Specific behaviour of thin-walled member joints with fasteners

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Preliminary note

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Due to small plate thickness, thin-walled members are characterized by some specific features. The theoretical and experimental study of behaviour of thin-walled member connections with mechanical fasteners, bolts and selftapping screws, is presented in the paper. The shear and tensile behaviour of connections is analyzed. Experimental results are compared with current European and American design codes. Characteristic shear and tensile resistance values of selftapping screws are also defined.

Key words:
thin-walled steel members, joints, bolts, selftapping screws, shear, tension

Prethodno priopćenje

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Specifičnosti ponašanja veza tankostijenih čeličnih elemenata

Kod veza tankostijenih elemenata je, zbog male debljine lima, prisutno niz specifičnosti. U radu su prikazana teorijska i eksperimentalna istraživanja ponašanja spoja tankostijenih čeličnih elemenata ostvarenih pomoću mehaničkih spojnih sredstava: vijaka i samonarezujućih vijaka. Analizirani su posmični i vlačno opterećeni spojevi. Rezultati ispitivanja uspoređeni su s aktualnim europskim i američkim propisima. Određene su i karakteristične nosivosti samonarezujućih vijaka na posmik i vlak.

Ključne riječi:
tankostijeni čelični elementi, veze, vijci, samonarezujući vijci, posmik, vlak

Vorherige Mitteilung

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Spezifisches Verhalten von dünnwandigen Stahlelementen mit Verbindungsmitteln

Bei Verbindungen dünnwandiger Elemente ist wegen der geringen Blechstärke eine Reihe von Spezifizitäten präsent. In der Arbeit sind theoretische und experimentelle Forschungen über das Verhalten von Verbindungen dünnwandiger Stahlelemente dargestellt, die mittels mechanischen Verbindungsmittel verwirklicht wurden: Schrauben und selbstschneidenden Schrauben. Es wurden schub- und zugspannungsbelastete Verbindungen analysiert. Die Forschungsresultate wurden mit aktuellen europäischen und amerikanischen Vorschriften verglichen. Es wurden auch charakteristische Tragfähigkeiten selbstschneidender Schrauben bezüglich Schub und Zugspannung festgesetzt.

Schlüsselwörter:
Dünnwandige Stahlelemente, Verbindungen, Schrauben, selbstschneidende Schrauben, Schub, Zugspannung

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1. Introduction

Rules and methods normally applicable for joints made of hot-rolled or welded sections can not be applied in the analysis and design of thin-walled cold-formed steel elements. Potential failure modes of shear and tensile joints of thin-walled elements differ from failure modes occurring in traditional steel structures. In order to obtain the most favourable and cost-effective connections in which bearing capacities of mechanical fasteners and base material are well balanced, mechanical fasteners such as bolts must be adjusted to this type of connections, although possibilities are also open for the use other mechanical fasteners as well. As the mode of failure along base material is most often relevant in such connections, the dimensions of fasteners are smaller when compared to those normally applied in building engineering. Usual fasteners are: bolts, self-tapping screws, blind rivets, and cartridge fired pins.

Self-tapping screws form a thread in the sheet steel to which they are attached, and this either by tapping or drilling. Nominal diameters range from 2,2 to 8 mm, and self-tapping screws 6,3 mm in diameter are most often used. They are made of carbon or alloy steel for cementing, and are used in connections loaded in shear and tension. Their role is especially significant in structures in which the stressed-skin design concept is applied.

Basic failure modes were registered during first experimental tests of shear connections, which were conducted immediately after World War Two in the USA [1]. It was established that the occurrence of a particular type of failure is dependent on the diameter and strength class of fastener, on the thickness and quality of base material, and on the spacing between fasteners. Because of specific behaviour of such connections, the experimental and numerical study has been intensified in this area [2 to 10] over the past two decades. The objective of these studies has been to improve and expand the existing knowledge, to improve and revise existing regulations, and to extend the area of their use.

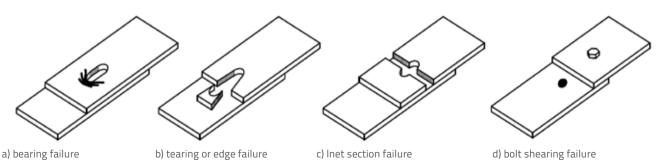Initial tests focused on joints with ordinary and self-tapping bolts. By varying the distance between the bolt and the edge of the sheet in the direction of the force, F, Zadanfarrokh, E.R. Bryan [2] have confirmed that the failure due to sheet tear may be expected when this distance to bolt radius ratio is less than 2.5, while the bearing failure around the hole occurs if the above ratio is greater. C. Rogers, J. Hanckok [3, 4, 5, 6] conducted an extensive study of shear connections using sheet steel of small thickness (t < 1 mm) and various qualities of base material. These tests were a valuable contribution in that they expanded the area of use of small-thickness sheets. The results regarding the influence of washer on bearing failure at the edge of the hole, were later on verified in analyses conducted by J.A. Wallace, R.M. Schuster, L.A. Laboube [7], and were included in the last revised edition of American regulations [11].

