STRENGTH TEST ON BOLTED CONNECTIONS USING HIGH-STRENGTH STEELS (HSS-STEELS) AS A BASE MATERIAL

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RESUME

The results of a series of tests on bolted connections using high-strength steel (HSS) as a base material are presented and analysed in this report. The base material used was HSF 640 (ISO 5951) which has a yield stress of 640 MPa.

The tests studied bearing resistance, net section failure and the block shear failure mode.

The test results have been analysed according to the Finnish specification for steel structures B7, the Swedish specification BSK, the NKB-specification and according to the Eurocode 3. The block shear failure mode has been analysed according to the American LRFD-specification.

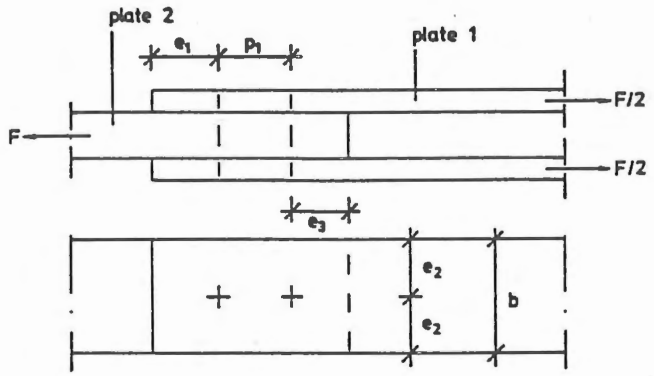
The aim of this study has been to provide experimental test results to allow the development of reliable calculation methods for connections using HSS steels in different types of steel structures.

INTRODUCTION

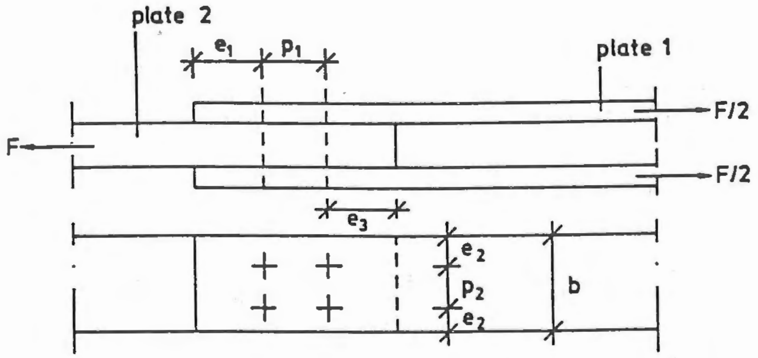
The Finnish specification B7 for steel structures is not valid for the design of steel structures made of high strength steels (HSS steels). HSS steel means here steel with a yield point greater than 400 MPa. Some codes like the Swedish BSK, the Canadian CSA-Standard and the American LRFD-code also give rules for structures made of HSS steels but HSS steels are not yet generally accepted in codes. The highest steel grade in the Eurocode 3/Annex D is FeE 460.

BEARING RESISTANCE OF BOLTED CONNECTIONS

Figure 1 shows the principal arrangements used in the tests. Measures are also shown in Figure 1. There were two bolts in the line in test series E and four bolts in two lines in test series F. The variation of distances between bolts is given in the figure 1. The e/d-values for test series F given in parentheses are measured on the other side of the steelplate.



Test	e_1/d_o	p_1/d_o	
E1	1,20	2,20	bolts M24, 10.9
E2	1,20	2,78	d = 24 mm (the diameter of the bolt)
E3	1,19	2,98	d_o = 26 mm (the diameter of the hole)
E4	1,50	2,18	e_3/d_o = 5, b = 200 mm
E5	1,49	2,79	plate 1, t = 4 mm
E6	1,50	2,99	plate 2, t = 8



Test		e_1/d_o	p_1/d_o	
F1	(1,75)	1,36	2,60	e_2/d_o = 1,5 (d_o = 24 mm)
F2	(1,75)	1,35	3,30	p_2/d_o = 6,0 (d_o = 20 mm)
F3		1,38	2,59	e_3/d_o = 5,9
F4		1,36	3,53	plate 1, t = 3 mm
F5		1,77	3,30	plate 2, t = 6 mm
F6	(1,77)	1,40	3,31 (3.54)	

Figure 1. Test for the bearing resistance, principal sketch and measured values, test series E and F.

