taken from the midwidth and from both edges of raw material plates. The flat specimens are machined into the shape prescribed in Annexes of standard EN 10002-1 (b = 20 mm). The gauge length of the extensometer is 80 mm. The width and thickness of all test pieces are measured before testing. The identification codes for material tests are given in Tables 3 and 4.

The tests are carried out under strain control, starting with a constant strain rate of 0.9%/min (0.00015/sec) until $R_{p2.0}$ (loading time 2.2 min). Thereafter the strain rate is 15%/min (0.0025/sec) (loading time 1–3 min). Strain rate 0.9%/min

corresponds to about 30 MPa/sec at low stress levels, but is much lower at $R_{p0,2}$–$R_{p2.0}$ stress levels. According to EN 10002-1 a constant stress rate up to the upper yield strength shall be 6–60 MPa/sec and after that the strain rate shall not exceed 0.0025/sec.

The tests are carried out with machine under strain control. All data from load sensors and strains is recorded at 0.2 second intervals. The stress strain curves are presented as shown in Appendix B of reference [3]. The material properties determined from the stress-strain curves, are shown as in Table 3.2 of reference [3].

5 Reporting

The test report is a full report about testing and its results. It includes all the information given so well that the tests can be reproduced by everyone else. The test report summarizes also the information given in this paper. The document concerning design recommendations (VTT), written later on by VTT, will refer to the data given in the test report. The report includes at least following information:

- Description of the final test programme.
- Drawings of the specimens including bolt dimensions (grades, washers), materials and hole diameters.
- True dimensions of specimens.
- Measured screw and fastener diameters (diameters: major/minor/thread-free zone).
- Manufacturing of specimens including holes.
- Photos of test specimens before and after tests.
- Testing equipment.
- Information about performing the tests (testing velocities, measurements, references, etc.).
- Written description of the failure modes of different test specimens (s. Appendix A).
- Test results (at least the results shown in reference [3] and in its appendices).

In addition all the load-displacement data and plot files, which are made from the data, are saved on a memory stick or CD for further needs.

References

[1] ECCS. 2009. The Testing of Connections with Mechanical Fasteners in Steel Sheeting and Publication 124, ISBN 92-9147-000-91

[2] Talja, A. 2005. Pull-out resistance tests of stainless steel screws with pre-drilled clearance holes. VTT Report code RTE50-IR-11/2005.

[3] Talja, A. 2003. Design of cold worked stainless steel members – Tests on weld and screw connections. VTT Report code RTE50-IR-9/2003.

Appendix A. Minimum edge distances and failure modes

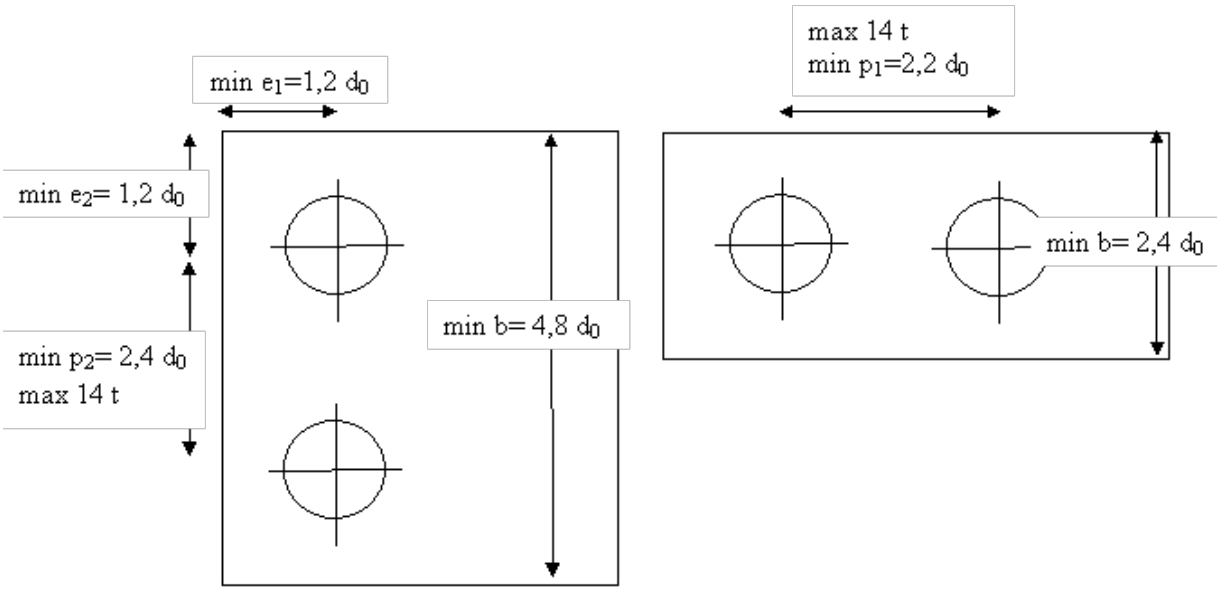

Figure 5. Minimum distances (EN 1993-1-1, Table 3.3).