In Europe, A.W. Toma [8] has tested connections with bolts and blind rivets. Lap joints with one fastener are analyzed, and the following parameters are varied: sheet thickness, bolt distance from the sheet edge in the direction of force, and specimen width. Connections with simple sheet bend at the edge, and connections with continuous double bevelled bend, have been tested. The primary objective of these studies has been to investigate behaviour of connections in case of extremely thin sheets, and in cases of small distance between bolts and the edge of the sheet or blind rivet, and also to examine the influence of bend. Basic specific features regarding behaviour of shear connections with self-tapping screws have been defined by T Pekoz [9], M.R. Babalola, and R.A. LaBoube [10]. Results of their studies constitute the basis for forming mathematical expressions for various failure mechanisms.
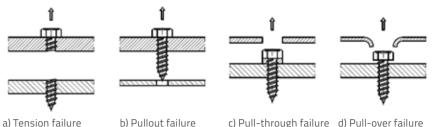
In case of tensile connections with self-tapping screws, four forms of failure can occur [9] (cf. Figure 2), depending on the bolt diameter, and the thickness and quality of material of the sheets that are being connected.
R. Francka, R.A. LaBoube [12] have contributed significantly to efforts that are being made to explain behaviour of connections loaded in tension They also analyze interactive action of shear and pullout in case of self-tapping screws.
Current international knowledge in this area is summarized in the European standard EN 1993-1-3 [13], and in regulations

a) bearing failure   b) tearing or edge failure   c) lnet section failure   d) bolt shearing failure

Figure 1. Typical modes of failure in case of shear connections with mechanical fasteners

a) Tension failure   b) Pullout failure   c) Pull-through failure   d) Pull-over failure

Figure 2. Modes of failure in case of tensile connections with self-tapping screws

prepared by the American Iron and Steel Institute (AISI) [11]. These documents set rules for the computation of mechanical fasteners in shear connections and tensile connections, and this for modern mechanical fasteners (bolts, self-tapping screws, blind rivets, and nails) that are used for thin-walled cold-formed sections and sheets. Nevertheless, expressions for computation of some forms of failure are not provided, and in such cases experimental testing is recommended ([13], Section 8, Table 8.2).

The actuality of this topic, and the wish to expand current level of knowledge and fill gaps in existing regulations, point to the need to conduct further research in this area. Analyses made in this paper are aimed at providing answers to all unresolved issues. The basic goal is to determine similarities and differences in the behaviour of bolts and self-tapping screws, verify failure modes, and determine bearing capacities of standard self-tapping screws, in order to enable their broader application in civil engineering structures.
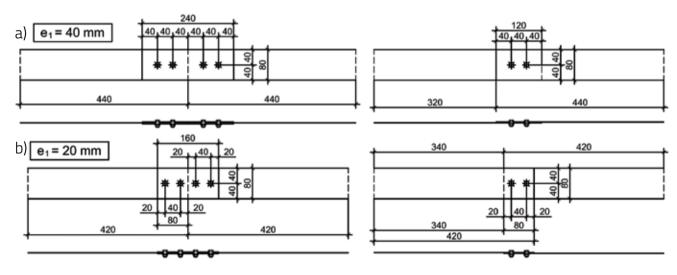
2. Presentation of experimental data

Experimental investigations and studies conducted at the Faculty of Civil Engineering in Belgrade primarily focus on shear connections with simple and self-tapping screws, while the

issue of tensile connections is considered phenomenologically and tested on a smaller number of specimens, so that potential forms of failure can be confirmed, and in order to determine tensile strength of self-tapping screws. In case of shear connections (specimen designation starts with *S – shear*), four parameters that significantly influence their carrying capacity were varied (Figure 3):

- type of fastener: ordinary bolts (*B – bolts*) and self-tapping screws (*S.T. – screws*)
- type of connection: lap (*L – lap*) and with splices (*S – splices*)
- sheet thickness: t = 2 mm and 4 mm (splice thickness is equal to the thickness of adjacent sheet)
- bolt to sheet edge distance e_1 = 20 mm and 40 mm (marks 1 and 2, respectively).

Each connection was made with two bolts. In order to justify the use of smaller diameter fasteners, ordinary bolts M8 (nominal strength class 5.8) and self-tapping screws 6.3 mm in diameter (type A – tip of thread with point), according to DIN 7976/ISO1479, were used.

Testing of connections loaded in tension was conducted on three series of specimens (Figure 4). In these specimens, the thickness was varied for the lower, load bearing sheet into which bolt (2 and 10 mm) is driven, while the shape and dimensions of the upper profiled sheet (standard trapezoidal sheet 0,85 mm in thickness) were the same for all specimens. In the series TS10k, steel backplates 4 mm in thickness were placed under the self-tapping screw head to prevent screw head pull-through failure, and to determine the tensile strength of self-tapping screws. A special tool is needed to properly test these specimens. Thus, all tests were conducted using the electronic cutting machine Shenck-

Meaning of the designation SBS2-1: shear connection with bolts and splices, sheet thickness: 2 mm, end spacing: 20 mm

Figure 3. Specimens of connections with mechanical fasteners loaded in shear: a) connections with splices (S), b) lap connections (L)
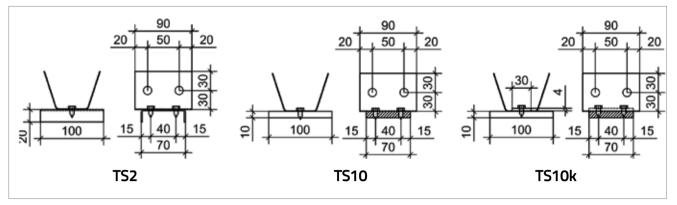
Figure 4. Specimens of connections with self-tapping screws loaded in tension

Trebel, 100 kN and 400 kN in load carrying capacity (Figure 5). During this testing, the deformation rate amounted to 15 mm/min, which is quite usual for static tests.

