EXPERIMENTAL RESEARCH ON SINGLE BOLT CONNECTIONS FOR HIGH STRENGTH STEEL S690

Sofia Teixeira de Freitas [1], Peter de Vries [2], Frans S. K. Bijlaard [3]

ABSTRACT

There is a tendency to use more and more High Strength Steel (HSS) elements in civil engineering structures. The rules described in Eurocode 3 for bolted connections in bearing can be applied on joints of plates of steel grades up to S700. However, these rules are based on test data of connections with 8.8 and 10.9 class bolts in mild steel plates. In fact "strong" bolts in “weak” steel plates. With the use of S690, S960 or even higher grade plates, in combination with conventional bolts, this changes to “weak” bolts in “strong” steel plates.

In this study, a series of tests was carried out using specimens designed according to the rules of Eurocode 3, part 1-8 “Design of joints”. The aim of the study was to investigate whether or not those rules are adequate for high strength steels.

The experimental programme consisted of ten different types of specimens of single bolt joints made with steel grade S690. End and edge distances were varied. In total, thirty tests were performed (three tests per each different type of specimen).

The test results show that the rules given by Eurocode 3 are conservative using steel grade S690, mainly when edge distance is smaller than $1.5d_0$. Therefore, a corrected function for the k_1 factor of the bearing resistance formula given by Eurocode 3 is proposed. The proposed correction is based on a statistical evaluation of the test results according to Annex D of EN1990: Basis of Design (formerly Annex Z of Eurocode 3: Design of Steel Structures).

This correction was made in the k_1 factor, since the main differences between experimental values and theoretical values were found in tests specimens with different edge distances. The test results further show that using HSS plates, the minimal values of edge and end distance can also be reduced from $1.2d_0$ to $1.0d_0$.

1. INTRODUCTION

The rules described in EC3 for bolts in bearing dependent on end-distance, edge-

[1] Graduated in Civil Engineering, Technical University of Lisbon, Portugal.
[2] Researcher, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands.
[3] Professor, Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands.

distance and pitch for 8.8 and 10.9 bolt classes are allowed to be used in plates of steel grade up to S700. However, these rules are based on data of steel plates in mild steel and not for high strength steel, 8.8 and 10.9 bolt classes in plates of steel grade up to S460. In fact "strong" bolts in "weak" steel plates. Steel grades of S690, S960 and even higher are being used in civil engineering structures more and more. So, in these cases "weak" bolts in "strong" steel plates. The question is now if the rules for bearing of bolts described in EC3 are adequate in case of bolts in bearing with these strong plates.

In order to answer this question an experimental program with single bolt joints was carried out. Ten different test specimens were designed to validate the maximum bearing resistance for each fastener as well as the minimum distances in a bolted joint with high strength steels – chapter 3, Part 1.8 EC3 [1]. If the high strength steels has less deformation capacity, they would need a larger end distance to get the same deformation but the plates have more strength, so it can handle a lower end distance to get the same resistance for each fastener.

Many kinds of studies were made concerning the influence on bearing resistance of a connection when using high strength steels. An experimental program carried out with steel grade S460 [2] proved that the rules described in EC3 for bearing resistance are conservative. The reductions in the design bearing resistance concerning the distance between the bolts does not need to be so large. Tests results also showed that the minimum edge distance and minimum bolt spacing can be reduced.

The yield-tensile ratio typically increases with the increasing levels in the strength. Studies were made [3] in order to investigate the effect of the ultimate-to-yield stress ratio on the bearing strength. Contrary to what was expected, specimens made by steel of a low ultimate-to-yield stress ratio have deformations capacities similar to those with a high ultimate-to-yield stress ratio with the corresponding end distance. As the end distance increased, the deformation at ultimate strength increased, therefore more deformation capacity can be achieved by increasing the end distance. The end distance is a more significant factor on deformation capacity than the ratio f_u/f_y. The test results were also compared with the design rules of EC3 and it is reported that EC3 recommendations are conservative by approximately 25%.

