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Stressed skin design of steel sheeting panels – Part 1: Shear resistance and flexibility of screw lapped joints

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Abstract

The shear resistance and flexibility of a steel roof diaphragm depend largely on shear resistance and slip flexibility of the single screw lap joint. In this paper, screw connections relevant to modern roof construction are investigated. The tests provided experimental values of shear/tearing resistance and joint flexibility of seam connections, cladding/purlin connections and purlin/rafter connections. The novel aspects of the experimental research include investigation of the behaviour of shear connections in 0.5mm thick sheeting and thick-to-thin connections in S550 high tensile steel. Overall, six series of tests were conducted and each test was repeated five times in order to demonstrate a scatter of test results. Test results were examined against existing semi-empirical formulas for predicting the shear resistance of screw joints. It was demonstrated that the design equation presented by Toma et al. (1993), without the additional condition included in Eurocode 3, offers the closest prediction in terms of joint shear resistance. In terms of joint flexibility, it was demonstrated that existing formulas developed for bolted connection (Zadanfarrokh and Bryan (1992) and Dubina and Zaharia (2006)) can be successfully used for screw connections. The flexibility reduction factor n_{pf}=0.4 was also proposed to take account of perfect fit screw connections.

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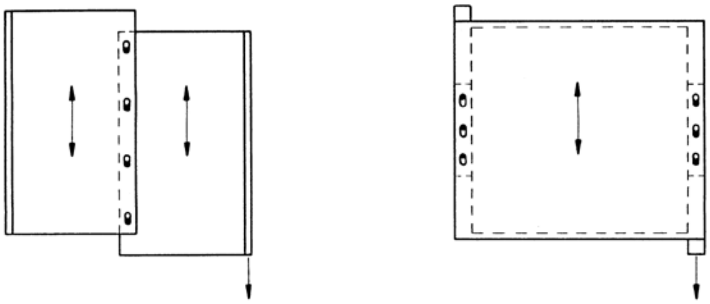
Introduction

The research on stressed skin action started at the University of Manchester in late 1960's proved that clad portal frames behave much differently from bare frames due to the stiffening effect of the cladding diaphragm (Bates et al. (1965)), Bryan and Mohsin (1972), Bryan (1973). The main motivation for this research was that, due to the introduction of higher grades of steel, portal frames had become more flexible. Depending on the ratio of the frame to cladding stiffness, the load is redistributed between adjacent frames and in some design cases, the failure can occur in the cladding first, rather than in the frame itself. Stressed skin design was extensively researched and published by Bryan (1973) and design recommendations were first presented in the 'European recommendations for the stressed skin design of steel structures' ECCS - XVII - 77-1E (1977). This document formed the foundation for later publications such as: 'Manual of stressed skin diaphragm design' Davies and Bryan (1982), BS 5950-9 (1994), ECCS TC7 (1995) and subsequently Eurocode 3 BS EN 1993-1-3 (2006).

The shear resistance and flexibility of a steel diaphragm depend largely on shear resistance and slip flexibility of the single fastener lap joint. Some of the diaphragm failure modes and deformations which are a result of the behaviour of the screw connection are presented in Figure 1.

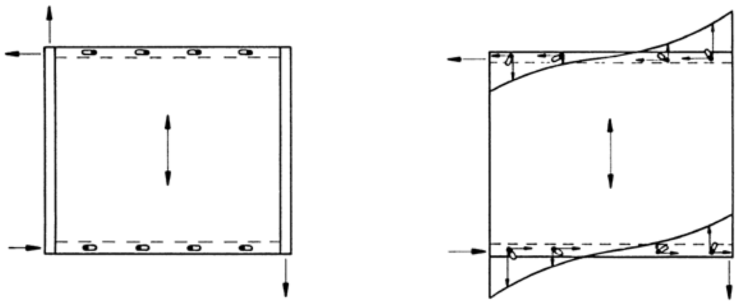
In practice, the mechanical characteristic of each joint could be established experimentally. However, design shear values for some popular fasteners are presented in Table 5 of BS 5950-9. A considerably larger database on the subject of resistance and slip of different fasteners can also be found in Davies and Bryan (1982) and Baehre and Ladwein (1994). Fan et al. (1997) focused on predicting the shear behaviour of single screw lap connections using Finite Element Analysis (FEA). Generally, good agreement between analytical and experimental results was observed but due to the complexity of the model, its computational effort/cost may exceed the cost of testing.