A typical load-deformation curve for all the tests is shown in Figure 2, test no E1. The notations "B7/220/lowest" in Figure 2 mean that the loadbearing resistance according to the Finnish code b7 is 220 kN. This means that the loadbearing resistance (220 kN) is calculated based on the lowest value of the loadbearing resistances of individual bolts. The notation "B7/357/sum" means that the total loadbearing resistance of the connection is 357 kN, which is calculated by summarizing the loadbearing resistances of the individual bolts. Corresponding notations are used in Figure 2, when the calculations have been made according to the Eurocode 3 or the Swedish BSK-regulations.

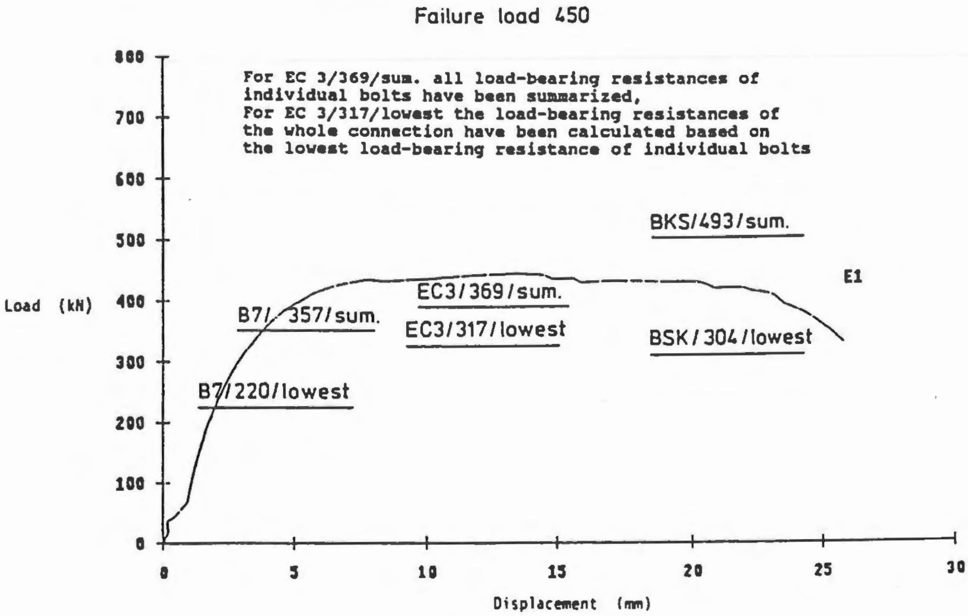


Figure 2. Typical load-deformation curve, tests E1.

CALCULATION METHODS

Design according to the Finnish B7 specification

The Finnish B7 specification (National Building Code of Finland) specifies

$$F_{Rh} = k_2 \cdot d \cdot t \cdot f_y/\gamma_m \quad (1)$$

where

$$k_2 = e_1/d - 0.5 \leq 2.5 \text{ or} \quad (2)$$
$$k_2 = p_1/d - 0.5 \leq 2.5$$

F_{Rh} for the whole connection have been calculated on the basis the following assumptions

a) with the limitation $k_2 \leq 2.5$ and using the lowest bearing resistance value for the bolts
b) summarizing the bearing resistances of individual bolts and with the limitation $k_2 \leq 2.5$ (not allowed under the B7 code)
c) summarizing the bearing resistances of individual bolts without the limitation of k_2 (not allowed under the B7 code).

Resistance of the gross-section (A_{gr}) is

$$N_{Ry} = A_{gr} \cdot f_y/\gamma_m \qquad (3)$$

Resistance of the net-section (A_n) is

$$N_{Ru} = A_n \cdot f_y/\gamma_m \qquad (4)$$

d is the nominal diameter of the bolt. If the shear plane intersects the threads or thread run-out, the diameter corresponding to the stress area A_s of the bolt is used for design purposes. Bolts with full threads were used in these tests. The d-value used in the calculation always corresponds to A_s (e.g. $d = d_s$), where d_s has been calculated according to the A_s values. In these calculations $\gamma_m = 1.0$ is used.