2. TEST SPECIMEN DESIGN RESISTANCE – EC3 PART 1.8

The objective is the study of bearing failure mechanism. Bolt shear failure, net section failure and gross section failure have to be avoided.

The following design resistance rules are based in clause 3.6.1 (1) in EC3, Part 1.8 [1] and were used in the design of the test specimens.

<u>Bearing Resistance – $F_{b,R}$</u>

$$F_{b,R} = k_1 \, \alpha_b \, f_u^h \, d \, t \tag{1}$$

where: $\alpha_b = \min\{\frac{e_1}{3\,d_0}; \frac{f_{ub}}{f_u}; 1.0\}$, $k_1 = \min\left\{2.8\frac{e_2}{d_0} - 1.7; 2.5\right\}$ and γ_{M2}=1.0.

Eurocode 3 applies also for minimum spacing between the joints - clause 3.5 of EC3: Part 1.8 [1]:

- Minimum end distance: $e_1 \leq 1.2\, d_0$
- Minimum edge distance: $e_2 \leq 1.2\, d_0$

The higher value for the ultimate tensile strength of the plates was taken to obtain the maximum value of the bearing resistance.

All the others failure mechanisms have to be avoided:

$$\underbrace{F_{b,R}}_{\text{maximum}} \ll \underbrace{\{F_{s,R}, N_{u,R}, N_{pl,R}\}}_{\text{minimum}} \tag{2}$$

Shear resistance – $F_{v,R}$

$$F_{v,R} = 0.6\ f_{ub}\ A \tag{3}$$

where the safety factor on the shear design resistance γ_{M2} was 1.0.

The following rules are given in clause 5.4.3 (1) of EC3: Part 1.1 [4].

Net cross section resistance – $N_{u,R}$

$$N_{u,R} = \frac{0{,}9\, A_{net}\, f_u^l}{1.25} \tag{4}$$

where the safety factor equal to γ_{M2} = 1.25, to reach sufficient safety. The lower value of the ultimate tensile strength f_u was used to minimize the resistance of the net section.

Gross section resistance – $N_{pl,R}$

$$N_{pl,R} = \frac{A_{gross}\ f_y}{1.0} \tag{5}$$

where γ_{M0} = 1.0.

3. DESCRIPTION OF THE EXPERIMENTAL PROGRAMME

3.1 Test specimens

Tests specimens are double lap joints, they have cover plates on both sides – Fig. 1.

Each test specimen has two joints. In order to focus the test in only one joint, one of the joints was deliberately designed with higher resistance capacity – strongest joint. The performance of the test specimen is only analysed in the test joint. The specimens were chosen to have bearing of the inner plate as failure mode.

To study the equation given in EC3 for bearing resistance – Eq. (1), on high strength steel the parameters that were varied were k_1 and α_b. This reduction factors are based on experimental data with mild steels and should be checked, if they are still conservative to use in high steel classes [5]. The value of these reduction factors depends on the geometrical properties of the joint - end distance e_1, edge distance e_2 and pitch distance p_1, as well as the ratio of the ultimate tensile strength of the bolt and of the steel plate.

The tests specimens were then designed with the combination of two main criteria:

- Varying the end/edge distance (different values of k_1 and α_b).
- The failure mechanism of the test specimen has to be bearing.

Concerning the geometrical properties, the reduction factors k_1 and α_d can be represented in linear functions. In this investigation study, they were extended beyond the edges described in EC3, considering that the minimum distances can change in high strength steel – Fig. 2.