Figure 5. Electronic cutting machine RM400, 400 kN in capacity

Based on test results obtained by statistical analysis according to EN 1993-1-3, Appendix A [13], typical resistance values were determined according to the expression used for series with at least four specimens:

$$F_k = F_m - ks \qquad (1)$$

where

F_m – mean value

s – standard deviation

k – coefficient dependent on the number of specimens (for series with four specimens it amounts to k=2,63).

For series with three specimens, the typical resistance values were defined using the expression:

$$F_k = \eta_k F_m \qquad (2)$$

where $\eta_k = 0{,}9$.

2.1. Mechanical properties of base material

Mechanical properties of material out of which specimens are made were determined by testing. Standard dimension specimens were cut out of sheets 2 mm (CR250) and 4 mm (S275JRG2) in thickness, and this for the longitudinal (L) and transverse (T) direction of rolling, and also out of the profiled trapezoidal sheet 0.85 mm in thickness (Figure 6).

σ-ε diagrams and mean values of mechanical properties, as obtained by three-specimen series testing, are presented in Figure 7.

Figure 6. Specimens with sheet thicknesses of 2 mm (T2-L), 4 mm (T4-L) and 0.85 mm (T1)
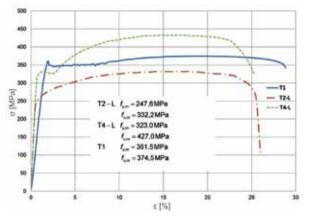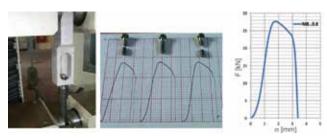

Figure 7. σ-ε diagrams and mechanical properties of base material specimens taken from sheet steel

2.2. Mechanical properties of fasteners

To determine tensile resistance and mechanical properties of bolts with metric thread, these bolts were subjected to tensile strength testing (Figure 8). The tensile resistance of self-tapping screws was determined based on specimen testing in tensile connections TS10k.

Fu = 27,36 kN f_u = 747,3 MPa $δ_u$ = 1,80 mm

Figure 8. Testing carrying capacity of ordinary bolts and ε diagrams

It was established during bolt testing that the dispersion of results is extremely small. Figure 8 shows typical force-strain

(F-$δ$) diagrams for bolts M8…5,8, and average test results: limit tensile resistance F_u, tensile strength f_u, and strain at failure $δ_u$. Tensile strength values obtained experimentally greatly exceed nominal values (by 49,5 %), which shows to what extent experimental determination of real mechanical properties is significant for subsequent interpretation of test results.

2.3. Shear bolted connections (SB)

Test results are shown in Table 1. In addition to ultimate force values F_u, which are given for each specimen, the following values are also presented: mean value Fm, standard deviation s, variance V, and typical force value F_k. Failure modes are also indicated.

Table 1. Bolted connection test results

Series	Type of joint	t [mm]	e_1 [mm]	Type of failure	F_u [kN]	$δ_u$ [mm]	F_m [kN]	s [kN]	V [%]	F_k [kN]
SBS2-1	Splice	2	20	Tearing failure	27,40	22	27,85	0,42	1,51	26,74
					27,60	27				
					28,30	28				
					28,10	25				
SBS2-2		2	40	Net section failure	43,20	65	41,92	1,33	3,17	38,42
					42,80	66				
					40,30	52				
					41,40	62				
SBL2-1	Lap	2	20	Sheet deformation and bolt head pull through failure	23,50	14	24,03	0,36	1,50	23,08
					24,20	15				
					24,10	14				
					24,30	13				
SBL2-2		2	40		24,10	12	24,65	1,00	4,05	22,02
					23,90	12				
					26,10	13				
					24,50	12				
SBS4-1	Splice	4	20	Bolt shearing failure	63,10	9,8	63,77	2,16	3,38	59,06
					63,10	8,8				
					60,30	7,4				
					63,80	8,0				
SBS4-2		4	40		65,20	6,6				
					64,30	7,0				
					66,60	6,8				
					63,70	7,1				
SBL4-1	Lap	4	20		37,30	3,0	37,28	0,64	1,71	35,89
					36,30	3,1				
					37,20	2,8				
					37,30	3,0				
SBL4-2		4	40		37,30	2,6				
					37,20	2,5				
					38,30	2,9				
					37,40	2,9				

In case of sheets 4 mm in thickness, failure occurs due to bolt shear, and this regardless of the type of connection and distance between the bolt and the sheet edge (Figure 9). The failure surface is flat and smooth, and strain values are small: from about 3 mm at lap joint to about 7 mm at splice joint.
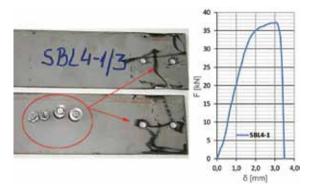

Figure 9. Bolt shearing failure at lap joints and the force – strain (F-δ) diagram

In case of lap joints, there are no visible deformations in the base material, and the shape of bolt holes remains unchanged (circular) even after the failure. As bolts are of double cutting type in case of splice connections, and because of the presence of two shear planes, the stress at failure is much greater at the base material, which leads to deformations in zones around holes for fasteners, and the total deformability of the connection is greater. For that reason, we should also take into account forces at deformations amounting to 3 mm (Table 2). It should also be noted that in case of double bolts one shear plane passes through the part of bolt body without thread, and the other through the part with thread, which is why the resistance of the double cutting bolt is not two times greater when compared to that of the single cutting bolt where shear occurs at the part of the body without thread.
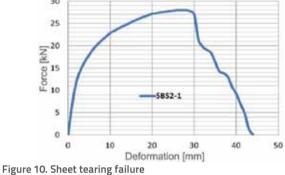
In case of sheets 2 mm in thickness, the sheer occurs along the base material. In splice joints the failure occurs by sheet tearing (Figure 10) or by net section failure (Figure 11), while in case of lap joints the failure occurs, due to eccentricity, by bending and pull-through failure (Figure 12). All these failure types are accompanied by extremely great deformations ranging from 20 to almost 70 mm.