<u>Design according to Eurocode 3 (EC 3)</u>

Bearing resistance EC 3 is determined from equation (5) under

$$F_{Rh} = F_{bRd} = (2.5 \cdot \alpha \cdot f_u \cdot d \cdot t)/\gamma_{m2} \qquad (5)$$

where α is the smallest of

1.0
$e_1/3d_o$
$p_1/3d_o - 0.25$ (6)
f_{ub}/f_u (the ultimate strength of the bolt/the base material)

γ_{M2} = 1.25 (in the comparative calculation, $\gamma_{M2} = 1.00$ is used because only the calculation methods have been compared to the test result calculations)
d_o is the diameter of the hole and
d the diameter of the bolt.

The diameter of the hole and the diameter of the bolt have to be taken into account in calculations made according to EC 3. However, EC 3 gives no rules on which diameters should be used if the threads are in the shear plane. In these tests the shear plane passes through the threaded portion of the bolt.

The comparative calculations have been made using two methods:

1) Using the value d_s based on the stress area in calculating α
   $\alpha = e_1/3d_o = e_1/3d_s$ or
   $\alpha = p_1/3d_o - 0.25 = p_1/3d_s - 0.25$

2) Using the hole diameter d_o in calculating α
   $\alpha = e_1/3d_o$ or
   $\alpha = p_1/3d_o - 0.25$.

Method 2) is given in EC 3. Method 1) is not given in EC 3, and is used here only for comparison.

Design according to the Swedish (BSK) specification

According to BSK regulations bearing resistance is calculated as

$$F_{Rh} = F_{Rbd} = 1.2\ (e_1/d - 0.5)\ d \cdot t \cdot f_{ud} \qquad (7)$$

where d is the diameter of the bolt

$$f_{ud} = f_{buk}/1.2 \qquad (8)$$

f_{ud} is the design value for the material and
f_{buk} the characteristic value for material (ultimate strength).

The coefficient 1.2 in equation (8) is a safety factor which has not been taken into account in the calculations below, which used the measured value f_u.

Design according to the Scandinavian (NKB) recommendations

Bearing resistance according to the NKB guidelines is the same as in BSK, except that the coefficient in equation (7) is 1.4 instead of 1.2.

The results calculated by the different methods are compared with the test results in tables 1a and 1b.

Table 1a. Calculated results compared to test results, series E.

Specimen		E1	E2	E3	E4	E5	E6
Test load (kN) (N_{test})		450	490	510	520	515	623
B7, lowest a) value (kN)		220	221	219	303	305	305
B7/N_{test}		0.489	0.450	0.429	0.583	0.592	0.490
B7, summation b) $k_2 \leq 2.5$ (kN)		357	387	384	398	431	431
B7/N_{test}		0.794	0.789	0.754	0.766	0.837	0.692
B7, summation c) without limitation of k_2 (kN)		357	440	465	398	485	513
B7/N_{test}		0.794	0.898	0.912	0.766	0.941	0.823
BSK, lowest a) value (kN)		304	305	302	419	421	422
BSK/N_{test}		0.675	0.622	0.593	0.805	0.817	0.677
BSK, summation b) (kN)		493	534	531	550	595	595
BSK/N_{test}		1.096	1.089	1.040	1.057	1.154	0.955
EC 3, lowest a) value (kN)	method 1)	317	317	315	397	399	399
	method 2)	255	254	252	294	319	320
EC 3/N_{test}	method 1)	0.704	0.648	0.618	0.763	0.774	0.641
	method 2)	0.568	0.518	0.494	0.565	0.619	0.513
EC 3, summation b) (kN)	method 1)	369	448	472	408	491	518
	method 2)	281	342	361	310	377	398
EC 3/N_{test}	method 1)	0.820	0.914	0.926	0.785	0.954	0.831
	method 2)	0.625	0.698	0.708	0.597	0.731	0.639

Table 1b. Calculated results compared to test results, series F.