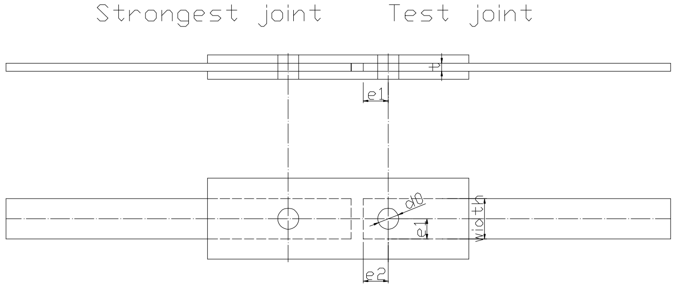

Fig. 1 – Specimen geometry and notation

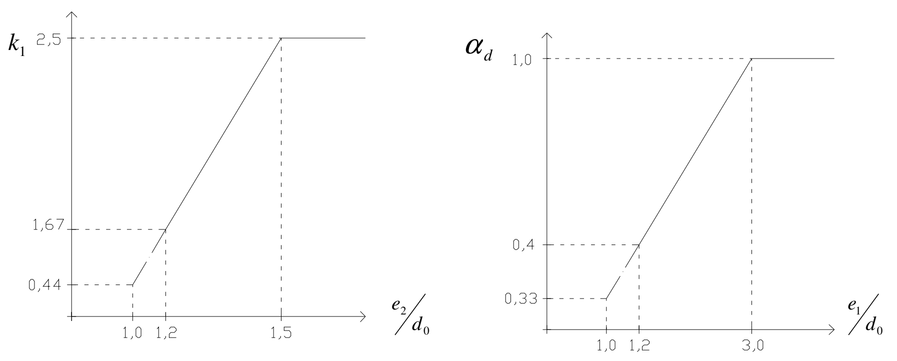

Fig. 2 – Functions to be validated for high strength steels

The steel plates used were S690 with 10 mm thickness. The steel grade was chosen in order to be included in the steel grades up to S700. The bolt classes used were 8.8 and 10.9. The bolt diameters used were M24 and M27.

The identification of the test specimens uses common matrix notation and mentions always the geometric characteristics of the inner plate of the test joint (Example: A2015, test specimen with end distance $e_1 = 2.0d_0$ and edge distance $e_2 = 1.5d_0$).

3.2 Geometrical properties

The experimental program for these single bolt test specimens had two phenomena to study: bearing of the plate –Series A and bearing of the bolt – Series B and two parameters were varied: end distance, e_1 and edge distance, e_2. A total of 30 tests were performed. Ten different types of specimens were designed varying the end and edge distance of the inner plate of the test joint.

The values chosen to the outer plates for both series were so that there weren't any reduction on k_1 and α_b so it would not be critical in the joint. Concerning the strongest joint, it has always higher resistance capacity than the test joint [6].

Only Series B has the same geometry of the plates on test and strongest joint. The difference was on the bolt strength since the goal was the failure of the bolt and not of the plate. Afterwards when the actual mechanical properties of the bolts were known the failure mode of series B test specimen changed from bearing of the bolt to bearing of the plate. Due to this both connections have similar loads at failure when concerning the bearing of the plate as failure mechanism. The series B was added in the same group as Series A, all with bearing of the plate as study phenomena.

3.3 Mechanical properties

3.3.1 Tension tests on the bolts

Three groups of tension tests were performed each one with 2 specimens – Table 1.

3.3.2 Tension test of the steel plates

For the characterization of the steel plates S690, three tension test were performed in a specialized laboratory. The tests were according to European Norm 10002-1 [7]. All the three specimens were parts of the strips used in the test joints. The average values of the test results are listed in Table 2.

Table 1 – Average characteristics values for the bolts

Bolt class	Group	f_u (MPa)
M24 10.9	1	1229.6
M27 8.8	2	974.4
M27 10.9	3	1178.8

Table 2 – Average characteristics values for the steel plates

	$f_{0.2\%}$ [N/mm^2]	f_u [N/mm^2]	A_u [%]	Z [%]	f_u/f_y [-]
S 690	769	821	18	75.00	1.07

3.4 Experimental procedure

The specimens were tested in a force driven testing machine (maximum test load 1000 kN). The tensile force was applied in the inner plates that were clamped to the anchorage devices. The bolts were hand-tightened and the load was applied up to failure of the test specimen. The bearing deformation was measured by means of two LVDT (Hewlett-Packard 7DCDT-250): Hp1 and Hp2. Fig. 3 illustrates a test specimen.