Table 2. Mean ($F_{ser,3,m}$) and typical (F_k) bolt shear resistance values at 3 mm deformations

Series	$F_{ser,3}$ [kN]	$δ_u$ [mm]	$F_{ser,3,m}$ [kN]	s [kN]	V [%]	F_k [kN]
SBS4-1 SBS4-2	50,00	9,7	48,30	3,26	6,76	41,18
	51,00	9,4				
	52,20	7,4				
	44,30	6,5				
	45,00	6,9				
	47,30	6,7				

This is why the force value at 3 mm deformation is highly significant in case of failure along the base material.

Figure 10. Sheet tearing failure

The net section failure occurred in cases of specimens belonging to series SBS2-2, where the distance between the bolt and the sheet edge is e_1=40 mm. A considerable deformation of 65 mm (Figure 11) occurred at failure, which is due to plasticisation of steel material.
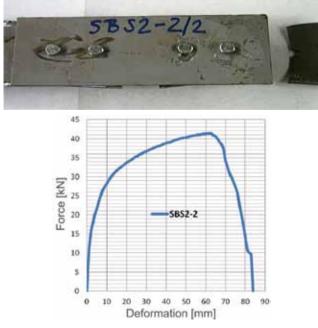

Figure 11. Net section failure

In case of all lap joint specimens made of thin sheets (t = 2 mm), the eccentric load results in sheet bending and in rotation of bolts, which turn approximately in the direction of tensile force action and, finally, after considerable deformation, the bolt head is pulled through the base material.

When the distance between the bolt and the sheet edge is sufficient, a complete and approximately circular image of plastic penetration below the bolt head can be formed (Figure 13a). In case of small distance between the bolt and the sheet edge, the image of penetration (pull-through) is deformed, as the penetration is followed by tear of a part of the base material between the first hole and the free edge of the element (Figure 13b).
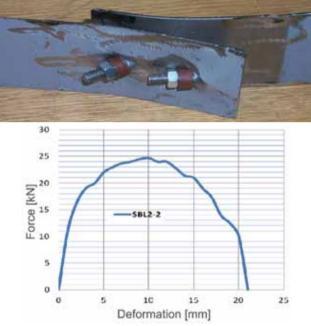

Figure 12. Sheet bending failure in case of lap joints

Figure 13. Bolt head pull through: a) big end spacing, b) small end spacing

2.4. Shear connections with self-tapping screws

The most often used self-tapping screws, i.e. those having 6,3 mm in diameter (according to DIN 7976/ISO1479) were subjected to this testing. The number of tested specimens was greater than in case of connections with ordinary bolts. Two groups of self-tapping screws (Type S and Type T), produced by different manufacturers, were tested. In this way, the number of specimens was increased and their resistance was analyzed. It was established that the resistance of self-taping screws of both types subjected to testing is very similar, and that there are no greater deviations with respect to quality. For that reason, the results from both groups of self-tapping screws were combined and used in statistical data analysis. Table 3 shows ult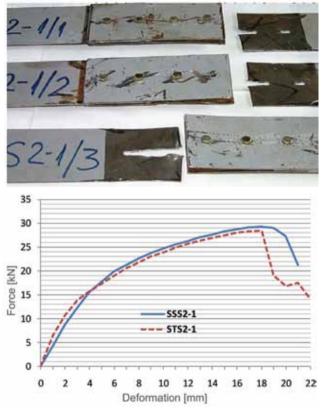imate force values F_u for each specimen, mean value F_m, standard deviation s, variance V, and typical value F_k.

Figure 14. Sheet tearing failure and comparison of F-δ diagrams for series SSS2-1 and STS2-1

In case of specimen series with slices and small edge spacing, made of sheets 2 mm in thickness (SSS2-1 series and STS2-1 series), the failure occurs by sheet tear in edge zone. Ultimate force values are very similar for both bolt types. The comparison of typical F-δ diagrams of SSS2-1 and STS2-1 series is given in Figure 14. In case of sheets 4 mm in thickness, the sheet tear failure did not occur even at small distance between the bolt and the sheet edge (20 mm). In fact, the failure occurred by shear of self-tapping screws (Figure 15). In case of connections with splices, force values at failure are approximately two times greater