Specimen		F1	F2	F3	F4	F5	F6
Test load (kN) (N_{test})		697	725	688	685	740	750
B7, lowest a) value (kN)		320	316	329	311	443	337
$B7/N_{test}$		0.460	0.436	0.478	0.455	0.599	0.449
B7, summation b) $k_2 \leq 2.5$ (kN)		495	488	476	479	533	487
$B7/N_{test}$		0.710	0.674	0.691	0.700	0.720	0.650
B7, summation c) without limitation of k_2 (kN)		540	646	512	672	693	639
$B7/N_{test}$		0.775	0.891	0.745	0.981	0.937	0.852
BSK, lowest a) value (kN)		447	441	436	434	596	454
BSK/N_{test}		0.641	0.609	0.634	0.634	0.805	0.605
BSK, summation b) (kN)		700	691	669	678	749	684
BSK/N_{test}		1.004	0.953	0.972	0.989	1.012	0.911
EC 3, lowest a) value (kN)	method 1)	454	448	434	436	546	446
	method 2)	362	357	346	348	435	356
EC $3/N_{test}$	method 1)	0.651	0.618	0.631	0.637	0.737	0.595
	method 2)	0.520	0.493	0.503	0.508	0.588	0.474
EC 3, summation (kN) b)	method 1)	555	608	527	593	644	600
	method 2)	424	505	401	523	541	499
EC $3/N_{test}$	method 1)	0.797	0.838	0.766	0.866	0.870	0.801
	method 2)	0.608	0.697	0.583	0.763	0.732	0.666

The following conclusions from the results in Table 1 can be made:

- the code B7 gives results, which are very much on the safe side (calculation method a))
- by summarizing all bearing resistances of individual bolts and ignoring the limitation $k_2 \leq 2.5$ we get results on the safe side
- from Figure 2 it can be seen that the deformations at the ultimate limit state are quite large (about the diameter of the bolt). The large deformation together with safety requirements for bolted connections are actually the reasons for the calculation method ($k_2 \leq 2.5$) given in code B7.

- EC 3 rules gives results on the safe side
- rules according to the BSK (summation) give results which are on the unsafe side in some cases. Generally BSK-rules seem to estimate quite well the test results (additional safety-factor 1.2 is not used in these comparisons).

Block shear failure mode

The block shear failure mode is illustrated in Figure 3.

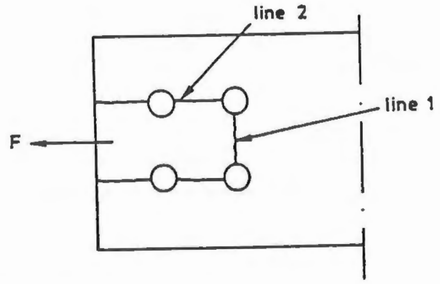
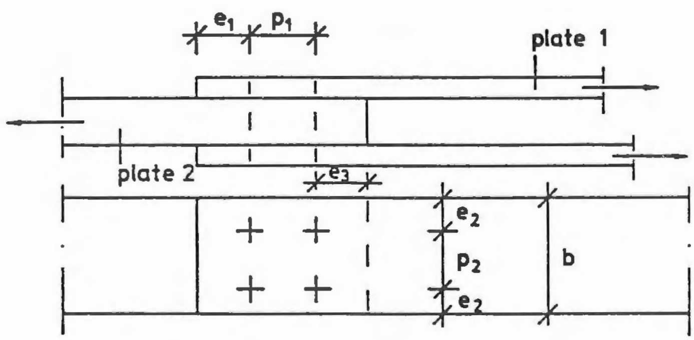


Figure 3. Block shear failure mode.

The dimensions for the block shear failure mode tests are given in Figure 4. The values given in parentheses are measured on the opposite side of the connections.



Test		e_1/d_o	p_1/d_o	
G1	(1,77)	1,41	3,54	$e_2/d = 1{,}5\ d_o = 26$ mm
G2		1,41	2,60	$p_2/d = 2{,}4\ d = 24$ mm
G3	(1,77)	1,42	3,54	$e_3/d = 5{,}9$
G4		1,75	2,60	plate 1, t = 3 mm
G5	(1,75)	1,42	3,30	plate 2, t = 6 mm
G6	(1,77)	1,40	3,31	

Figure 4. Block shear failure mode, test series G, measured values.