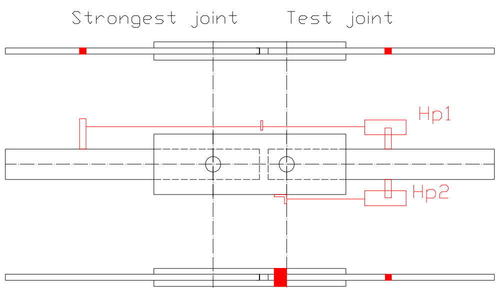

Fig. 3 – Illustration of the test set-up

4. RESULTS

4.1 Test results and observations

Nine test specimens had bearing as failure mode. One specimen skipped out from the predicted failure mechanism and failed on the net section – A1210. This specimen will be out of some further analyses since the phenomenon in study is bearing failure. The test results confirmed that the net section failure has less ductile behaviour then the bearing failure when comparing test specimens with the same end distance – Figs. 4 and 5.

The test results reveal that the end distance is much more related to the ultimate force and the deformation at failure then the edge distance. Therefore, more deformation capacity and resistance can be achieved by increasing the end distance rather than edge distance – Figs. 6 and 7.

All specimens had significant bearing deformation. At the far end, the specimens failed either on the plate or on the bolt (exception made to the specimen with net section failure). The specimens with end distance smaller than $2.0d_0$ failed with shear fracture of the plate. Where shear fracture occurred and specimens had small edge distances ($e_2 \leq 1.2d_0$) the end of the plate split – Fig. 8(a). For specimens with bigger edge distances the end of the plate just shears-out without splitting – Fig. 8(b). The test specimen with $2.0d_0$ end and edge distance (A2020) failed with tensile fracture started at the end of the plate mixed with shear fracture – Fig. 8(c).

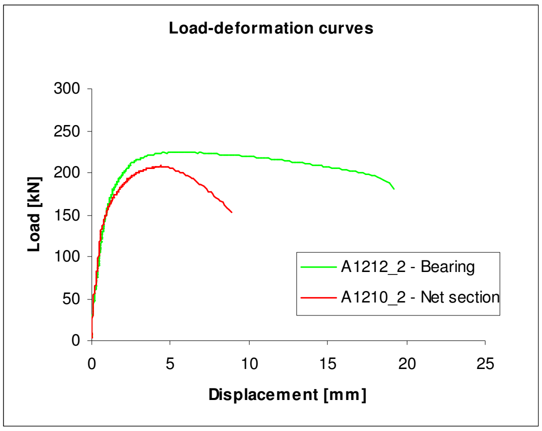

Fig. 4 – Load-displacement curves for the two different failure mechanisms

(a) bearing failure A1212_2

(b) net section failure A1210_2

Fig. 5 – Failure of the inner plates of the test joint of specimens A1212_2 and A1210_2

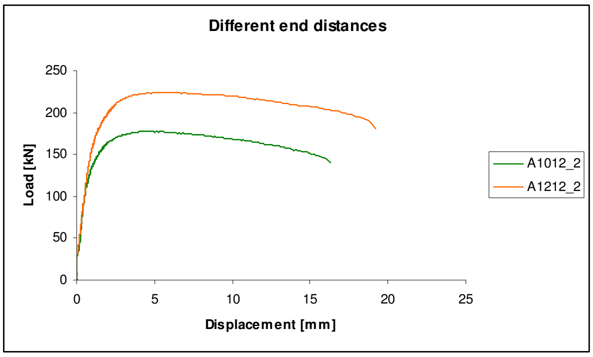

Fig. 6 – Load-displacement curves of specimens with the same edge distance and different end distance