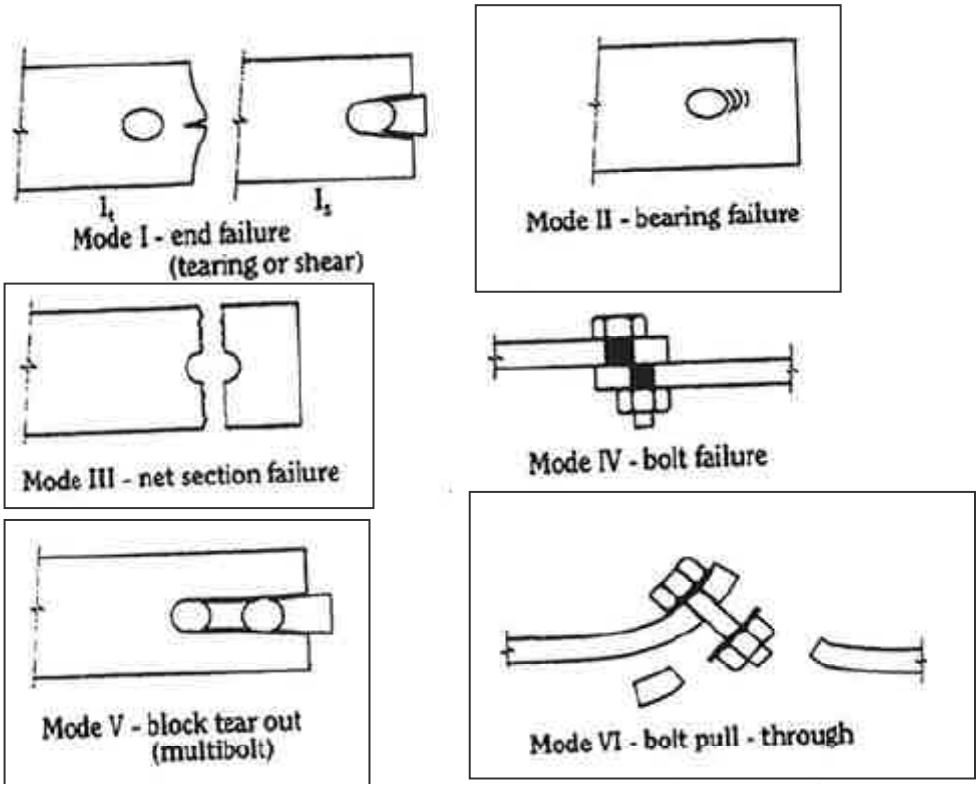

Figure 6. Failure modes of bolted connections.