According to the American LRFD-code (Load and Resistance Factor Design) the loadbearing resistance of the connection is calculated using equations (9) and (10).

$$F_{block1} = \phi \; (0.6 \cdot f_y \cdot A_{vg} + f_u \cdot A_{nt}) \quad (9)$$
$$F_{block2} = \phi \; (0.6 \cdot f_u \cdot A_{ns} + f_y \cdot A_{tg}) \quad (10)$$

where $\phi = 0.75$ ($\phi = 1.0$ is used here for an analysis of the test results

A_{vg} is the gross area subjected to shear,
A_{tg} the gross area subjected to tension,
A_{ns} the net area subjected to shear and
A_{nt} the net area subjected to tension.

The controlling equation is one that produces the larger force.

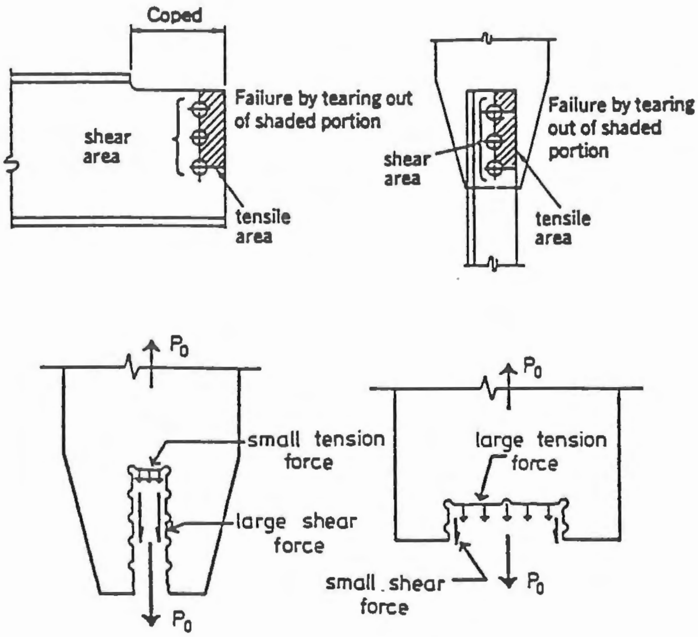


Figure 5. Block shear failure mode, LRFD-specification.

Under EC 3 the design ultimate shear resistance $V_{u.R}$ for rupture along a block shear failure path is taken as:

$$V_{u.R} = \frac{0.6 \; f_u \; A_{v.net}}{\gamma_{M2}} \quad (11)$$

where $A_{v.net}$ is the net area subjected to block shear.

The net area $A_{v.net}$ subjected to block shear is determined, as indicated in Figure 6, as follows:

$$A_{v.net} = t\,[L_v + L_1 + L_2 - nd_o] \tag{12}$$

in which L_1 and L_2 are given by:

$$L_1 = 2.5d_o \text{ but } L_1 \le a_1$$
$$L_2 = 5.0d_o \text{ but } L_2 \le a_2 \tag{13}$$

where n is the number of fastener holes on the block shear failure path.

