

STUDY ON BOLTED AND BLIND-BOLTED SINGLE SHEAR CONNECTIONS OF COLD-FORMED STEEL MEMBERS

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Abstract

The paper presents the results of tests on single shear bolted connections of cold-formed steel sections with a wall thickness of 4 mm made with standard fully threaded M16 grade 8.8 bolts. The tests were performed for connections with washers and without washers. The obtained results were referred to earlier studies of analogous connections using blind fasteners Huck BOM R16. The failure mode was identified, the load capacity and stiffness were compared, and a method to determine the non-linear load-displacement characteristics of such connections was proposed. The effect of stiffness of joints on structural response of exemplary cold-formed steel frame was shown.

Keywords: Bearing resistance; Blind fasteners; Bolted shear connections; Cold-formed steel frames; Semi-rigid joints, Translational stiffness.

1. INTRODUCTION

1.1. Cold-formed steel frames with shear-bolted connections

Modern industry increasingly tends towards the so-called industry 4.0, which consists among others on the integration of systems used for design and production. This also applies to steel structures made of cold-formed steel (CFS), where LGS / HGS (Light / Heavy Gauge Steel) systems are more and more popular. These are comprehensive solutions combining the most important elements of the production process: from BIM design, through prefabrication to assembly. Individual structural members can be produced on one compact device, which automatically shapes, cuts, makes holes for fasteners and marks them accordingly. Open sections with various dimensions (most often types C and U) cold-formed from zinc-coated high strength steel sheets with a thicknesses in the range of 1.2 to 2 mm (LGS) and 3 to 6 mm (HGS) can be made on the same machine. These systems are characterized by very high precision and production speed reaching over a dozen running meters of profile per minute.

Cold-formed structural systems are most often designed as frame or lattice structures, taking into account their cooperation with sheeting [1]. Individual members are joined with various types of self-drilling screws, standard bolts or other types of mechanical fasteners. This allows for designing structures with a span of over a dozen meters and a self-weight not exceeding 0.2 kN/m², that are easy to prefabricate, transport and install.

For structures with larger spans, e.g. twenty-four meters (Fig. 1a), it is rational to use Rectangular Hollow Section (RHS) members with wall thicknesses from 3 to 6 mm [2]. To connect hollow section with open section members, the so-called blind fasteners HUCK BOM (*Blind, Oversize, Mechanically locked*) [3] (see Fig. 1d, e and f) can be used. The introduction of eccentricity at nodes allows the design of the lattice structure without gusset plates (Fig. 1b and c).

The main advantages of the BOM fasteners are the possibility of connecting elements with only one side access and tight filling of the hole by the sleeve of the connector during installation. After installation with

special hydraulic or pneumatic tool the design diameter of the fastener d is equal to the diameter of the hole d_0 (cf. Fig. 1d and f), which significantly limits the slip in the connection. According to the producer's data [3], the BOM R16-4 fastener with a diameter $d = 13.6$ mm can be installed in a hole with a diameter $d_0 = 13.8 \div 14.8$ mm; thus the permissible tolerance is greater than in the case of fitted holes, where the clearance between the bolt shank and the wall in the hole should not exceed 0.2 mm. The technology of these connections is described in more detail in [4] and [5].

Due to the higher cost of BOM fasteners compared to conventional bolted connections, blind bolts should be used only where it is necessary for technological reasons (cf. Fig. 1b) and, above all, due to the required stiffness of the connection (slip limitation). In other cases, when both sides access is possible (cf. Fig. 1c), ordinary bolted connections can be used. The use of M16 bolts i.a. in the field splices of frame can also significantly facilitate the installation of the structure on site, since the standard bolts holes are enlarged by 2 mm in relation to the bolt diameter.

1.2. Behaviour of shear-bolted connections

In the single-shear bolted connections, after application of the load, permanent mutual displacement of connected plates can be observed. It is caused by slip which is related with bolt-hole clearance, plastic deformations of the material in the place of bearing (hole elongation) and bolt tilting. The magnitude of these deformations undertakes to treat these connections definitely as semi-rigid, and the basis for including this phenomenon in static calculations of CFS frames is to determine the physical relationship in the form of load-displacement characteristics [6 to 9].

The behaviour of bolted shear connections is the subject of many studies. Zadanfarrokh and Bryan [6] analysed both experimentally and theoretically the flexibility of connections with M16 bolts in cold-formed steel sections with a thickness of 1.5 to 3.0 mm, and gave a formula for the flexibility of a single lap bolted joint. Lim and Nethercot [7] have performed experimental and numerical tests of similar connections to analyse the behaviour of CFS portal frames. Zaharia and Dubina [8] tested connections with M8 to M16 bolts to extend the formula purposed in [6] for various bolt diameters in order to predict the structural behaviour of CFS trusses. In [9] Dubina summarises i.a. the results of experimental and analytical study on full scale portal frame including the effect of stiff-

ness of bolted-shear joints on the basis of component method in EC3 [10]. Wallace and Shuster [11] developed an investigation to study the behaviour of bearing failure on bolted connections without washers and recommended 25% reduction of bearing strength in the case of single shear joints. In [12] He and Wang focused on developing the method of calculating the deformation capacity of thin-walled plates with a single bolt shear connections. The extensive parametric study on bearing strength were made by Konkong and Phuvoravan [13] to modify the bearing factor for thin G550 and G300 steel sheets. Aziz and Lip [14] studied the effect of bolt thread on stiffness of double-shear connections finding that the threads reduce the initial stiffness but increase the final stiffness. In [12, 15, 16] attention was drawn to the possibility of using the component method in EC3 [10] to assess the initial translational stiffness of bolted shear connections. Some other recent research in the field of bolted shear connections in CFS members are referred in [17], while structural response of CFS frames with such joints is discussed in [18].

The joints with blind fasteners of the type BOM are not included in the provisions of the design standards, so it was required to carry out extensive research, which aimed to determine their load capacity and stiffness. In the paper [19] Wuwer presents a method of calculating any arbitrary lap joint loaded simultaneously with shear force and bending moment, which is based on a non-linear force-displacement relationship. In [20] Swierczyna and Wuwer provide formulas for determining the bearing resistance of a single fastener. Paper [5] by Słowiński and Wuwer describes the method of strengthening the RHS columns. The structural response of a CFS frame with semi-rigid blind-bolt joints were discussed by Swierczyna and Wuwer in [2]. Paper [21] presents the results of tests of connections in alternating load. A summary of previous activities in this area is included in [4].