Roof systems are consistently evolving often leaving existing standards out-of-date. In this paper screw connections relevant to modern roof construction are investigated. The novel aspects of the experimental research include investigation of the behaviour of shear connections in 0.5mm thick sheeting and shear connections in S550 high tensile steel.



a) Seam fasteners

b) Sheet/shear connector fasteners



c) Sheet/purlin fasteners (4 sides fastened)

d) Sheet/purlin fasteners (2 sides fastened)

Figure 1 Shear resistance and flexibility design issues according to BS 5950-9 (1994), pp.18

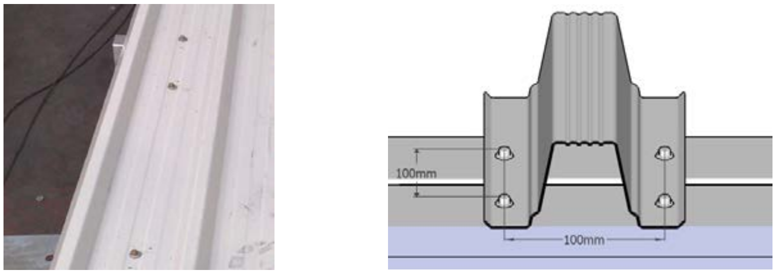
Single lap screw connections

Considering that the shear resistance and stiffness of the roof panel are largely dependent on the ultimate resistance and flexibility of individual connections, this section presents the component tests on connections used in full panel assemblies. All the connections can be classified as single lap screw connections. Parameters such as: thickness of the connected parts, grade of steel, screw diameter, size and type of the washer, are expected to contribute to the performance of such joints. For this reason, the analytical study is carried out parallel with the experimental investigation to allow comparisons. In terms of establishing the slip in individual fixings, BS 5950-9 (1994) advises that this parameter should be obtained experimentally for each particular connection.

In order to use the calculation method to predict the shear flexibility and the shear resistance of the full-scale panel assembly, the shear characteristic of each individual joint must be analysed. The typical shear panels contain the following single lap connections:

a) Seam connection joining two adjacent sheets through the use of 6.3mm stitching screws (see Figure 2a);
b) Cladding/purlin connection joining cladding profile and usually thicker purlin member through the use of 5.5mm diameter screws (see Figure 2b);
c) Cladding/shear connector connection joining cladding profile and usually thicker purlin member through the use of 6.3mm diameter stitching screws (see Figure 2c);
d) The purlin/rafter connections shown in Figure 2d were made using four 6.3mm diameter frame screws.

a) Seam connection b) Cladding/purlin



c) Cladding/shear connector d) Purlin/rafter

Figure 2 Different types of connections

Fasteners

The self-drilling, self-tapping screws were used in order to form a variety of joints in the investigated shear roof panels. The screws are classified based on the different joints they are used for and their dimensions are presented in Figure 3. Two different diameters are considered: 5.5mm and 6.3mm following the industry standards. All the screws passing through the weather sheets contain metal washers with EPDM rubber seals. The diameter of the washer was 16mm for the single skin sheeting. The mechanical characteristics of each screw including ultimate shear strength ($F_{v,Rd}$) and ultimate tensile strength ($F_{v,Rd}$), as provided by the manufacturer, are presented in Figure 3.