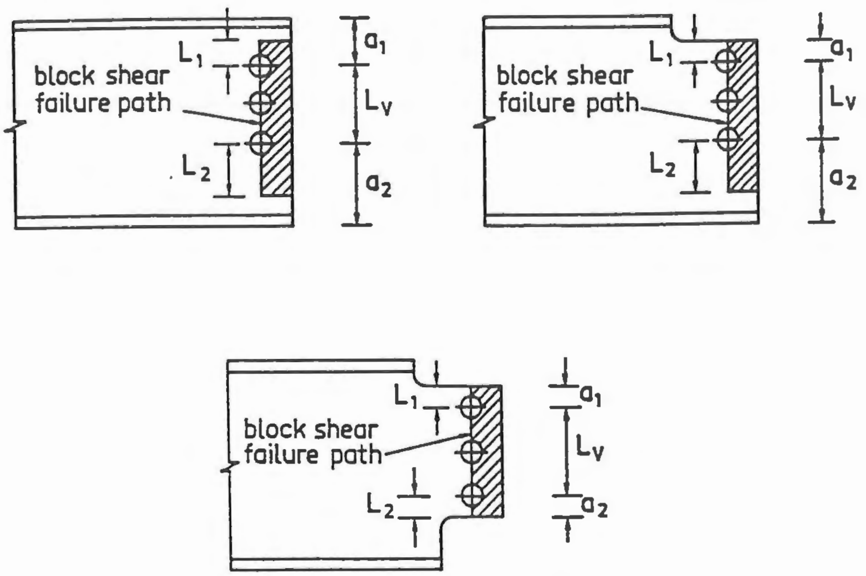


Figure 6. Net shear area - block shear, Eurocode 3.

The results of the comparison are given in Table 2.

Table 2. Comparison of the test results with the calculated values, block shear failure mode.

Test	F_1/F_{test} According to LRFD-code	F_2/F_{test}	N_R/F_{test} According to EC 3
G1	1.05	0.99	0.79
G2	1.01	0.92	0.69
G3	1.10	1.06	0.85
G4	0.90	0.83	0.64
G5	0.90	0.85	0.67
G6	1.10	0.95	0.74

The results in Table 2 show that the LRFD-code gives quite good results and the calculation method in EC 3 gives results on the safe side. It should be mentioned that in the comparison given in the table the material factor is 1.00 (γ_{m2} = 1.0 and ϕ = 1.0).

Failure at the net section

The test pieces in test series H were designed so that the failure would occur in the net section. The failure loads have been calculated using the equation (14)

$$N_u = f_u \cdot A_{net} \tag{14}$$

The ratio N_{test}/N_u is given in Table 3.

Table 3. Test series H, the failure at the net section.

Test	N_{test}/N_u
H1	1.04
H2	0.99
H3	0.97
H4	1.05
H5	1.03
H6	1.01

For design poposes EC 3 gives the formula (15)

$$N_u = 0.9 \cdot f_u \cdot A_{net}/\gamma_{m2} \tag{15}$$

where γ_{m2} = 1.25 (as general for bolted connections).

CONCLUSIONS

The bearing resistance (18 test specimens) and block shear failure (6 test specimens) of various bolted connections were tested and analysed. The base material was high-strength steel (according to ISO 5951) with a nominal yield stress of 640 MPa. The connections had two shear planes. The results of the bearing resistance tests were compared to the analytical values calculated by using the methods given in the Finnish, Swedish and Scandinavian codes and Eurocode 3. The results of the block shear tests were compared to the analytical values calculated using the American LRFD specification.

The following conclusions can be made from the bearing resistance tests:

- All the calculation methods used here give results on the safe side, if the bearing resistance of the whole

connection is calculated using the lowest bearing resistance of individual bolts.
- If the bearing resistance of the whole connection is calculated by summarizing the bearing resistances of each individual bolt, the Finnish B7 code and Eurocode 3 give results on the safe side while the Swedish BSK code seems to overestimate the bearing resistance of the whole connection if the additional safety factor of 1.2 (BSK) is not taken into account.
- If the bearing resistance of the whole connection is calculated by summarizing the bearing resistances of each individual bolt, the deformations at the ultimate limit state can be quite large (the magnitude of the diameter of the bolt).
- Because of the different load-deformation behaviour of individual bolts (depending on the proportional end distance (e/d) and the proportional pitch (p/d)), it is recommended here that the bearing resistance of the whole connection should be calculated using the lowest individual bearing resistance. This will prevent the deformations from being excessive.

The calculation method for block shear failure given in the American LRFD specification seems to give satisfactory results for design purposes. The method for block shear failure mode given in EC 3 seems to underestimate load-bearing capacity.

The ultimate load at the net section can be calculated based on the ultimate tensile strength and the net section to an accuracy of approx. 5 %.

The calculation methods given in the Finnish B7 code for steel structures can be used for HSS steels but the results produced seem to be on the safe side. Regulations for block shear failure should be added to the code.

Statistical analysis based on additional test results on HSS steels needs to be made if more exact calculation methods are to be produced.

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