1.3. Aim and scope of the study

The load transfer mechanism in both blind fasteners BOM and standard bolts is the same, but their structure varies significantly. The effective use of these connectors require a good understanding of their structural behaviour, thus the research was developed to analyse the behaviour and compare these connectors. The paper presents the experimental study on single-shear bolted connections of cold-formed steel members with a wall thickness of 4 mm using M16 bolts. The results are illustrated in the form of static equilib-

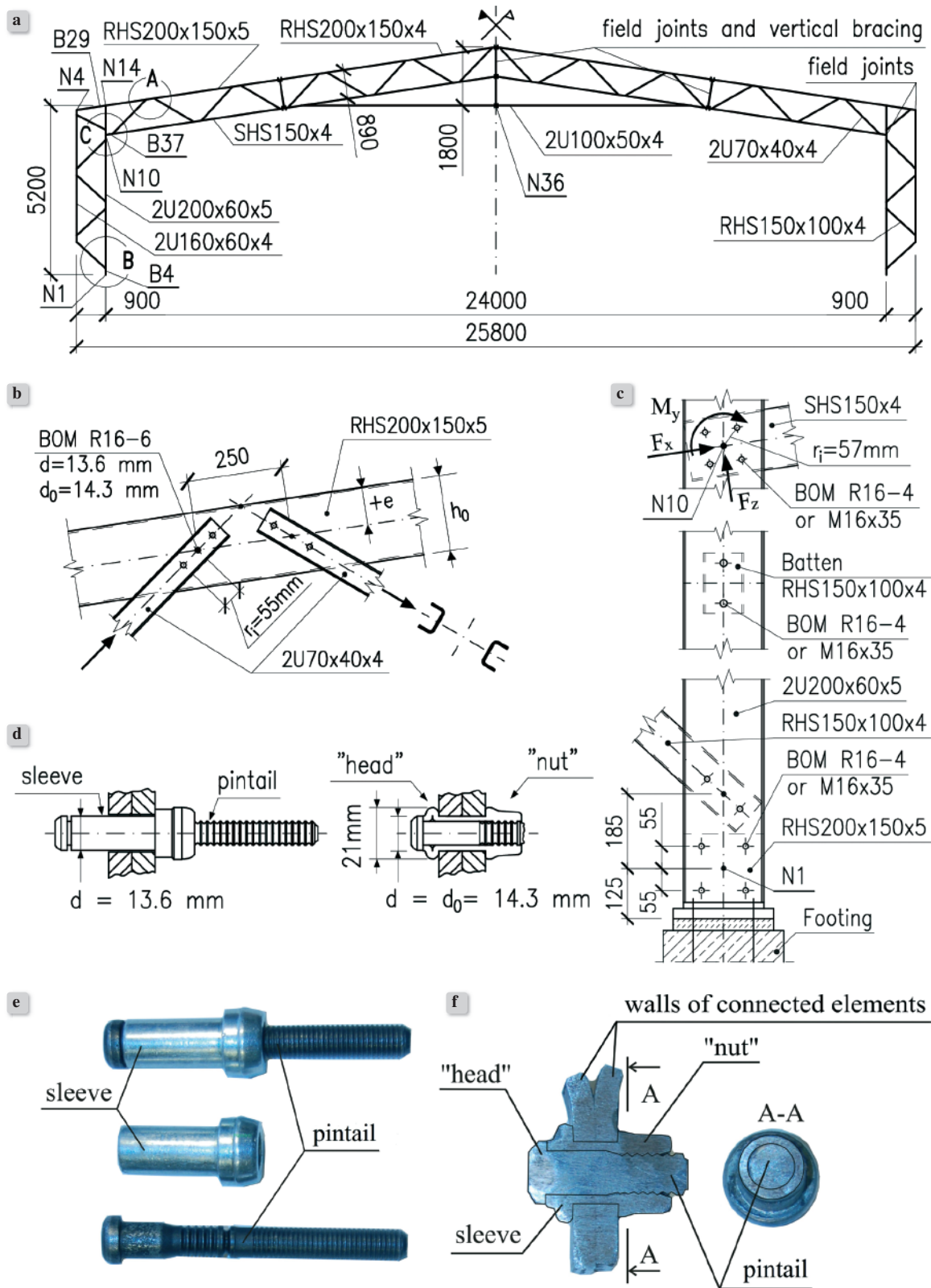


Figure 1.

Cold-formed steel frame with single-shear bolted connections [2]: a) geometry, b) detail “A” – structure of the truss joint, c) detail “B” and “C” – structure of the column, d) cross-section of the fastener before and after installation, e) view of the fastener before installation, f) cross-section of the fastener after installation

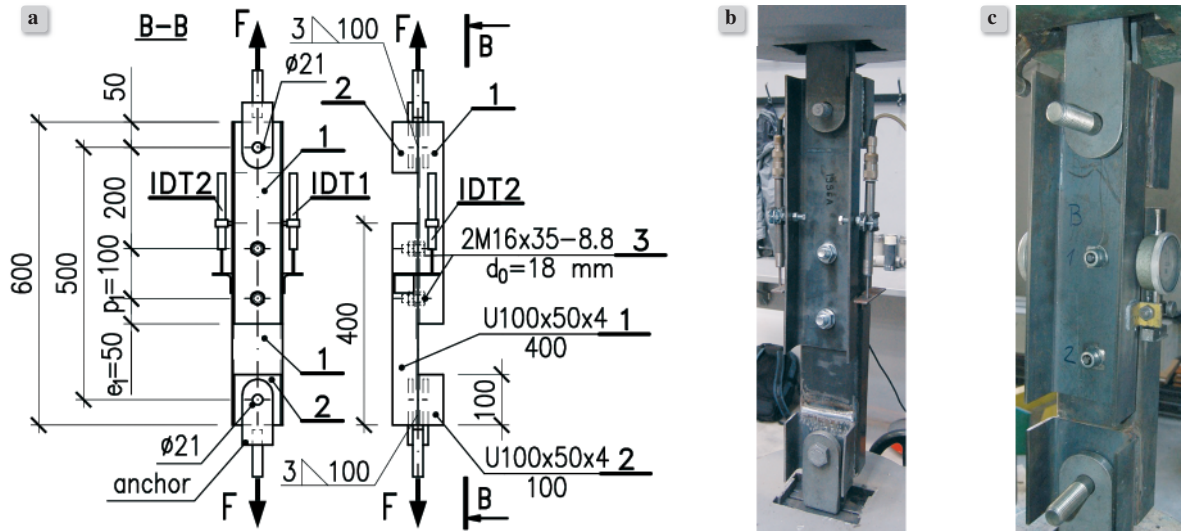


Figure 2. Test specimen: a) construction and dimensions, b) specimen with M16 bolts, c) specimen with BOM R16-4 fasteners