d_s - 6.3mm, l_s – 25mm

$F_{v,Rd}$ =8.36kN

$F_{t,Rd}$ = 14.10kN

a)Frame screw

d_s - 6.3mm, d_w – 16mm, l_s – 22mm

$F_{v,Rd}$ = 12.70kN

$F_{t,Rd}$ = 17.20kN

b) Seam screw

d_s - 5.5mm, d_w – 16mm l_s – 25mm

$F_{v,Rd}$ = 8.36kN

$F_{t,Rd}$ =12.50 kN

c) Cladding screw

Figure 3 Dimensions and mechanical properties of screws

Lap joint testing methodology

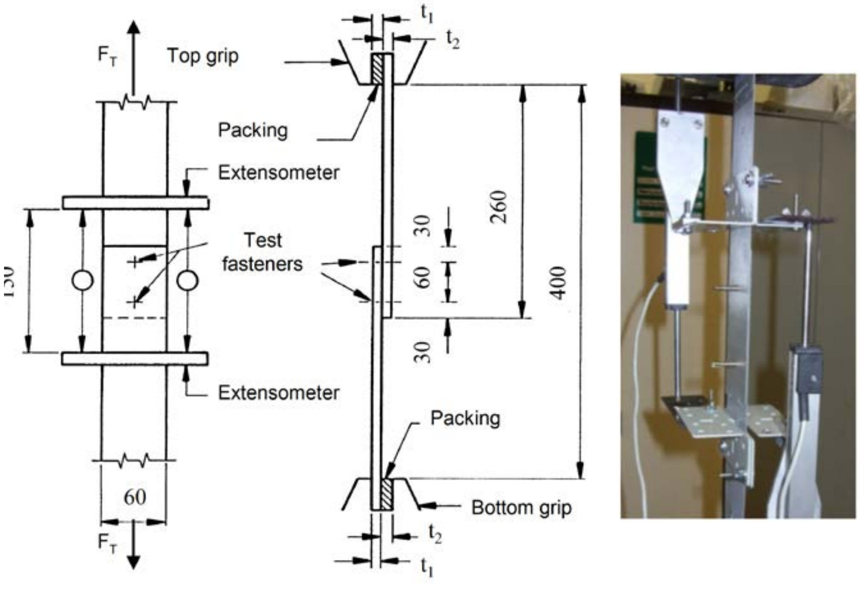
In order to establish shear characteristic of different lap joints the testing procedure described in Section 11 of BS 5950-9 (1994), using two fasteners per lap joint, was adopted. The details of the test arrangement are presented in Figure 4. For these tests, the standard Zwick Roell tensile machine was used. The displacement between two points outside the jointed part was measured by a set of LVDTs. The load was applied to the specimen continuously at a rate of

0.01mm/s to meet standard requirements. The load and a corresponding slip of the joints were logged during the experiment. The relationship between total load (F_T) and average slip (s) was then plotted. Each type of joint was tested 5 times in order to carry out a statistical analysis.

The test tearing resistance of the joint (F) was established as the maximum test load (F_T) for a slip value less or equal to 3mm. By following this procedure the serviceability requirement proposed in ECCS TC7 TWG 7.10 No.124 (2009) is also incorporated. The characteristic tearing resistance of the joint was calculated according to the equation:

$$F_k = F_m - kSD \tag{1}$$

Where:
F_m – mean value of the experimental tearing resistance $F_1 \ldots F_i$
k – coefficient based on the number of tests
SD – standard deviation according to BS 5950-9 (1994) pp. 59



d) Test arrangement after BS 5950-9 (1994) pp. 59

e) Photograph of the test in progress

Figure 4 Single lap screw joint – test arrangement

The design tearing resistance of the joint was calculated from:

$$F_d = F_k / 1.11 \tag{2}$$

Where:
F_k – characteristic tearing resistance
1.11 – partial factor of safety according to BS 5950-9 (1994)

The joint flexibility was taken from the experimental plot as a mean value of the displacement at the serviceability load, which is approximately 60% of the characteristic tearing resistance according to the equation:

$$s = \text{mean}\,(s_1/0.6F_k, \ldots\, s_i/0.6F_k) \tag{3}$$

Where:
$s_{1\ldots i}$ – the displacement measured at $0.6F_k$ for each individual test
It should be noted that two fastener joints were tested therefore the characteristic tearing resistance (F_k) obtained from the test was divided by two for a single fastener joint.