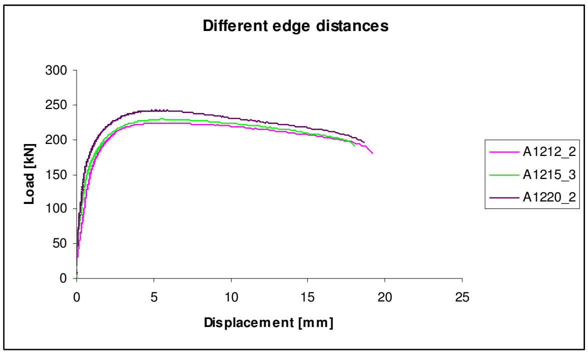

Fig. 7 – Load-displacement curves of specimens with the same end distance and different edge distance

(a) A1010_1

(b) A1220_1

(c) A2020_1

Fig. 8 – Shear fracture with splitting (a) and without splitting (b); Shear and tensile fracture (c)

Series B test specimens had not only bearing of the plate but also a small bearing deformations on the bolt – Fig. 9.

(a) bolt deformation

(b) plate deformation

Fig. 9 – Bearing deformations on B3025_1 test specimen

4.2 Comparison with EC3

Table 3 lists the failure mechanism, the maximum load, F_u and its displacement, δ_u as well as the resistance predicted value for each test specimen. The percentage of error is also listed and always considering the design bearing resistance.

Table 3 – Test results for specimens with bearing failure

Test specimen	F_u [kN]	$F_{b,R}$ [kN]	error%	δ_u [mm]	Failure mechanism
A1010	178.1	70.5	152.5	5.4	Bearing
A1012	183.1	102.3	79.1	5.0	Bearing
A1212	226.2	124.4	81.8	4.8	Bearing
A1015	192.0	167.7	14.5	5.7	Bearing
A1215	228.2	198.8	14.8	5.6	Bearing
A1020	195.3	166.2	17.5	4.7	Bearing
A1220	240.6	200.4	20.1	5.1	Bearing
A2020	390.8	331.8	17.8	11.7	Bearing
B3025	631.4	566.4	11.5	22.3	Bearing
A1210	209.0	83.9	149.1	4.1	Net section

All values for the percentage of error are positive which means that the predicted values given by EC3 are conservative. Two mean values of errors are observed:

- Group I: where $e_2 \leq 1.2d_0$, the mean value for error is 95% – Fig. 10.
- Group II: where $e_2 \geq 1.5d_0$, the mean value for error is 15% – Fig. 11.

The formula for bearing resistance as given in EC3 is too much conservative for edge distances $e_2 \leq 1.2d_0$ and lightly conservative for edge distances $e_2 \geq 1.5d_0$. The reason for failure of the net section instead of bearing is the excessive conservative values given by EC3 to the bearing resistance for small edge distances.

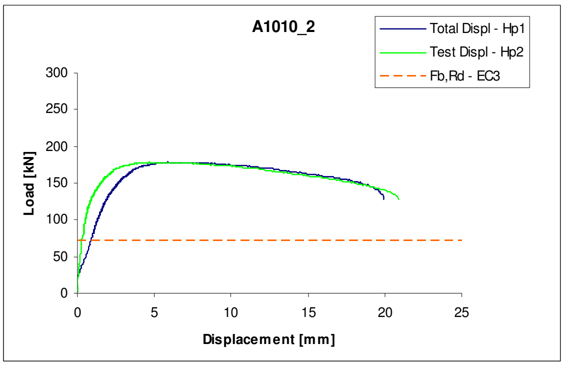

Fig. 10 – Load-displacement curves for A1010_2 (Group I)