Table 1. Parameters of specimens with M16 bolts and BOM R16-4 fasteners

Specimen	Type	d [mm]	d_0 [mm]	e_1/d_0	p_1/d_0	A [mm ²]	t [mm]	Steel grade	f_y [MPa]	f_u [MPa]	$f_{u,d,t}$ [kN]
1	2	3	4	5	6	7	8	9	10	11	12
M16.4	M16x35-8.8	16.0	18.0	2.78	5.56	157	3.69	S235	283	393	23.2
BOM-S.4	BOM R16-4	13.6	14.3	3.50	6.99	161*	4.06	S235	260	343	19.9*
BOM-KSW.4	BOM R16-4	13.6	14.0	3.57	7.14	154*	4.00	S355	362	522	29.2*

* for BOM fasteners after installation $d = d_0$

rium paths on the graphs of the relationship between the load F and the relative displacement δ of the connected walls. The appropriate relationship determined on the basis of the EC3 [10] standard and the proposed formulas enabling the determination of non-linear load-displacement characteristics of the tested joints were illustrated on the graphs. Test results are referred to the previous study [4, 20] of analogous connections with BOM R16-4 fasteners to compare the bearing strength and stiffness of these joints. Furthermore the effect of joints on structural response of exemplary CFS frame were shown.

2. TEST PROGRAMME

Standard M16x35 grade 8.8 bolts with fully thread shanks made in accuracy class B were selected for testing. The connections were tested on the example of axially loaded specimens with a similar construction as the previously tested connections for BOM fasteners (Fig. 2) [4]. The same type of cold-formed channel sections made with 4.0 mm thick S235 steel

and the same bolt hole edge distance $e_1 = 50$ mm and the spacing $p_1 = 100$ mm were adopted. In each specimen two bolts were installed in standard holes with a diameter $d_0 = 18$ mm, and hand tightened to achieve firm contact between plates and to ensure that the load was transferred primarily by the bearing.

The parameters of the specimens are summarized in Table 1, where they can be compared with the parameters of the selected, previously tested, specimens with BOM fasteners [4, 20]. It should be emphasized that the cross-section area A of the BOM fasteners after installation is comparable to the shear area of the threaded part of M16 bolt.

Standard 3 mm thick washers with a diameter of 30 mm and hardness 200 HV have been used [22]. The specimens marking system was adopted, where M16.4/ w - i specifies: M16.4 – bolt type and thickness of the connected walls 4 mm, w – the total number of washers used, i – the specimen number. Following types of specimens were tested: with washers under the nuts only ($w = 2$), with washers under the nuts

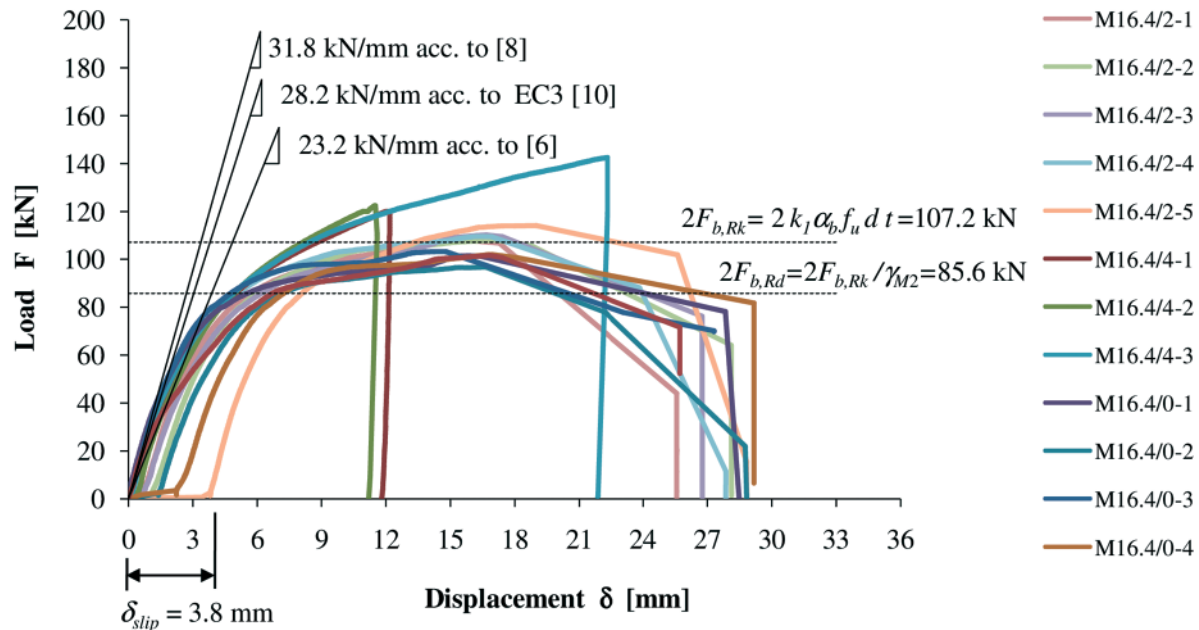


Figure 3.
The load-deformation characteristics of M16.4 specimens

and heads ($w = 4$), and – similarly as in [6] and [11] – without washers ($w = 0$).

The specimens were axially loaded with a force F using a ZD100 testing machine. In the range of $0 \div 80$ kN, the load rate was 5 kN/min and above this range: 2 kN/min. A relative displacement δ between the connected channels was measured by two inductive displacement transducers (IDT – cf. Fig. 2). All measuring devices were connected to an external universal recording unit.

3. TEST RESULTS

3.1. Specimens with M16 bolts

The results of tests for specimens with M16 bolts are presented on the graph of the relationship between the loading F and the relative displacement δ (Fig. 3), which was calculated as the mean value of the measurements made by IDT1 and IDT2 sensors. On the graph, dashed lines indicate the values of characteristic $2F_{b,Rk} = 2k_1\alpha_b f_u d t$ and design $2F_{b,Rd} = 2F_{b,Rk} / \gamma_{M2}$ bearing resistance calculated according to Table 3.4 in Eurocode 3 [10] for the actual measured connection parameters listed in Table 1, where the bearing factor $k_1\alpha_b = 2.5 \cdot 0.926 = 2.31$ and $\gamma_{M2} = 1.25$.