Test series

Generally, three different lap joints were investigated each one of them in two thicknesses of steel. The steel pieces for a lap joint tests were cut out from the formed sheeting profiles or rectangular test pieces were provided by the manufacturer whenever geometry of the section did not permit cutting the specimen. This was done so an accurate shear characteristic of different connections, can be obtained. Overall, six series of tests were conducted, as described in Table 1, along with the characteristic of each component. Each test was repeated five times, however in two tests data became corrupted and final results had to be calculated based on four test in these series. The thickness t_1 is the thickness of steel piece in contact with the head of the screw and the thickness of the steel piece away from the head is denoted t_2. Generally, two steel sheets of 0.5 and 0.7mm nominal thickness were investigated. The 0.5 and 0.7mm thick coil finished with leather-grain embossed PVC (Plastisol), were used for all of the tested weather sheets. The description of the steel used for sheeting profiles is presented in Table 2 including the net thickness of the steel core (t_{cor}) and mechanical properties of the steel based on the average values obtained from Mills Test Certificates. The mechanical properties of galvanised steel pieces of 1, 2 and 3mm thickness were established experimentally using standard coupon tests according to BS EN 10002-1:2001 (2001) (see Table 2).

Table 1 Summary of tested components

		Steel pieces				Fastener		
Test series	No. of tests	Grade of steel – bottom piece	t_2 mm	Grade of steel – top piece	t_1 mm	Type	d_s mm	d_w mm
S1/0.5/0.5	5	S250GD +AZ150[3]	0.5	S250GD +AZ150[3]	0.5	SS	6.3	16
S2/0.7/0.7	5	S250GD +AZ1503[3]	0.7	S250GD +AZ150[3]	0.7	SS	6.3	16
S3/1.0/0.7	4*	S550GD +AZ150[3]	1.0	S250GD +AZ150[3]	0.7	CS	5.5	16
S4/2.0/0.7	5	S350GD +Z275[3]	2.0	S250GD +AZ150[3]	0.7	CS	5.5	16
S5/2.0/1.0	5	S350GD +Z275[3]	2.0	S550GD +AZ150[3]	1.0	FS	6.3	-
S6/3.0/1.0	4*	S350GD +Z275[3]	3.0	S550GD +AZ150[3]	1.0	FS	6.3	-

* – data logger malfunction the slip data not available, SS – seam screw, CS – cladding screw, FS – frame screw, [3] BS EN 10326:2004 (2004)

Table 2 Mechanical characteristic of the steel test pieces

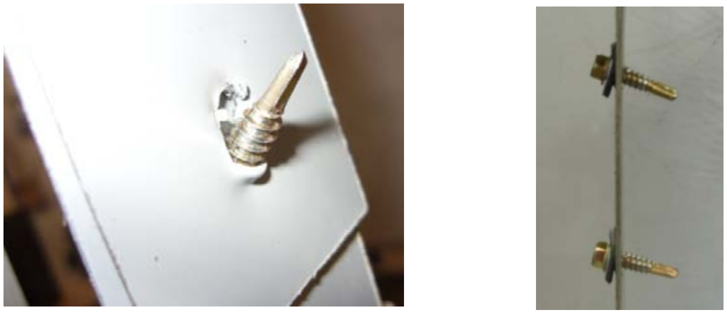
Steel coil type	t mm	t_{cor} mm	$f_{y,nom}$ N/mm^2	$f_{u,nom}$ N/mm^2	f_y N/mm^2	f_u N/mm^2
0.5mm Plastisol	0.5	0.48	250	330	334	405
0.7mm Plastisol	0.7	0.65	250	330	301	380
1.0mm galvanised	1.0	0.96	550	560	580	599
2.0mm galvanised	2.0	1.96	350	420	398	514
3.0mm galvanised	3.0	2.96	350	420	383	483

$f_{y,nom}$ – nominal yield strength, f_y – actual yield strength, $f_{u,nom}$ – nominal ultimate tensile strength, $f_{u,}$– actual ultimate tensile strength

The tests provided experimental values of shear/tearing resistance and joint flexibility of seam connections, cladding/purlin connections and purlin/rafter connections.