Table 3. Test results for self-tapping screws

Series	Type of joint	t [mm]	e_1 [mm]	Type of failure	F_u [kN]	δ_u [mm]	F_m [kN]	s [kN]	V [%]	F_k [kN]
SSS2-1	Splice	2	20	Sheet tearing	28,8	16	28,18	0,92	3,3	26,17
					28,1	18				
					29,2	16				
STS2-1					26,5	13				
					28,2	16				
					28,3	18				
SSL2-1	Lap	2	20		13,6	2,0				
					13,3	4,2				
					12,5	4,1				
SSL2-2			40		14,3	4,4				
					13,1	3,9				
					15,3	4,0				
SSS4-1 STS4-1	Splice	4	20		27,40/2=13,70	3,7	12,97	0,78	6	11,68
					26,10/2=23,05	4,0				
					27,20/2=13,60	3,9				
					24,70/2=12,35	4,1				
					24,40/2=12,20	4,0				
					22,00/2=11,00	3,8				
SSS4-2 STS4-2		4	40	Bolt body shearing	29,10/2=14,55	3,2				
					26,30/2=13,15	3,0				
					26,60/2=13,30	4,0				
					24,70/2=12,35	4,4				
					23,80/2=11,90	3,8				
					23,40/2=11,70	3,7				
SSL4-1 STL4-1	Lap	4	20		11,8	1,5				
					12,6	1,4				
					12,9	1,4				
					13,2	1,8				
					13,3	2,3				
					14,1	2,0				
SSL4-2 STL4-2		4	40		13,5	1,9				
					12,3	1,6				
					12	1,5				
					12,7	1,7				
					12,6	1,4				
					12,7	1,6				

when compared to those at lap connections. The behaviour of splice connections made of sheets 2 mm in thickness, with 40 mm distance between the bolt and the sheet edge, is quite interesting. In case of specimens coming from these series, the failure occurs by shear of self-tapping screws, with considerable deformation in the zone of holes for fasteners.

2.5. Tensile connections with self-tapping screws

To get a clearer picture about behaviour of self-tapping screws in thin-walled steel element connections, the connections subjected to tensile load were tested. Taking into account potential modes of failure in case of thin-walled element

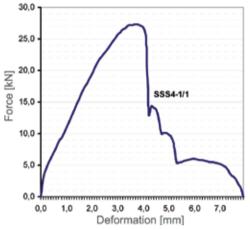Figure 16. Testing specimens in connections loaded in tension

Figure 15. Shearing failure of SSS4-1 series self-tapping screws

connections subjected to tension, the specimens were defined in such a way that all three different forms of failure can be seen. The testing was conducted using a specially designed tool (Figure 16). Test results are presented in Figure 4.

Table 4. Test results for connections loaded in tension

Series	Type of failure	F_u [kN]	F_m [kN]	F_k [kN]	s [kN]	V [%]
TS2	Bolt pullout from the lower sheet	3,9	4,83	4,35	0,83	17,23
		5,5				
		5,1				
TS10	Bolt head pull through the upper sheet	10,0	10,9	9,81	0,82	7,51
		11,6				
		11,1				
TS10k	Bolt tensioning	23,5	23,6	21,24	0,66	2,78
		23,0				
		24,3				

Due to small lower sheet thickness (t_{sup} = 2 mm) in specimens belonging to TS2 series, the failure actually occurs by tear, i.e. by pullout of self-tapping screws from the lower load bearing sheet (Figure 17). Deformations occurring at such type of failure are mostly due to flexibility of the upper profiled sheet.

When the lower load bearing sheet is characterized by greater thickness, such as in case of specimens belonging to the series TS10, the failure occurs by bolt head pull through (Figure 18). It should be noted that the testing was made without washers, and so the shape of failure is very similar to the shape of the bolt head (hexagon).
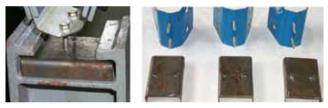

Figure 17. Failure of self-tapping screws by pullout from the lower sheet (t=2mm)

Figure 18. Failure of the self-tapping screw head by pull through the profiled sheet

Specimens belonging to the series TS10k were conceived in such a way that the failure occurs precisely by loss of tensile strength at the bolt level (Figure 19). These specimens were obtained through modification of the series TS10, i.e. by inserting a washer under the bolt head. This washer prevents failure due to pull through or pull over.

Figure 19. Failure of self-tapping screws loaded in tension

3. Analysis of test results

3.1. Shear connections with bolts

In table 5, typical force values obtained experimentally were compared with typical joint resistance values determined according to relevant standards [13] and [11], for each potential mode of failure, taking into account real (measured) properties of materials. As measured sheet thicknesses did not significantly deviate from nominal values, nominal thicknesses were adopted in the determination of typical resistance values. In all specimens with sheets 4 mm in thickness the failure occurs as a result of bolt body shear. According to EN 1993-1-3 [13] the design shear resistance of bolts is determined in the same way as for traditional steel structures, according to expression (3) from Table 5, where As is the area of the cross section tested, while fub is tensile strength of the bolt material. As this is a well known phenomenon and as bolts are highly

standardized, deviation of test results with respect to typical design values are relatively small, and range from 3 to 9 percent. In case of sheets 2 mm in thickness the failure occurs along the base material. In case of connections with splices, and small distances between the bolt and sheet edge $-e_1$ (SBS2-1), the failure occurs due to sheet tear (Figure 10). This type of failure occurs by tear of base material along two adjacent quasi-parallel planes that are formed in the direction of force action in the element. The tear starts in the end zones of the first hole and reaches all the way to the free edge of the element. The start of shear plane is situated somewhere in between the centre of the hole and its outside edge. The bearing distress at the hole envelope occurs due to stress concentration at the contact between the bolt body and the base material. The state of stress concentration occurs in this relatively narrow zone due to disturbance to the uniform force transmission. By further increase in load, these zones are plasticised and deformed – torn.