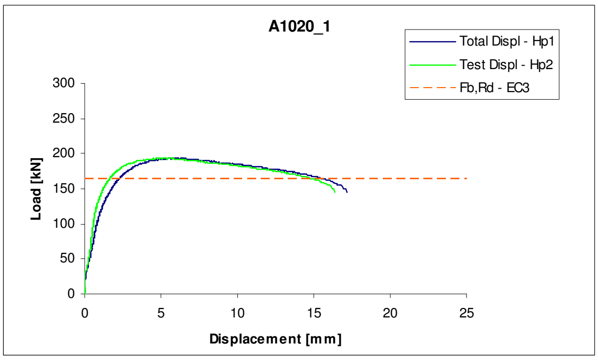

Fig. 11 – Load-displacement curves for A1020_2 (Group II)

5. STATISTICAL EVALUATION

Annex D of EN1990: Basis of Design (formerly Annex Z of Eurocode 3: Design of Steel Structures [8]) describes a standard procedure for determining characteristic values, design values and partial factors for resistance γ_R from the test results. The efficiency of the resistance function for bearing resistance, $F_{b,R}$ (design model) is checked by means of a statistical interpretation of the available test data. The necessary assumptions were taken in order to follow this procedure [6]. The test specimen A1210 (net section failure) was taken off from this analyses.

The test results were split in the same two groups mentioned in the previous chapter: Group I, $e_2 \leq 1.2d_0$ and Group II, $e_2 \geq 1.5d_0$. This way we are preventing a wrong influence between those two different results.

5.1 Standard procedure

Following the standard procedure, the characteristic values and design values are determined from the test results. From these results, a new partial safety factor γ_R is determined. This safety factor is the corrected value for the formula of bearing resistance according to the tests results [6].

$$\underbrace{F_{b,Rd} = \frac{\alpha_b k_1 f_u dt}{\gamma_{M2}}}_{\text{EC3}} \rightarrow \underbrace{F_{b,Rd}^{new} = \frac{\alpha_b k_1 f_u dt}{\gamma_R}}_{\text{Test results}} \tag{6}$$

To keep the same value of the safety factor in the formula of bearing resistance given in EC3, $\gamma_{M2} = 1.25$, this resistance function should be modified by means of a corrections factor, CF. Table 4 lists the values of CF and γ_R for each group of test specimens.

$$F_{b,Rd}^{new} = \frac{\alpha_b k_1 f_u dt}{\gamma_R} \times \frac{\gamma_{M2}}{\gamma_{M2}} = \frac{\alpha_b k_1 f_u dt \times \gamma_{M2}/\gamma_R}{\gamma_{M2}} = F_{b,Rd} \times \underbrace{\gamma_{M2}/\gamma_R}_{\text{CF}} \tag{7}$$

Table 4 – Values γ_R, γ_{M2}/γ_R obtained for each Group I and II

	Group I $e_2 \leq 1.2d_0$	**Group II** $e_2 \geq 1.5d_0$
γ_R	0.93	1.16
$CF=\gamma_{M2}/\gamma_R$	1.34	1.08

As expected the correction factors are bigger than 1.0, due to excessive conservative values of resistance obtained from the bearing formula given by EC3.

5.2 Proposed correction for the k_1 factor

The correction factor obtained was attached to the k_1 factor since the split of tests results was based on the edge distance of each test specimen. Therefore, a new function for k_1 is proposed for steel grade S690 based on the statistical evaluation.

$$F_{b,Rd}^{p} = \frac{\alpha_b (CF \times k_1) f_u dt}{\gamma_{M2}} = \frac{\alpha_b k_1^p f_u dt}{\gamma_{M2}} \tag{8}$$

The minimum distance required in the EC3 for edge distance and end distance is also to sever. These values can both be reduced from $1.2d_0$ to $1.0d_0$.

Table 5 lists the present rules in the EC3 and the corresponding proposed modification for each one. Fig. 12 plots the function k_1 given in EC3, its proposal modification and the k_1 values for the 27 tests results.