Test results

Each series contained 5 tests on the same type of joint however on two occasions malfunctions of the data logging system occurred thus the experimental values in series 3 and 6 were derived based on 4 tests. Generally, the same mode of failure was observed in every joint named by ECCS TC7 TWG 7.10 No.124 (2009) as bearing and tilting (B+T). The failure mechanism is shown in Figure 5.



a) Tearing of material and the hole elongation

b) Screw tilting

Figure 5 Single lap screw joint – shear mode of failure

Typical load-slip relationships obtained from 5 tests of series S1/0.5/0.5 are presented in Figure 6. The mean (F_m), characteristic (F_k) and design values (F_d) of tearing resistance along with slip flexibility value were calculated using Eq. (1) and Eq. (2). The joint contained two steel plates of 0.48mm thickness and two screws of 6.3mm diameter. Similar to the test results presented by Fan et al. (1997) significant scatter of test results from the same joints were reported, both in terms of resistance and flexibility. The test results from the remaining 5 series were post-processed in the same way and are summarised in Table 3. In the case of series 4 and series 5, one out of 5 tests showed greater slip within the serviceability range of deflections which influenced the mean value.

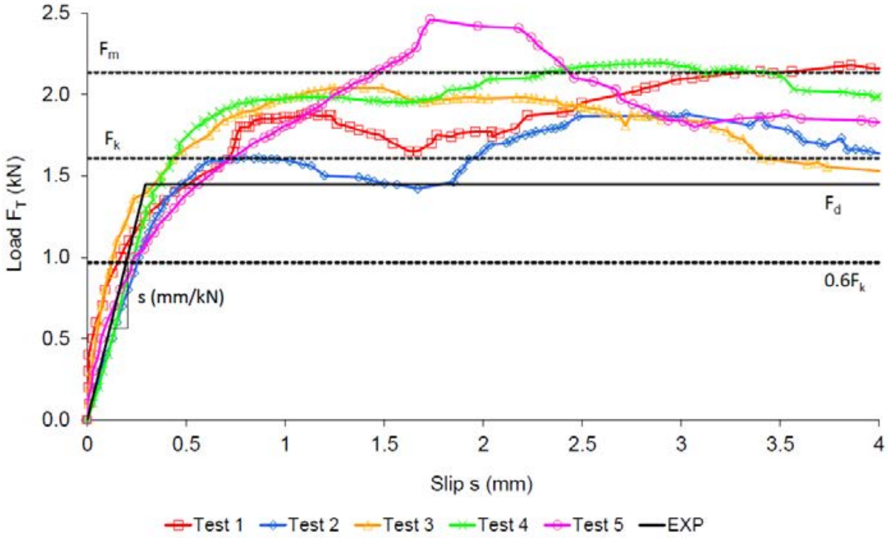


Figure 6 Test series S1/0.5/0.5

Table 3 Experimental shear resistance of the a single fastener connection

Test series	Sheet remote from the screw head			Sheet in contact with the screw head			Resistance		
	$t_{2,cor}$	f_y	f_u	$t_{1.cor}$	f_y	f_u	F_{min}	F_k	F_{max}
	mm	N/mm^2	N/mm^2	mm	N/mm^2	N/mm^2	kN	kN	kN
S1/0.5/0.5	0.48	334	405	0.48	334	405	0.94	0.81	1.23
S2/0.7/0.7	0.65	301	380	0.65	301	380	1.56	1.30	2.07
S3/1.0/0.7	0.96	580	599	0.65	301	380	2.56	1.90	3.28
S4/2.0/0.7	1.96	398	514	0.65	301	380	2.64	2.16	3.42
S5/2.0/1.0	1.96	398	514	0.96	580	599	5.36	4.67	6.90
S6/3.0/1.0	2.96	383	483	0.96	580	599	8.02	7.07	9.07

Experimental results versus analytical methods

Many semi-empirical formulas for predicting the shear resistance of screw joints have been presented i.e. Baehre and Berggren (1973), ECCS TC7 No. 21