Table 5. Bearing resistance of shear connections with bolts

Series	Type of failure	F_k [kN]	$F_{k,EC3}$ [kN]	$F_{k,AISI}$ [kN]	$F_k / F_{k,EC3}$	$F_k / F_{k,AISI}$
SBS2-1	Sheet tearing	26,74	22,15	26,59	1,21	1,01
SBS2-2	Net section	38,42	41,88	47,19	0,92	0,81
SBL2-1	Sheet bending and bolt head penetration	23,08	22,15	20,16	1,04	1,14
SBL2-2		22,02	26,58	20,16	0,83	1,06
SBS4-1 SBS4-2	Bolt body shear	59,06	64,92	57,51	0,91	1,03
SBL4-1 SBL4-1		35,89	37,57	33,24	0,95	1,08

EN 1993-1-3	AISI - American Iron and Steel Institute
Shear resistance $$F_{k,EC3} = 0,5 \cdot f_{ub} \cdot A_s \qquad (3)$$	Shear resistance $$F_{k,AISI} = A_b \cdot F_n \qquad (6)$$
Resistance to compression along the hole envelope $$F_{k,EC3} = 2,5 \cdot \alpha_b \cdot k_t \cdot f_u \cdot d \cdot t \qquad (4)$$	Sheet bearing resistance $$F_{k,AISI} = C \cdot m_f \cdot d \cdot t \cdot f_u \qquad (7)$$ Sheet tearing resistance $$F_{k,AISI} = t \cdot e \cdot f_u \qquad (8)$$
Net section resistance $$F_{k,EC3} = \left(1 + 3 \cdot r \cdot (d_0 / u - 0,3)\right) \cdot A_{net} \cdot f_u \qquad (5)$$	Net section resistance $$F_{k,AISI} = A_n \cdot f_u \qquad (9)$$

The resistance of sheet to tear of end bolts depends on the distance from the edge, sheet thickness, and quality of base material, while resistance to bearing distress at the hole envelope, manifested by sheet piling in the zone in front of the bolt, is a function of the bolt diameter, sheet thickness, and its tensile strength. It can be seen that in both cases the sheet thickness and tensile strength are parameters of decisive significance for the determination of carrying capacity. It should be noted that the resistance to sheet tear does not greatly depend on bolt diameter, and that resistance to bearing distress at the hole envelope does not depend on the distance from the edge. The relationship between these two values must be determined in such a way that the resistances to tear, and bearing distress at hole envelope, are approximately the same.

In EC3 [13] the sheet tearing failure and bearing failure at hole envelope were integrated into a unified type of failure called failure by compression at hole envelope. In fact, the bearing failure at hole envelope is not a real failure but rather an initial stage in which we have local plasticisation of base material n the zones of contact with bolt, resulting in considerable elongation of the hole, while the real formal failure occurs either by sheet tearing in the end zone, or by sheet bending and the bolt head pull through. According to EN 1993-1-3 [13], the design carrying capacity of bolt, with respect to compression along the hole envelope, is determined via expression (4) given in Table 5, where the coefficient α_b is dependent on the relationship between the bolt distance from the sheet edge and the bolt diameter ($\alpha_b = \min(1; e_1/3d)$), while the coefficient kt comprises the above mentioned specific features of very thin sheets, and amounts to one for sheets more than 1,25 mm in thickness. AISI [11] makes a distinction between these two phenomena. It separately provides the expression for failure due to bearing distress at hole envelope as a function of sheet thickness, bolt diameter, and use of washer under the head and nut, and separately for failure due to sheet tear, as a function of bolt distance from the edge of the sheet and sheet thickness. In addition, it offers the possibility to take into account the influence of washer on the carrying capacity of the connection. It is assumed that for that reason a better correspondence was obtained between experimental results and typical load bearing values based on AISI (difference amonts to 1 percent only), than based on EC3 which provides a much more conservative value (the difference is 21 percent).

Regardless of the sheet edge to bolt distance, in case of lap joints made of sheet steel 2 mm in thickness the eccentric load results in inclination failure accompanied with bolt head pull through the base material. The bolt pull through occurs regularly under the hexagonal head and this gradually: bolt head vertexes penetrate – one after

another – through the relatively thin sheet. Deformations are progressively widening and, at failure, the bolts are inclined by almost 90 degrees with respect to their initial position. Similar failure modes have also been noted by other authors [8] in case of lap joint testing with thin sheets.

It can be concluded that in case of thin sheets even small eccentricities exert a significant influence on the behaviour of lap joints. This is due to small flexural stiffness of these sheets. Failure mechanisms are complicated and difficult for numerical modelling, and so the basis for the analysis should be sought in existing regulations. After comparison of experimental results with typical resistance values obtained in accordance with existing standards (Table 5), we can note that deviations range from 4 to 17 percent which, considering the complexity of this phenomenon, can be considered acceptable.

The net section failure occurs when the sheet edge to bolt distance is sufficiently great, so that failure due to tearing of base material can not be realized, and when the sheet width is relatively small. The net section failure is regularly followed by narrowing of the section. It is typical for connections of small thickness and lower quality of base material steel. In case of small thickness sheets, it is often followed by bearing distress and sheet piling in the zone of the holes [3], while in case of lap joints we can also note bending which is due to eccentricity [8]. In case of thin walled members, the typical carrying capacity of net section (according to EN 1993-1-3) differs from that of traditional steel structures (EN 1993-1-1) and depends on the number of bolts in the cross section, total number of bolts, sheet width, and bolt to sheet edge distance, and is determined using the expression (5) from Table 5, where r is the relationship between the number of bolts in one row and the total number of bolts in the joint, while $u = 2e_2$ but not greater than p_2. After comparison of test results with the value obtained according to EC3, expresion (5), the difference of 8 % can be noted, while deviations with respect to AISI amount to as much as 19 %.