The load-displacement characteristics of the tested connections proved to be non-linear over the entire load range. The deformations in individual specimens are characterized by a significant dispersion which is

caused, among others, by various values of slip at the initial stage of loading. This phenomena is related mostly with the clearance in standard holes with a diameter of $d_0 = 18$ mm. For example, in the M16.4/2-5 specimen, that was deliberately installed in such a way that the connected walls were offset from each other in the opposite direction to the loading direction, the slip was 3.8 mm (cf. Fig. 3). Similar behaviour was also observed in many studies [6, 8, 11].

The behaviour of all specimens was similar. The beginning of clearly visible plastic deformations, which manifested in the tilting of the bolts and local deformation of the connected walls out of the connection plane, was observed at a load approximately equal to $2/3 F_{b,Rd}$. In the final stage of the test, when the tilt of the connectors was near 45° , the bolt heads were pulled through strongly deformed holes with simultaneous punching shear of the walls material under the bolt heads (Fig. 4).

The exception were the specimens M16.4/4-1 and M16.4/4-2 in which washers were used both under the nut and the bolt head ($w = 4$), where the test was stopped at a load $F = 120$ kN due to the limited capacity of anchors. In the specimen M16.4/4-3 the shear failure occurred in anchor at load $F = 142.5$ kN. The shape of the paths of static equilibrium without characteristic plateau indicates the possibility of a different form of failure in those specimens. The increased strength of these connections

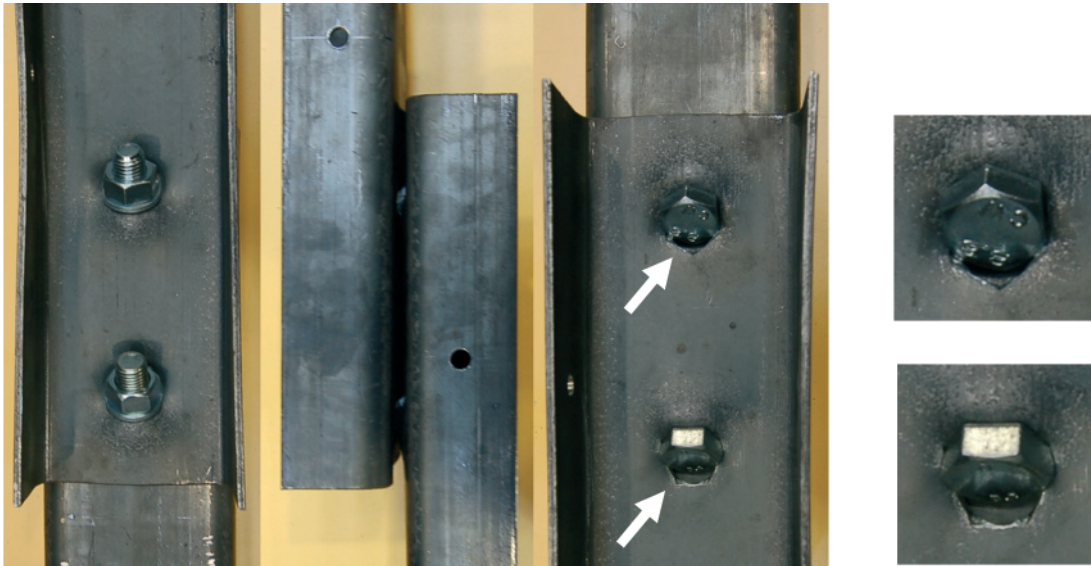


Figure 4.
Typical failure mode in specimens M16.4/2 with washers on nut side only

Table 2.
Test results for specimens M16.4/2 with washers under the nut only

Specimen	Number of washers w	F_{max} [kN]	$\delta(F_{max})$ [mm]	Bearing factor acc. to test $F_{max}/2f_{u,d}$	Bearing factor acc. to EC3 [10] $k_1\alpha_b$	Characteristic bearing resistance acc. to EC3 [10] $2F_{b,Rk} = 2k_1\alpha_b f_{u,d}$ [kN]	$F_{max}/(2F_{b,Rk}) \cdot 100\%$
1	2	3	4	5	6	7	8
M16.4/2-1	2	108.2	15.4	2.33	2.31	107.2	101
M16.4/2-2		107.9	17.1	2.33			100
M16.4/2-3		110.2	16.7	2.37			103
M16.4/2-4		109.6	16.3	2.36			102
M16.4/2-5		114.1	19.0	2.46			106

Table 3.
Test results for specimens M16.4/4 with washers under the bolt head and nut

Specimen	Number of washers w	F_{max} [kN]	$\delta(F_{max})$ [mm]	Bearing factor acc. to test $F_{max}/2f_{u,d}$	Bearing factor acc. to EC3 [10] $k_1\alpha_b$	Characteristic bearing resistance acc. to EC3 [10] $2F_{b,Rk} = 2k_1\alpha_b f_{u,d}$ [kN]	$F_{max}/(2F_{b,Rk}) \cdot 100\%$
1	2	3	4	5	6	7	8
M16.4/4-1	4	120.0 ¹⁾	12.0	-	2.31	107.2	112
M16.4/4-2		122.4 ¹⁾	11.5	-			114
M16.4/4-3		142.5 ²⁾	9.1	-			133

¹⁾specimen unloaded before failure, ²⁾failure occurred at anchor

was associated with better stabilization of the bolts by washers fitted on both sides, which limited the tilting and pulling of the fasteners.

Tables 2 to 4 list the values of the maximum load F_{max} and displacement $\delta(F_{max})$ recorded during the test. The bearing factors calculated as a ratio of $F_{max}/2f_{u,d}$

can be compared there with the value of bearing factor $k_1\alpha_b = 2.31$ according to [10].