(1990), Peköz (1990), Toma et al. (1993), BS 5950-5 (1998) and BS EN 1993-1-3 (2006). In this section, only three of those formulas will be considered:

1) Baehre and Berggren (1973)

$$P_{v,Baehre} = K_1(d+10)(t_1^2+0.22)f_u \qquad (4)$$

Where:

$K_1=0.156[(t_2/t_1)-1]^2+0.35$ if $t_2/t_1<2.5$

$K_1=0.7$ if $t_2/t_1 \geq 2.5$

d – screw diameter (mm)

t_1 - thickness of the thinner sheet in contact with the screw head (mm)

t_2 – thickness of the thicker sheet remote from the screw head (mm)

f_u – ultimate tensile strength of the thinner sheet

2) ECCS TC7 No. 21 (1990) and BS 5950-5 (1998)

$$P_{v,BS} = K_1 f_y \qquad (5)$$

Where:

$K_1=\min(3.2(t_1^3 d)^{0.5}, 2.1t_1 d)$ if $t_2/t_1=1$

$K_1=2.1t_1 d$ if $t_2/t_1 \geq 2.5$

$K_1=$ from linear interpolation if $1< t_2/t_1<2.5$

f_y – design yield stress of the thinner sheet

3) Toma et al. (1993) and BS EN 1993-1-3 (2006)

$$P_{v,EC} = K_1 t_1 d f_u \qquad (6)$$

Where:

$K_1=\min(3.2(t_1/d)^{0.5}, 2.1)$ if $t_2/t_1=1$

$K_1=\min(3.2(t_1/d)^{0.5}, 2.1)$ if $t_2/t_1 \geq 2.5$ and $t_1<1$mm

$K_1=2.1$ if $t_2/t_1 \geq 2.5$ and $t_1 \geq 1$mm

$K_1=$ from linear interpolation if $1< t_2/t_1<2.5$

The shear resistance equations are based on the factor (K_1) derived experimentally for different thick/thin ratios. In fact the K_1 factors in Eq. (5) and (6) have the same numerical values. The other fundamental difference between the equations is that Eq. (4) and (6) uses the ultimate tensile strength where Eq. (5) uses design yield strength of the steel. In addition, in the latest Eurocode 3 design equation (Eq. (6)), a further condition is added in which a lower bound value of strength is assumed if the thinner sheet thickness is less than 1mm. This condition was not included by Toma et al. (1993) whose research formed the base to the Eurocode 3 equation. For the tested lap joints, the analytical shear resistance was computed and is presented in Table 4 along with the mean and characteristic values obtained in the experimental study.

Table 4 Experimental shear resistance versus analytical prediction

Test series	$t_{2,cor}/t_{1,cor}$	d	Experimental values		Analytical values			
			F_k	F_m	Baehre	BS	Toma	EC3
		mm	kN	kN	kN	kN	kN	kN
S1/0.5/0.5	1.0	6.3	0.81	1.07	1.04	0.89	1.08	1.08
S2/0.7/0.7	1.0	6.3	1.30	1.87	1.39	1.27	1.60	1.60
S3/1.0/0.7	1.5	5.5	1.90	2.79	1.46	1.53	1.93	1.93
S4/2.0/0.7	3.0	5.5	2.16	3.00	2.65	2.26	2.85	1.49
S5/2.0/1.0	2.0	6.3	4.67	6.21	5.79	6.45	6.67	6.67
S6/3.0/1.0	3.1	6.3	7.07	8.36	7.80	7.37	7.61	4.53

The geometrical and material characteristics were presented in Table 3. As can be seen, the design equation presented by Toma et al. (1993) and that published in BS EN 1993-1-3 (2006) gives the same numerical values apart from joints with a thickness ratio around 3. In this case, the shear resistance predicted by the Eurocode is significantly reduced and this reduction is not confirmed by experimental data.