6. CONCLUSIONS

The test results showed that the rules given by EC3 are conservative using steel grade

Table 5 – Comparison between the present rules in EC3 and the proposed ones

	EC3		Proposal	
Bearing resistance, $F_{b,Rd}$	$k_1 = \chi_{red} \times 2.5$		$k_1 = \chi_{red}^{p} \times 2.5$	
	$e_2 = 1.2d_0$	$\chi_{red} = 2/3$	$e_2 = 1.0d_0$	$\chi_{red}^{p} = CF^{GroupI} \times \chi_{red} = 1.34 \times 2/3$
	$e_2 \geq 1.5d_0$	$\chi_{red} = 1.0$	$e_2 \geq 1.5d_0$	$\chi_{red}^{p} = CF^{GroupII} \times \chi_{red} = 1.08 \times 1.0$
	$1.2d_0 < e_2 < 1.5d_0$	Linear interpolation	$1.0d_0 < e_2 < 1.5d_0$	Linear interpolation
Minimum distances	$e_2^{\min} = 1.2d_0$		$e_2^{\min} = 1.0d_0$	
	$e_1^{\min} = 1.2d_0$		$e_1^{\min} = 1.0d_0$	

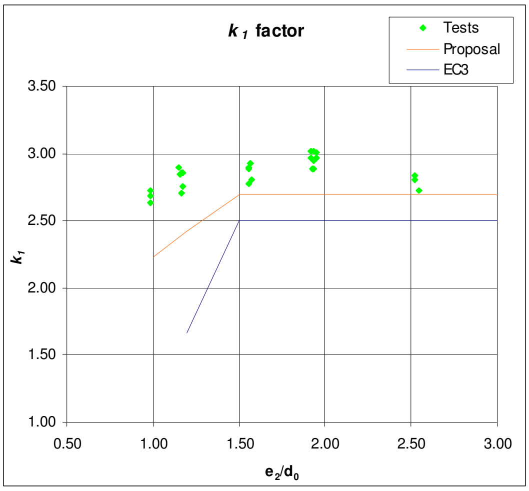

Fig. 12 – Values for the factor k_1

S690. In order to present a correction for the bearing resistance formula using the available test data from this experimental programme, a statistical evaluation according to EC was carried out (27 tests results). The statistical evaluations gave the following corrections:

- For edge distances $e_2 \leq 1.2d_0$, the bearing resistance values given by the EC3 rules can be 34% higher.
- For edge distances $e_2 \geq 1.5d_0$, the bearing resistance values given by the EC3 rules can be 8% higher.

This correction was made in k_1 factor, since the main differences between experimental values/theoretical values were found in tests specimens with different edge distances. There fore a new k_1 functions is suggested for the steel grade S690. The minimum values to edge and end distances can also be reduced from $1.2d_0$ to $1.0d_0$.

This study is based on a limited number of geometrical properties, there fore more test should be carried out, even with the same steel grade, in order to have a higher range of end and edge distance.

A statistical analysis should be then followed using all the test data available and adjust the suggested k_1 factor for all the steel grades and geometry properties of one-bolt joints.

7. LIST OF SYMBOLS

d nominal bolt diameter;

d_0	hole diameter for a bolt;
e_1	end distance;
e_2	edge distance;
t	thickness of the plate;
A	gross cross-section area of a bolt;
A_s	tensile stress area of the bolt;
f_y	yield stress of a plate;
f_u	ultimate of tensile stress of a plate;
f_u^h	higher value of tensile stress of a plate;
f_u^l	lower value of tensile stress of a plate;
f_{yb}	yield stress of a bolt;
f_{ub}	ultimate or tensile stress of a bolt;
$F_{v,\mathrm{Rd}}$	design shear resistance per bolt;
$F_{b,\mathrm{Rd}}$	design bearing resistance per bolt;
γ_{M2}	partial safety factor;
A_u	percentage elongation after fracture;
Z	percentage reduction of area;
F_u	maximum load of the connection;
δ_u	displacement at the maximum load.

8. REFERENCES

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