In all connections where two washers were used ($w = 2$) the value F_{max} slightly exceeded the characteristic bearing resistance $2F_{b,Rk}$, determined according to EC3 [10]. The maximum loading in the connections

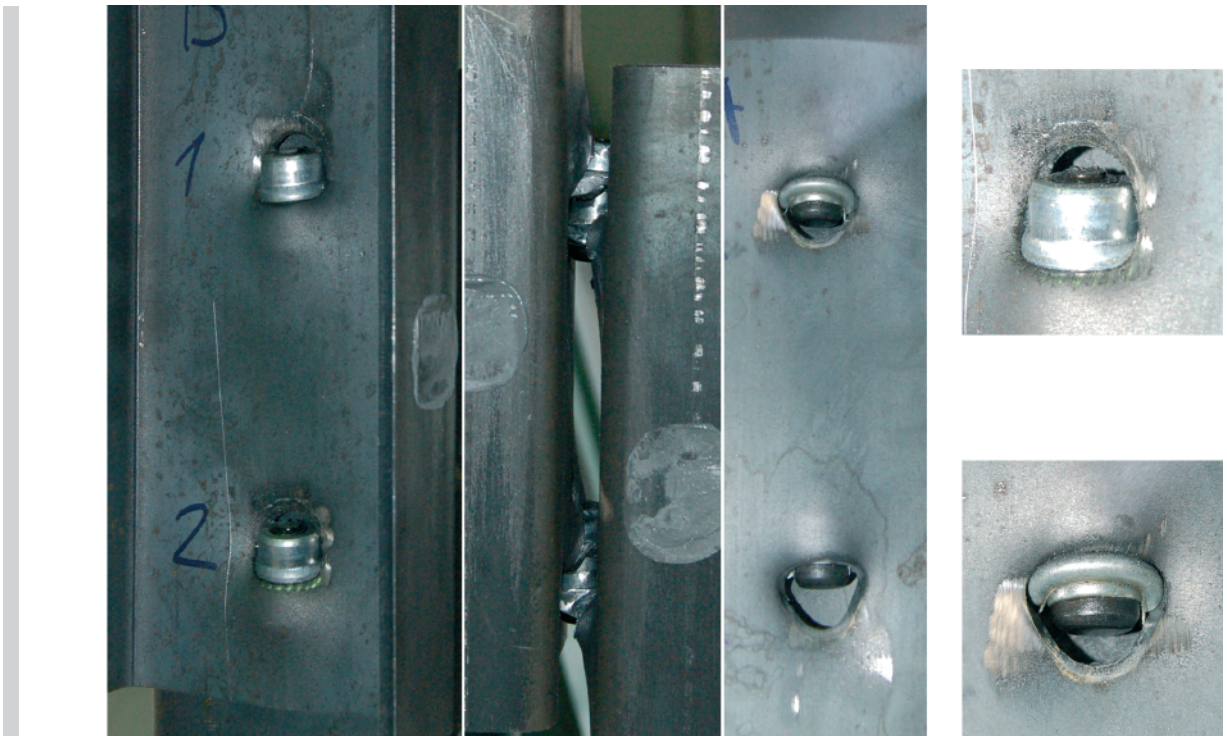


Figure 5.
Typical failure mode of BOM R-16 connections

Table 4.
Test results for specimens M16.4/0 without washers

Specimen	Number of washers w	F_{max} [kN]	$\delta(F_{max})$ [mm]	Bearing factor acc. to test $F_{max}/2f_u d t$	Bearing factor acc. to EC3 [10] $k_1 \alpha_b$	Characteristic bearing resistance acc. to EC3 [10] $2F_{b,Rk} = 2k_1 \alpha_b f_u d t$ [kN]	$F_{max}/(2F_{b,Rk})$ ·100%
1	2	3	4	5	6	7	8
M16.4/0-1	0	101.6	15.8	2.19	2.31	107.2	95
M16.4/0-2		96.7	16.6	2.08			90
M16.4/0-3		103.3	14.3	2.23			96
M16.4/0-4		102.1	16.8	2.20			95
M16.4/0-5		101.6	16.8	2.19			95

where $w = 4$ proved to be significantly higher than in the other specimens, although the failure loading was not reached during the test. In the connections where no washers were used ($w = 0$), the bearing capacity was lower by up to 10% compared to the theoretical value (cf. Table 4, specimen M16.4/0-2).

Apart from the specimens in which washers were installed under the nut and bolt head, relative displacements at F_{max} were on average 16 mm, while the maximum displacement at failure reached about 28 mm, which indicates a high deformation capacity of these connections.

3.2. Specimens with blind fasteners BOM R16

The results of the previous studies on BOM fasteners were summarized in [4] and [20]. A total of fifty-five axially loaded specimens (cf. Fig. 2b) with connections of cold formed sections made of steel with $f_u = (340 \div 540)$ MPa and thickness $t = (3 \div 5)$ mm made with BOM R10 and R16 fasteners installed in the holes with a diameter $d_0 = (9 \div 14.5)$ mm were included. The behaviour and form of failure of connections with BOM fasteners (Fig. 5) is similar to that observed in the specimens M16.4/2 and M16.4/0 (cf. Fig. 4). The results of selected tests will be discussed in more detail in the next section.

4. ANALYSIS OF TEST RESULTS

4.1. Prediction of load-displacement characteristics

Methods for predicting the load-displacement characteristic of single-shear bolted connections in the form of a linear relationship were proposed, among others, in works [6] and [8]. Currently, however, the most widely known way to determine the stiffness of joints is the so-called component method proposed in EC3 [10]. A formulas to determine the elastic stiffness coefficients for bolts in shear k_{11} and bolts in bearing k_{12} have been provided there. They are associated with a specific case of beam-to-column joint with a bolted angle flange-cleats, however, as mentioned in the standard, they are for general application. In works [15] and [16] those formulas are presented in a form suitable to determine the stiffness of a single fastener:

$$k_{11} = \frac{8d^2 f_{ub}}{d_{M16}} \text{ and } k_{12} = 12k_b k_t d f_u, \quad (1a, b)$$

where:

$$k_b = \min \left\{ \begin{array}{l} 0,25 e_b / d + 0,5 \\ 0,25 p_b / d + 0,375 \\ 1,25 \end{array} \right\}, \quad k_t = \min \left\{ \begin{array}{l} 1,5 t_j / d_{M16} \\ 2,5 \end{array} \right\},$$

- d – diameter of the bolt,
- d_{M16} – nominal diameter of an M16 bolt,
- f_{ub} – ultimate tensile strength of the bolts,
- f_u – ultimate tensile strength of the steel on which the bolt are pressed,
- e_b – distance from the bolt-row to the free edge of the plate in the direction of load transfer,
- p_b – spacing of the bolt-rows in the direction of load transfer,
- t_j – thickness of the elements against which the bolt is pressed; $t_j = t'$ or $t_j = t''$, (Fig. 6).