There is no codified method to predict flexibility of the lapped joint connection, but De Matteis and Landolfo (1999) suggested that the empirical formula developed by Zadanfarrokh and Bryan (1992) can be used with sufficient accuracy. The equation used to calculate the flexibility of the joint was originally developed for bolted lap joints with slip due to tolerance of the holes. Thus an additional flexibility reduction factor is considered following the findings of Zadanfarrokh (1991). The self-drilling, self-tapping screw lap joint is an example of perfect fit fastener joint. Two equations presented in the literature are used to calculate the joint flexibility:

1) Eq. (7) by Zadanfarrokh and Bryan (1992) with flexibility factor n=5

$$c_{Zad}=5n\,(10/t_1+10/t_2-2)\,10^{-3}\ (mm/kN) \tag{7}$$

where:

t_1, t_2 – thicknesses of the sheet of metal (t_1 and $t_2 \leq 8$mm)

n - flexibility factor

2) Eq. (8) by Zaharia and Dubina (2006)

$$k_{Zah} = 6.8 \frac{\sqrt{D}}{\left(\frac{5}{t_1}+\frac{5}{t_2}-1\right)} (kN/mm) \qquad (8)$$

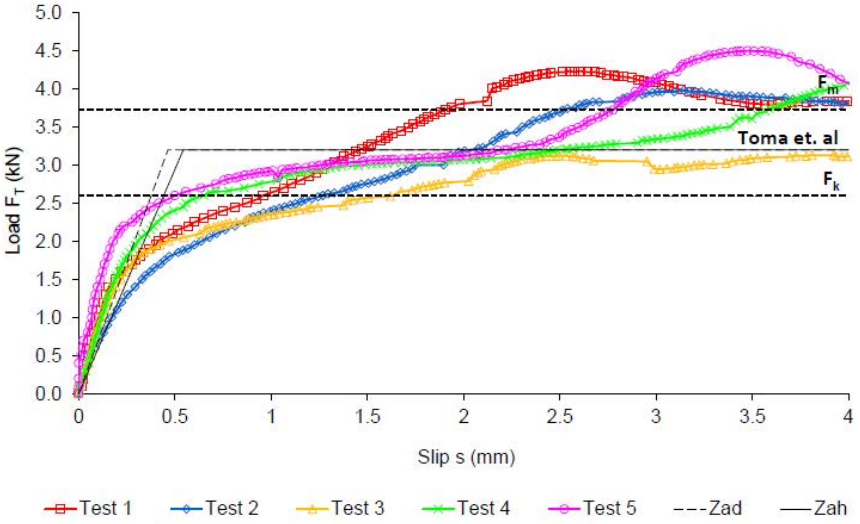
where:
t_1, t_2 – thicknesses of the sheet of metal (2mm $\leq t_1$ and $t_2 \leq$ 4mm)
D – nominal diameter of the bolt

In both equations, an additional flexibility reduction factor n_{pf}=0.4 due to perfect fit fasteners is proposed and a comparison of the mean experimental flexibility versus analytical flexibility is presented in Table 5.

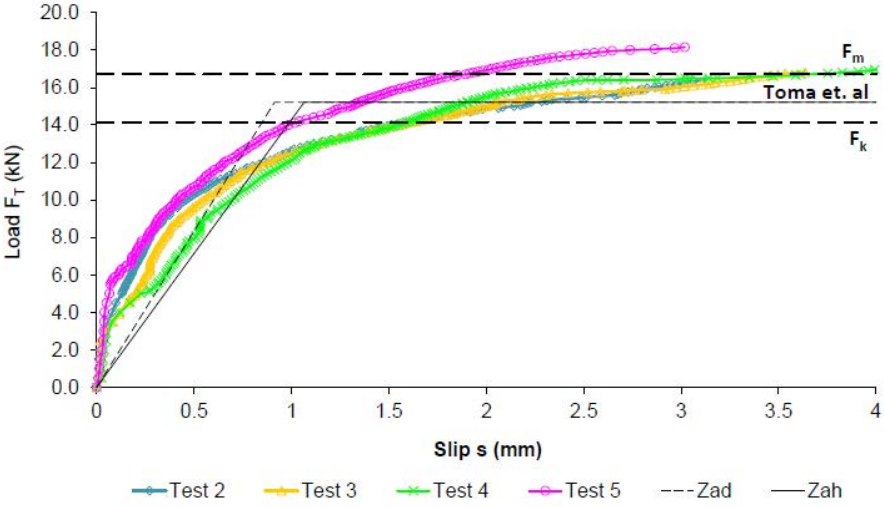
Table 5 Experimental slip flexibility versus analytical prediction