3.2. Shear connections with self-tapping screws

Two types of failure can be noted in shear connections with self-tapping screws: failure by sheet tear and failure by self-tapping

Table 6. Bearing resistance of shear connections with self-tapping screws

Series	Type of failure	F_k [kN]	$F_{k, EC3}$ [kN]	$F_{k, AISI}$ [kN]	$F_k / F_{k, EC3}$	$F_k / F_{k, AISI}$
SSS2-1 STS2-1	Sheet tear	26,17	30,20	39,63	1,15	1,51
EN 1993-1-3				AISI		
Resistance to compression along hole envelope				Resistance to compression along hole envelope		
$F_{k,EC3} = \alpha \cdot d \cdot t \cdot f_u$ (10)				$F_{k,AISI} = 4,2 \cdot \sqrt{t_2^3 \cdot d} \cdot f_{u2}$ (11)		

screw shear. It should be noted that bolt shear failure is present in a greater number of specimens, and so a greater number of data was obtained for statistical analysis, and hence a reliability of results increased. Typical force values obtained experimentally were compared with typical load bearing values obtained according to [13] and [11] for sheet failure by tear (cf. Table 6).

In case of connections with self-tapping screws, ultimate load carrying capacity values for sheets subjected to tear are approximately equal to values obtained at equivalent connections formed using ordinary bolts (Figure 20). In fact, a typical ultimate sheet tear force value amounts to 26,74 kN (Table 5) for bolted connections, while in case of self-tapping screws this value is slightly lower and amounts to 26,17 kN (Table 6). Thus the difference is only 0,57 kN, or about two percent.

This points to a very significant fact: the load carrying capacity of sheet subjected to tear is practically independent from the size and type of the fastener. It can also be noted that the ultimate strain is approximately equal to the edge distance e1, which is also true for connections with ordinary bolts.
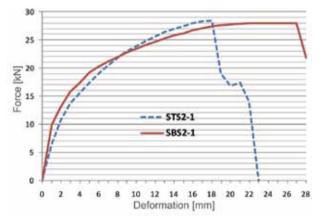

Figure 20. Comparison of F-δ diagrams (series: SBS2-1, STS2-1)

Test results are approximately 15 percent higher that the typical load carrying capacities according to EC3, while the difference with respect to AISI amounts to as much as 51 percent, which shows that expressions presented in this standard are quite conservative (Table 6).

Neither European nor American regulations give recommendations for determining the load carrying capacity of self-tapping screws loaded in shear. Instead, they propose experimental determination. In case of tested specimens, the typical load carrying capacity of self-tapping screws subjected to shear is equal to one half of the typical load carrying capacity of connections, as connections are each

realized with two self-tapping screws, and as their proportion in the carrying capacity of the connection is approximately equal. Consequently, the typical load carrying capacity of 6,3 mm selftapping screw specimens subjected to shear along a single shear plane amounts to 11,68/2 = 5,84 kN.

3.3 Tensile connections with self-tapping screws

The comparison of carrying capacity of self-tapping screws in tensile connections, with typical carrying capacities determined according to standards [13] and [11], is shown in Table 7, for failure by bolt pullout from the lower sheet (series TS2), and failure by bolt head pull-through (series TS10), for which recommendations are given. In case of samples belonging to the series TS2, the failure occurs by pullout, i.e. by extraction of self-tapping screws from the lower sheet, due to small thickness of the lower sheet (t_{sup} = 2 mm). Deformations occurring at such failure are primarily due to flexibility of the upper profiled sheet. Unlike the upper sheet, the lower sheet into which self-tapping screws are screwed has small barely noticeable deformations in form of a bulge. Thus the failure occurs due to destruction of thread made in the lower load bearing sheet. At that, metal filings pulled out of the lower sheet 2 mm in thickness are clearly visible. Because of hardness of surface layers of material out of which self-tapping screws are made, their threads have remained undamaged.

The load carrying capacity depends on the bolt diameter d, thickness of the lower load bearing sheet tsup, and tensile strength of material out of which it is made fu,sup. It should also be noted that the smallest lower sheet thickness in connections with self-tapping screws subjected to tensions, as given in EC3 [13], is very small (t_1 > 0,9 mm) and that it should be used with caution. The authors consider that the

Table 7. Carrying capacity of connections with self-tapping screws in tensile joints

Series	Type of failure	F_k [kN]	$F_{k, EC3}$ [kN]	$F_{k, AISI}$ [kN]	$F_k/F_{k, EC3}$	$F_k/F_{k, AIS}$
TS2	Bolt pullout from the lower sheet	4,35	5,44	7,12	0,80	0,61
TS10	Bolt head pull through the upper sheet	9,81	8,25	12,38	1,19	0,79

