Lap shear tests of bolted and screwed ferritic stainless steel connections
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Bolted connections, specimens

Failure mode | Single shear | Double shear
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Net section | A1 | A2
Bearing | B1 | B2
Bearing | C1 | C2
Block tearing | D1 | D2
Bearing | E1 | -
Net section | F1 | -

Materials
EN 1.4509 (ASTM 441)
Hole $\phi$ 13 mm
Bolt M12

Thicknesses
A-D: $t = 0.8, 1.2, 2.0, 3.0, 4.5$
E-F: $t = 3.0, 4.5$
Net section failure
Bearing failure

![Graph showing force vs. displacement](image-url)
Bearing failure

Force [kN] vs. Displacement [mm]

C1-33
Block tearing failure

![Diagram of force vs. displacement]

D1-55

![Image of block tearing failure]
Net section failure, angles

Force [kN] vs. Displacement [mm] for F1-33
Screwed connections, specimens

Materials

EN 1.4509 (ASTM 441)
A2 Self-drilling screws (EN ISO 1478)
✓ nominal diameter: d=5.5 mm
✓ outer thread diameter: 5.28–5.46 mm
✓ inner diameter: 3.99–4.17 mm
✓ thread pitch: 1.8 mm
✓ clearance hole: 4.0 mm

Thicknesses

<table>
<thead>
<tr>
<th>t [mm]</th>
<th>t₂ [mm]</th>
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<tr>
<td>0.5</td>
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<tr>
<td>0.5</td>
<td>2</td>
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<td>0.8</td>
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Bearing & Out-of-plane bending
Bearing

Force [kN] vs. Displacement [mm]

S0808-2a
Bearing & Pull-out

![Graph showing force vs. displacement with a peak at S1212-2a](image)
Eurocode design

Net section resistance

**Flats:** \( N_{u,Rd} = \frac{k_r A_{\text{net}} f_u}{\gamma_{M2}} \)

EC 1-1: \( k_r = 0.9 \)

EC 1-3 = EC 1-4

\( k_r = [1 + 3r \left( \frac{d_o}{u} - 0.3 \right)] \leq 1.0 \)

**Angles:** EC 1-8

\( N_{u,Rd} = \frac{\beta_2 A_{\text{net}} f_u}{\gamma_{M2}} \)

\( \beta_2 = 0.4 - 0.7 \)

Bearing resistance

EC 1-8: \( F_{b,Rd} = \frac{k_1 \alpha_b f_u dt}{\gamma_{M2}} \)

Factors \( k_1 \) and \( \alpha_b \) are depending only on dimensions, not on \( t \)

EC 1-3: \( F_{b,Rd} = \frac{2.5 \alpha_b f_u k_t dt}{\gamma_{M2}} \)

Factor \( \alpha_b \) is depending on dimensions and \( k_t \) is depending on \( t \)

EC 1-4 = EC 1-8 but using \( f_{u,\text{red}} = 0.5f_y + 0.6f_u \leq 1.0 \)

Block tearing resistance

EC1-8:

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

Self-tapping screws

EC 1-3: \( F_{b,Rd} = \frac{\alpha f_u dt}{\gamma_{M2}} \) ; EC 1-4 = EC 1-3

\( \alpha = 3.2 \sqrt{t/d} \leq 2.1 \) for \( t=t_1 \) and for \( t_1 \geq 2.5t ; t<1.0 \) mm

\( \alpha = 2.1 \) for \( t_1 \geq 2.5t ; t \geq 1.0 \) mm

\( \alpha \) for \( t < t_1 < 2.5t \) by linear interpolation
Failure criterion

• In the interpretation of the test results it is essential, which criterion is applied to the ultimate limit state.
• The Commentary Part of the Design Manual: Use of $f_{u,red}$ limits the bearing deformation to 3 mm. There is also proposed that a 1.75 mm permanent deformation is acceptable at the serviceability state, and a 5 mm permanent bearing deformation is acceptable at the ultimate limit state.
• AISC Steel Construction Manual: Deformation of 6.35 mm has been adopted in developing design guidance for carbon steel connections (Salih & al. 2011).
• ECCS testing guidance for screwed connections: Failure load is the maximum load, when the corresponding total elongation is less than 3 mm; otherwise the failure load is the load at an elongation of 3 mm.
• Many recent studies has used the maximum load in developing design guidance, although the deformations are large, e.g. 20–25 mm in the case of M12 bolts.
• Two criteria are used here: The first is based on the maximum load without limited deformation ($F_{\text{max}}$ criterion) and the second on the elongation (displacement criterion). For bolted connections the elongation is 3 mm per plate and for screwed connections the 3 mm elongation is the total elongation.
Salih & al. 2011 propose different design equations for SLS and ULS for bearing resistances of bolted connections.

The equations for both thick and thin-walled materials base on a parametric FEM study which is verified by test results of stainless steel connections.

The resistance for SLS is based on a hole elongation of 1.0 mm and the resistance for ULS is based on the maximum load attained in calculation.
Results of bolted connections: $F_{\text{max}}$ criterion

Net section resistance
- Plates (N=11): EN 1993-1-1 with $f_{u}$ and even with modified $k_r=1.0$, and present EN 1993-1-3, are both safe
- Angles (N=3): 1993-1-8 with $f_{u}$ is safe

Bearing resistance
- Plates (N=23): EN1993-1-8 and EN 1993-1-3 with $f_{u}$ are both very safe

Block tearing resistance
- Plates (N=11): EN 1993-1-8 with $f_{u}$ is safe
Results of bolted connections: Displacement criterion

**Net section resistance**
- Plates (N=11): EN 1993-1-1 with $f_u$ and existing $k_r=0.9$ is safe
- Angles (N=3): 1993-1-8 with $f_u$ is safe

**Bearing resistance**
- Plates (N=23): EN 1993-1-8 with $f_u$ even with an extra multiplication factor 1.10, and EN 1993-1-3 as it is at the moment, are both safe

**Block tearing resistance**
- Plates (N=11): EN 1993-1-8 with $f_u$ and with an extra reduction factor 0.9 is safe
Results of screwed connections

- In the case of thick back plates, condition for $t > 1.0$ mm in EN 1993-1-3 is used also for $t < 1.0$ mm, because otherwise the results are too conservative and differ remarkably from other test series.
- $N = 54$
- EN1993-1-3 with $f_u$ results in safe design if the failure criterion is $F_{\text{max}}$.
- If the criterion is displacement, EN 1993-1-3 with $f_u$ and with an extra reduction factor 0.9 is safe.
Conclusions and future research needs

- 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 with $f_u$ 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.

- The design expressions of screwed connections can be same for thickness 0.5–1.2 mm. EN 1993-1-3 approach with $f_u$ is recommended. Extra condition for $t<1$ mm is not 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.

- 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 design of block tearing resistance of bolted connections and in design of 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 characteristic values, Annex A recommends the use of same $\gamma_M$-values as in the case of normal calculation.

- More favourable results may be achieved, if statistical determination of resistance models according to Annex D of EN-1990 is used. Then the study should also include test results from other sources and other steel grades.
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