In the case of single shear connection (Fig. 6), the stiffness is a sum of flexibilities of bolts in shear

$1/(m \cdot k_{11})$ and bolts in bearing to wall with a thickness t' : $1/(m k'_{12})$ and t'' : $1/(m k''_{12})$.

The translational stiffness of a joint is directly proportional to the number m of fasteners:

$$S_{\delta,m} = \frac{1}{\frac{1}{m k'_{12}} + \frac{1}{m k_{11}} + \frac{1}{m k''_{12}}}. \quad (2)$$

Straight lines corresponding to the stiffness values calculated for M16.4 specimens according to formula (2) and formulas proposed in [6] and [8] are plotted on the graph in Fig. 3. Referring those lines to the test results, it can be stated, that the stiffness determined on the basis of EC3 [10] and [8] represent the initial stiffness, whereas the value calculated according to [6] corresponds to the secant stiffness (cf. Fig. 3). However, taking into account the characteristic dispersion of the test results, it can be assumed that these differences are not significant.

As the tests has shown, at loading about 70% of the design bearing resistance, the cumulative plastic deformations cause the load-deformation characteristic become clearly non-linear. These observations are consistent with the provisions of EC3 [10], where the elastic initial stiffness determined on the basis of the component method should be used for loads not exceeding 2/3 of the design load capacity of the joint. Above this value, secant stiffness or nonlinear relation should be adopted on the basis of appropriate coefficients, but the standard [10] does not provide values suitable for the tested joints.

In [23] it was proposed that the non-linear load-displacement characteristic of bolted shear connections can be described by means of an exponential function. Assuming that the translational stiffness of the connection is directly proportional to the number m of fasteners, the function takes the form:

$$F = m a_F (1 - e^{-b_F \delta}). \quad (3)$$

The important advantages of the above formula are simplicity and the possibility of physical interpreta-

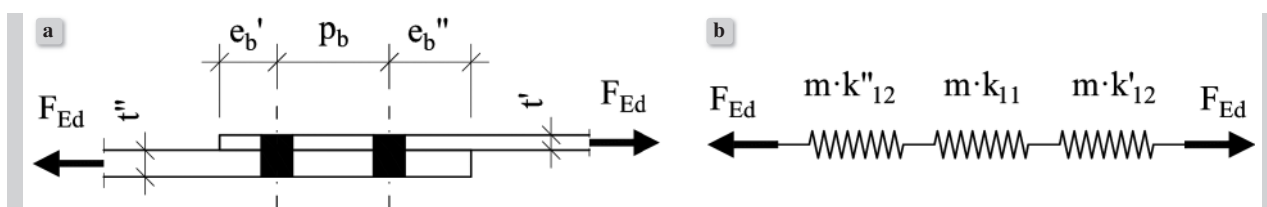


Figure 6. Single-shear bolted connection: a) scheme and dimensions, b) mechanical model

tion of its parameters. The value of a_F can be associated with the load causing plasticizing of the connection, while the product of a_F and b_F determines the initial stiffness of the connection.

In the case of bolted connections, the values of the parameters of the exponential function are proposed to be determined as follows:

$$a_{F,b} = F_{b,Rk} = k_l \alpha_b f_u d t, \quad (4a, b)$$

$$b_{F,b} = S_{\delta,1} / a_{F,b},$$

where $S_{\delta,1}$ according to eq. (2) for $m = 1$.

In the following figures, the results of experimental tests for the specimens with M16 bolts are plotted on the graphs of the relationship between the average load of a single fastener with a shear force $F_1 = F/2$ and the mutual displacement δ , where they can be compared with the exponential curves.

In cases where there is no significant slip, the exponential function describes well the behaviour of the specimens M16.4/2 with washers fitted only under the bolt nuts. Connections M16.4/4 where washers were used both under the nut and the bolt head have a load capacity much higher than predicted by the for-

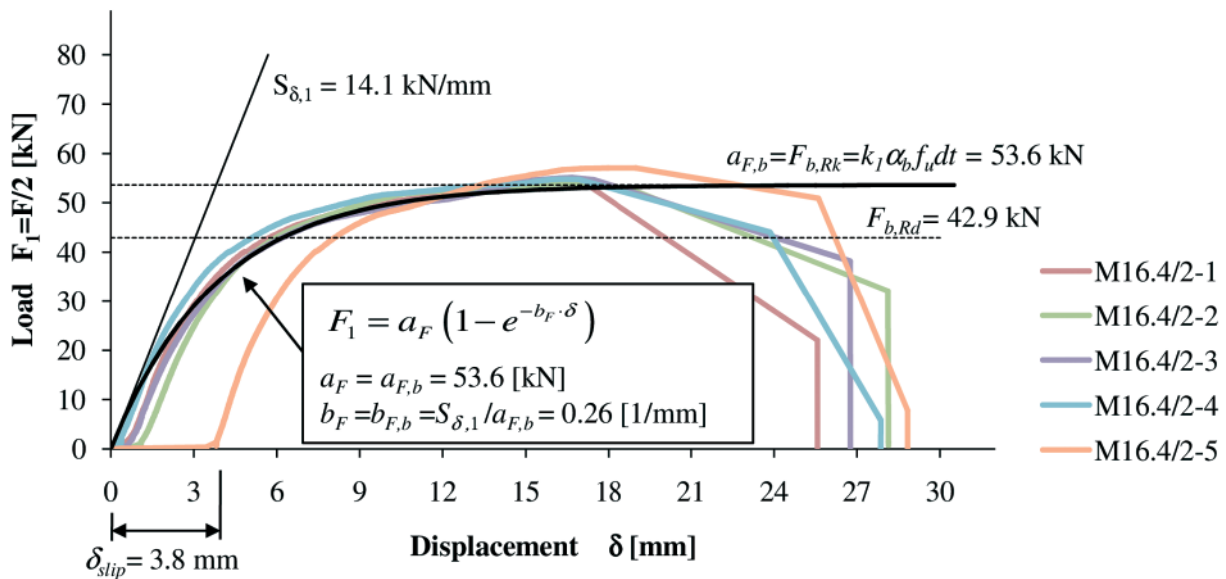


Figure 7.
Comparison of analytical and experimental F_1 - δ characteristics for specimens M16.4/2