Test series	$t_{2,cor}$/ $t_{1,cor}$	d	Exp. values s (s_{min}, s_{max})	Analytical values Zadan.	Scatter	Zahar.	Scatter
		mm	mm/kN	mm/kN	%	mm/kN	%
S1/0.5/0.5	1.0	6.3	0.41 (0.25,0.52)	0.40	3.3	0.46	-13.4
S2/0.7/0.7	1.0	6.3	0.29 (0.15,0.45)	0.29	0.8	0.34	-16.2
S3/1.0/0.7	1.5	5.5	0.34 (0.31,0.37)	0.24	30.0	0.30	12.2
S4/2.0/0.7	3.0	5.5	0.33 (0.28,0.37)	0.18	44.0	0.23	29.7
S5/2.0/1.0	2.0	6.3	0.18 (0.09,0.2)	0.14	24.9	0.16	12.0
S6/3.0/1.0	3.1	6.3	0.09 (0.07,0.13)	0.12	-31.1	0.14	-53.6
					12.0	Mean	-4.9

The analytically predicted stiffness of two types of connections are compared against experimental data in Figure 7. In this figure, elastic-perfectly plastic models based on shear stiffness equations by Zadanfarrokh and Bryan (1992) and Zaharia and Dubina (2006) and shear resistance calculated to Toma et al. (1993) are drawn onto test results of series S2 and S6. It can be concluded from the Figure 7 that analytical methods offer a good estimation of the stiffness for two plates of the same thickness acting in shear (S2). In case of the thick-to-thin plate connection (S6) experimental data shows that linear stiffness approximation does not match a true behaviour of the connection which is much stiffer in the initial stage of loading and bi-linear stiffness model would be more representative.



a) S2/0.7/0.7



b) S6/3.0/1.0

Figure 7 Test results versus analytical models for shear resistance and flexibility

Conclusions

Generally, the accuracy of the analytical prediction of the shear resistance was much better for connections consisting plates of the same thickness. Whenever thick–to-thin plates were connected, analytical predictions tend to be less accurate. When comparing the mean resistance (F_m) obtained from the 6 series of tests against the unfactored resistance from three calculation methods, the following results were obtained:

- Baehre and Berggren (1973) – average error of 16.8%, and all 6 results were safe,
- BS 5950-5 (1998) – average error of 21.1%, and 1 of 6 results was unsafe,
- Toma et al. (1993) – average error of 8.5%, and 2 of 6 results were unsafe.

Based on test results, it can be concluded that the design equation presented by Toma et al. (1993), without the additional condition included in Eurocode 3, offers the closest prediction (min. positive average error) in terms of joint shear resistance. It was demonstrated in the tests that the repeatability of the results was not very consistent and thus it is important to include the standard deviation in the analysis. When the calculated resistances are compared against characteristic test resistances (F_k) the following results are obtained:

- Baehre and Berggren (1973) – average error of -11.8%, and 5 of 6 results were unsafe,
- BS 5950-5 (1998) – average error of -5.8%, and 4 of 6 results were unsafe,
- Toma et al. (1993) – average error of -23.4%, and all results were unsafe.

In terms of joint flexibility prediction, both calculated methods were considered to be satisfactory when proposed flexibility reduction factor n_{pf}=0.4 was implemented. An average scatters of 12.0% and -4.9% respectively for the Zadanfarrokh and Bryan (1992) and Dubina and Zaharia (2006) formulas were recorded. In most of the test series, the calculated flexibilities from both methods fitted within or just outside the flexibility envelope marked by 5 test results of the same series. The most significant difference was observed in series S6/3.0/1.0. In this test series, the calculated flexibility fell outside the flexibility envelope where the tested joints proved to be significantly stiffer than calculation methods predicted.

Acknowledgements

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Appendix. – References

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