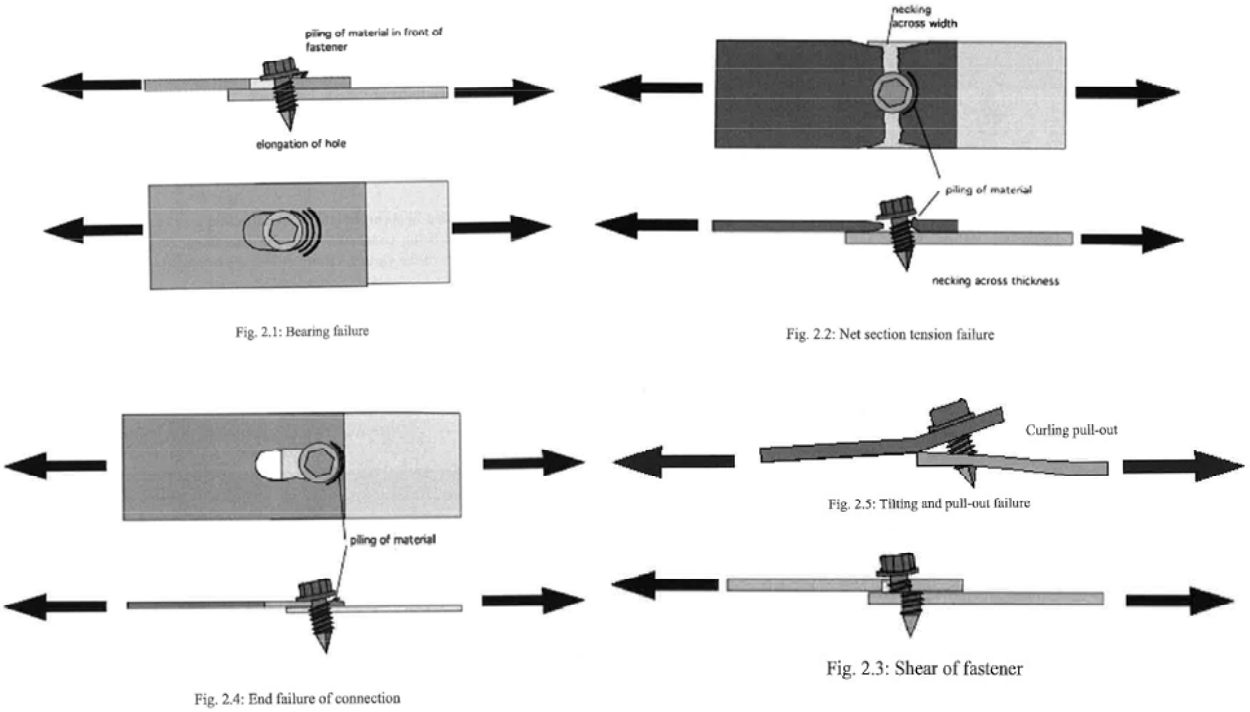

Figure 7. Failure modes of screwed connections.

Table 6. Summary of failure characteristics for connections tested in shear.

Failure mode	Elongation of hole	Piling of material	Necking/ tearing	Pull-out of fastener	Location of failure
bearing failure	√	√			either one or both sheets
net section failure	√	√	√		either one or both sheets
shear of fastener					fastener
end failure	√	√	√		either one or both sheets
tilting and pull-out				√	between sheet and fastener

Appendix B. Predicted maximum loads

The predicted maximum loads, which is given in Tables 7–9 and, are based on values of f_y = 250 MPa and f_u = 500 MPa except of tests for S355 for which f_y = 350 MPa is used. True values can be about 20–50 % higher.

Table 7. Bolted connections (based on EN-1993-1-8, EN-1992-1-4).

	Test identification code	A1	B1	C1	D1
Single shear tests (8 tests)	A1-33, B1-33, C1-33, D1-33 A1-55, B1-55, C1-55, D1-55	40 kN 60 kN	50 kN 75 kN	40 kN 60 kN	120 kN 180 kN
Double shear tests (12 tests)	A2-36, B2-36, C2-33, D2-36 A2-510, B2-510, C2-510, D2-510 A2-510S, B2-510S, C2-510S, D2-510S	70 kN 115 kN 115 kN	95 kN 155 kN 180 kN	75 kN 120 kN 140 kN	220 kN 370 kN 410 kN
	Specimen type	E1	F1		
Angle bar test (4 tests)	E1-33, F1-33 E1-55, F1-55	20 kN 30 kN	45 kN 70 kN		
Material tests (b = 20 mm)	M-3a, M-3b, M-3c M-5a, M-5b, M-5c M-6a, M-6b, M-6c S-3a, M-3b, M-3c S-5a, M-5b, M-5c	30 kN 45 kN 55 kN 45 kN 100 kN			

Table 8. Screwed connections (based on EN-1993-1-3).

Plate thicknesses in test (see Fig. 3)						
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 code						
1 screw, e_1 = 30 mm (3x6 = 18 tests)	S0505-1a 1.3 kN	S0520-1a 1.3 kN	S0808-1a 2.7 kN	S0820-1a 2.7 kN	S1212-1a 4.9 kN	S1220-1a 5.5 kN
1 screw, e_1 = 3d = 16.5 mm (3x16 = 18 tests)	S0505-1b 1.3 kN	S0520-1b 1.3 kN	S0808-1b 2.7 kN	S0820-1b 2.7 kN	S1212-1b 4.9 kN	S1220-1b 5.5 kN
2 screws e_1 = 30 mm, d_1 = 60 mm (3x6 = 18 tests)	S0505-2a 2.7kN	S0520-2a 2.7kN	S0808-2a 5.4 kN	S0808-2a 5.4 kN	S1212-2a 9.9 kN	S1220-2a 11 kN
material tests (b = 20 mm)	S05-1…3 5 kN		S08-1…3 8 kN		S12-1…3 12 kN	S20-1…3 20 kN

Table 9. Bolted sheeting connections (based on EN 1993-1-1, EN 1993-1-3, EN 1993-1-4, EN 1993-1-8).

	Test identification code	A1	B1	C1	D1
Single shear tests (4x4 = 16 tests)	S0808-A1, S0808-B1, S0808-C1, S0808-D1 S0820-A1, S0820-B1, S0820-C1, S0820-D1 S1220-A1, S1220-B1, S1220-C1, S1220-D1 S2020-A1, S2020-B1, S2020-C1, S2020-D1	10 kN 10 kN 15 kN 26 kN	10 kN 10 kN 17 kN 30 kN	10 kN 10 kN 17 kN 30 kN	33 kN 33 kN 50 kN 80 kN