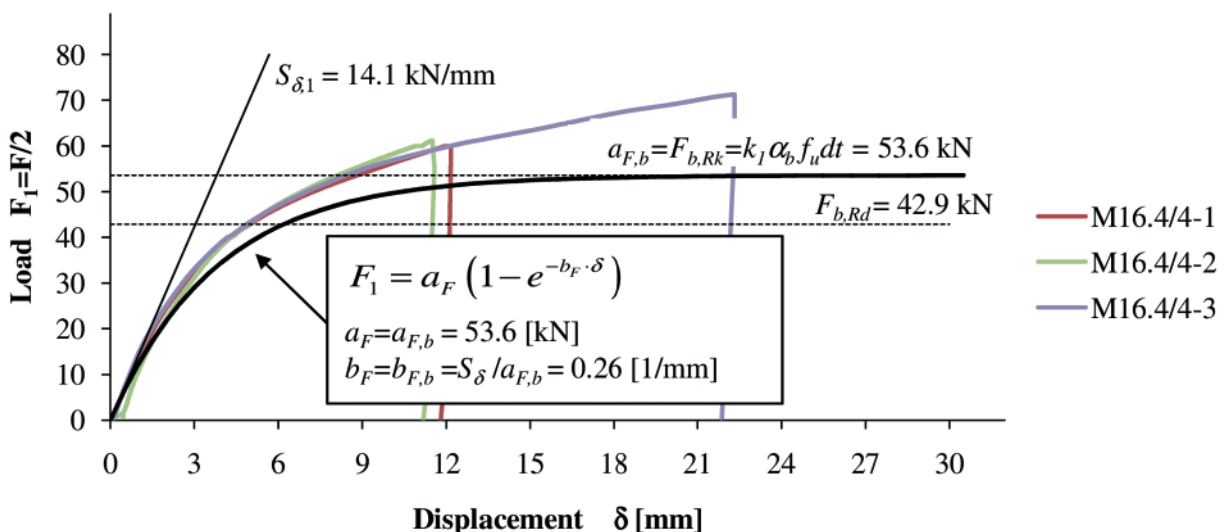


Figure 8.
Comparison of analytical and experimental F_1 - δ characteristics for specimens M16.4/4

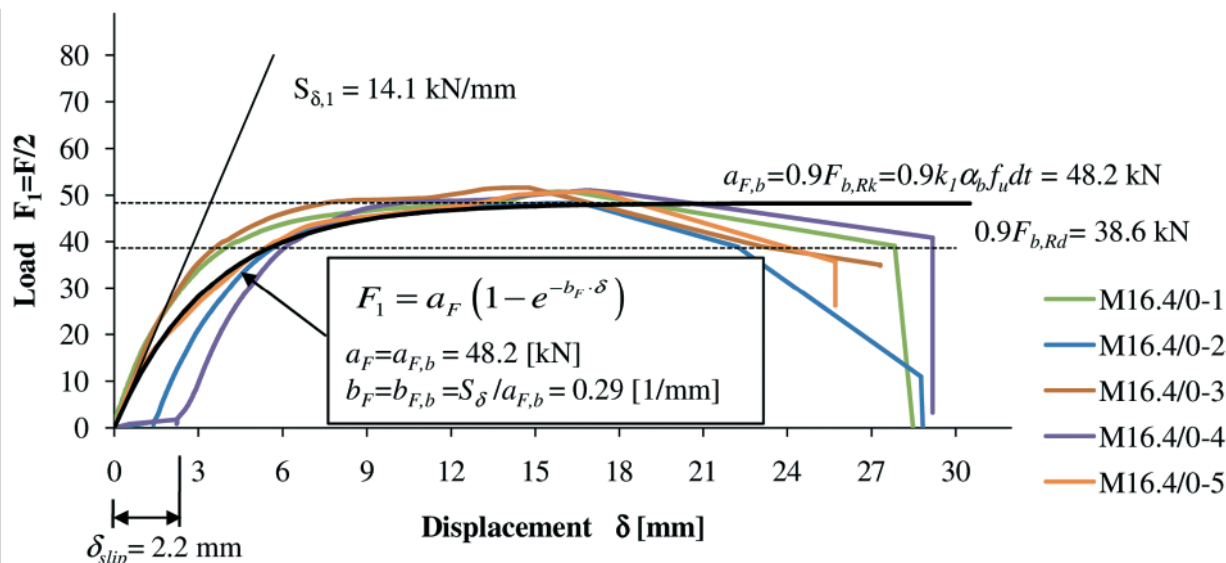


Figure 9.
Comparison of analytical and experimental F_1 - δ characteristics for specimens M16.4/0

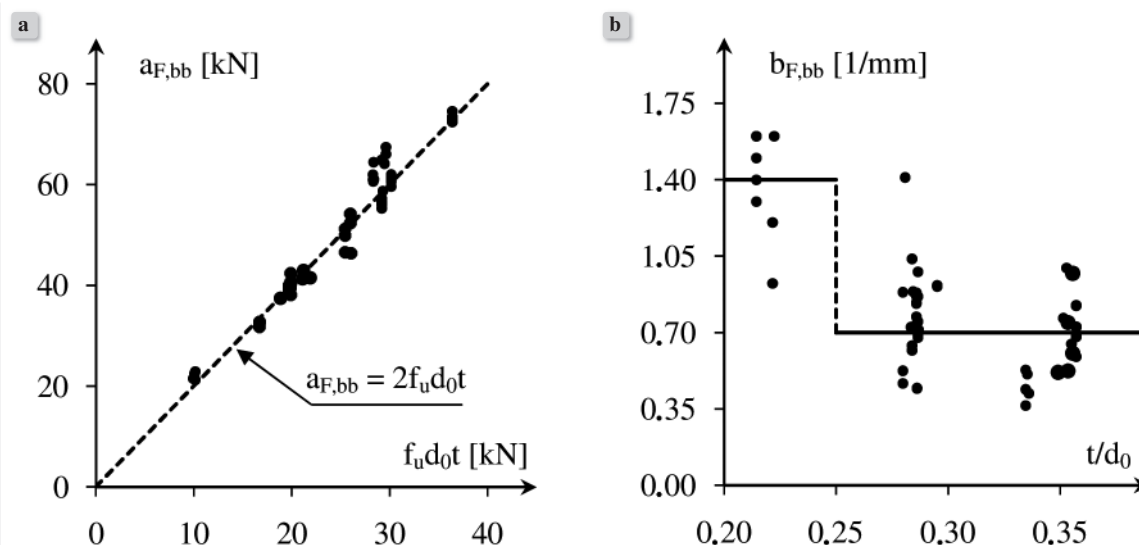


Figure 10.
Parameters of exponential function versus test results for connections with BOM fasteners: a) relation between $a_{F,bb}$ parameter and product of $f_u d_0 t$, b) relation between $b_{F,bb}$ parameter and ratio of t/d_0

mula (4a), thus their behaviour is also described in the safe way. In the case of joints M16.4/0 in which no washers were used, the value of the parameter $a_{F,b}$ was reduced by 10% due to the lower load capacity of these joints. The value of the reduction factor was estimated on the basis of test results listed in Table 4, where the lowest ratio $F_{max}/(2F_{b,Rk}) = 0.9$ for specimen M16.4/0-2. It should be noted that in [11] a 25% reduction of resistance for connection without washers was proposed which indicates that the exact prediction of the behaviour of connections without

washers may require more extensive research. The lack of washers did not visibly affect the deformation capacity of these joints.