EN 1993-1-3	AISI
Resistance to pullout $F_{m,EC3} = 0,65 \cdot d \cdot t_{sup} \cdot f_{u,sup}$ (12) Resistance to bolt head pull-through $F_{m,EC3} = d_w \cdot t \cdot f_u$ (13)	Resistance to pullout $F_{m,AISI} = 0,85 \cdot d \cdot t_c \cdot f_{u2}$ (14) Resistance to bolt head pull-through $F_{m,AISI} = 1,5 \cdot d_w \cdot t_1 \cdot f_{u1}$ (15)
Range of applicability: 0,5 mm ≤ t ≤ 1,5 mm i t_1 ≥ 0,9 mm f_u ≤ 550 /mm²	

smallest thickness of the lower sheet into which the bolt is screwed tsup should be a function of the self-tapping screw diameter, i.e. of the pitch of the thread. The obtained typical load carrying capacities are smaller by 11 percent when compared to recommendations from EC3, which is probably due to an unfavourable relationship between the thickness of the lower load bearing sheet and the pitch of thread of the self-tapping screw. In proper design of such connections, one should not allow that the pullout failure be relevant when dimensioning the tensile resistance, and this can be achieved by slightly increasing the lower sheet thickness. However, the upper sheet thickness is normally small as self-tapping screws are usually used for fastening roof and façade linings whose thickness is always small ($t ≤ 1$ mm), and so in most cases the relevant mode of failure is either pullout or pull-through. The resistance to head pullout or pull-through in case of connections for self-tapping screws depends on the thickness of the upper sheet and its mechanical properties, and also on the size of the bolt head and on diameter of the washer dw, if any. The washer diameter to bolt diameter ratio d_w/d will determine whether the bolt head pull-through will occur, or whether we will have the pullover through the upper sheet. The pullover will occur if this ratio is higher and, in the other case, which is much more frequent, the bolt will be pulled through the upper sheet.

It should be noted that the tests were made without washers, and so the shape of failure is approximately equal to the shape of bolt head.

The carrying capacity of self-tapping screws subjected to tension, not covered by standards, was determined by testing specimens from the series TS10k, for which other modes of failure were not allowed. The F-δ diagram shows not only the total maximum carrying capacity of the tensile joint, but also the carrying capacity of the bolt. In fact when reaching the maximum force, a self-tapping screw failure ocurred, as this screw was subjected to a somewhat higher load due to a small and unavoidable asymmetry. After that, following a sudden drop in force, the force started to rise once again and achieved the level at which the tension-related carrying capacity of an another screw was exhausted. It is on this basis that we can determine the carrying capacity of each individual self-tapping screw in the joint (Table 8). Thus, based on three test specimens, we can obtain data about carrying capacity of six self-tapping screws. The mean and typical bearing capacities of self-tapping screws were obtained by statistical analysis of test results (Table 8). The relationship between the tensile strength and shear strength (10,53/5,84 = 0,541) was obtained by comparison of typical carrying capacity values of self-tapping screws with regard to shear (5.84 kN) and tension (10,53 kN).

The comparative analysis of different failure types of specimens tested (Figure 21) has revealed great differences

Table 8. Typical bearing capacities, Fk, of self-tapping screws with regard to tension

Series	F_u [kN]	F_m [kN]	s [kN]	V [%]	F_k [kN]
TS10k	11,30	11,80	0,58	4,94	10,53
	23,50-11,30=12,20				
	12,80				
	24,30-12,80=11,50				
	11,40				
	23,00-11,40=11,60				

with respect to carrying capacities of individual connections. By selecting an appropriate lower sheet thickness as a function of bolt diameter, we can achieve that the resistance to pullout is greater than the resistance to pull-through. Thus it can reasonably be expected that in such connection types the resistance to bolt head pull-through will become relevant. It can additionally be increased by adding washers.
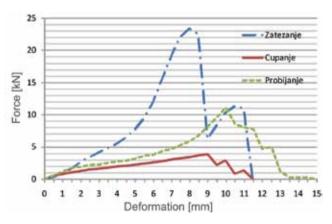

Figure 21. Comparison of F-δ diagrams for different modes of failure

4. Conclusion

The study of shear and tensile joints presented in this paper confirms failure modes that can be expected in thin-walled steel elements. It can be concluded that similar modes of failure are likely to occur in case of joints with ordinary and self-tapping screws. An important conclusion is that the resistance of shear joints to sheet tear is approximately the same for ordinary and self-tapping screws, and that it dominantly depends on the distance between the screws and the failure edge, $e1$. The testing has also shown that the use of smaller diameter bolts in thin-walled steel members is quite justified. Although the testing was conducted using bolts type MB which are smaller than minimum bolts that are traditionally used for usual steel structures in building construction (M12), it was revealed

that in sheets 2 mm in thickness all failures occur along the base material, which means that the bolt was not worn out. In other words, the use of smaller diameter bolts in case of thin-walled steel members such as purlins, façade gates, and other secondary elements, can be considered as fully cost-effective. Lap connections should be avoided as, due to small eccentricity, great bending deformations may be expected, and these deformations cause specific failure by sheet bending and bolt head pull-through, which results in lower carrying capacity and non-linear behaviour of the connection. Shear connections with self-tapping screws generally have a lower carrying capacity when compared to connections with bolts. Relevant present-day regulations EN 1993-1-3 and ANSI 2001 do not give recommendations for calculating resistance of self-tapping screws to shear and tension, but rather recommend experimental testing. Typical resistance values of 6.3 mm self-

tapping screws loaded in shear and tension were defined in the scope of testing presented in this paper. Resistance values defined in this way can be used in the design as indicative values only. To enable broader use of self-tapping screws, the manufacturers should declare, based on more extensive test series, typical or design carrying capacities of self-tapping screws loaded in shear and tension. This would certainly open the door to wider application of self-tapping screws, not only for connections in roof structures and façade linings, but also for connections in secondary parts of steel structures. Test results coincide, to a greater or smaller extent, depending on failure mode, with results obtained by computations based on EN1993-1-3, and AISI 2001, as presented in full detail in this paper. Deviations are greater in case of more complex and les tested failure mechanisms, which points to the direction to be taken in future studies.

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