As shown i.a. in [4] the exponential function (3) can be used to describe the behaviour of connections with BOM blind fasteners. Results of the tests were analyzed looking for the relationship between the measured values of ultimate tensile strength f_u of connected steel plates, their thickness t and diameter $d = d_0$ of the fasteners and experimentally determined param-

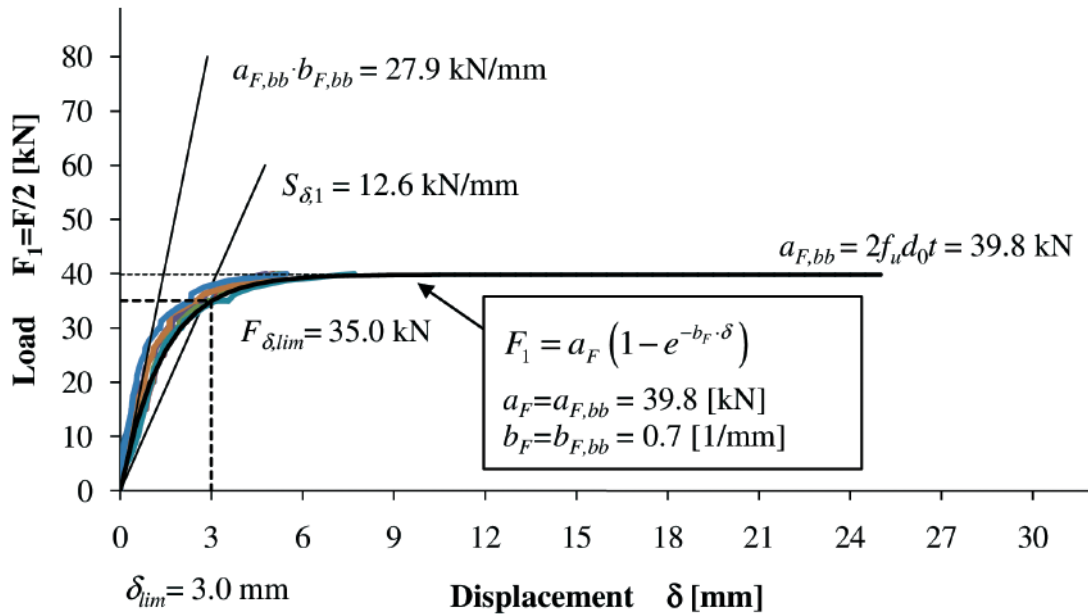


Figure 11.
Comparison of analytical and experimental F_1 - δ characteristics for specimens BOM-S.4

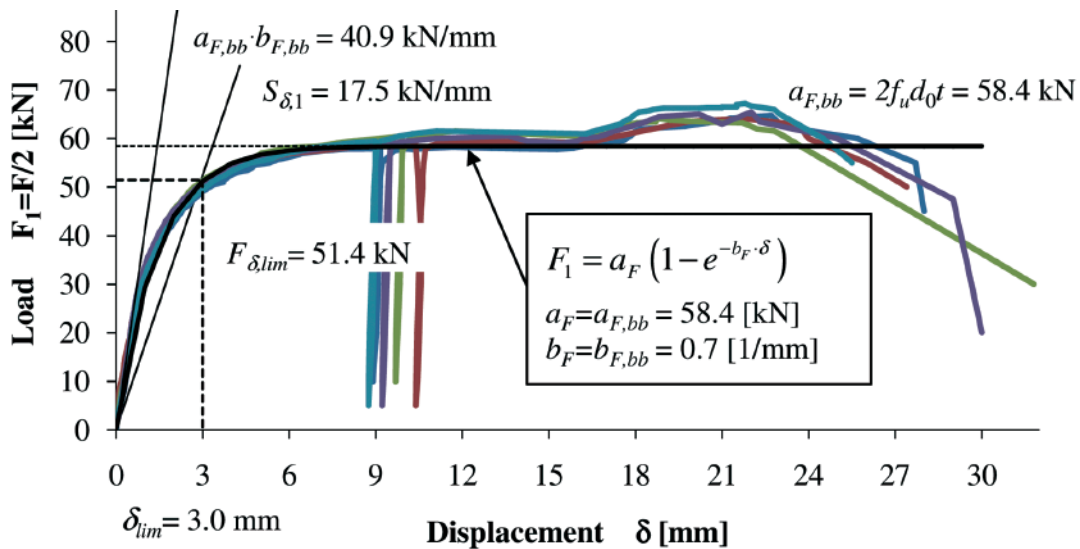


Figure 12.
Comparison of analytical and experimental F_1 - δ characteristics for specimens BOM-KSW.4

ters $a_{F,bb}$ and $b_{F,bb}$ of exponential curves describing the behaviour of the joints in tested specimens. The dependencies adopted in [4] are illustrated in Fig. 10. The next figures illustrate the results of tests and exponential curves for selected specimens with BOM R16 fasteners. On the F_1 - δ diagrams the straight lines corresponding to stiffness $S_{\delta,1}$ calculated according to eq. (2) for $m = 1$ and parameters of BOM fasteners were added. They can be compared with the straight

lines representing the initial stiffness calculated as the product of $a_{F,bb}$ and $b_{F,bb}$.

A series of five BOM-S.4 specimens (cf. Table 1) were tested for displacements not exceeding 8 mm (Fig. 11). Following the ECCS Recommendations [24] the bearing capacity $F_{\delta,lim}$ was taken for the limit displacement criterion $\delta_{lim} = 3$ mm. However, the load was high enough to observe a visible plastic deformations of the joints.

Table 5.
Comparison of bearing factors for specimens with M16 bolts and blind fasteners BOM R16

Bearing factor			Differences [%]	
$a_{Fb} / f_u d t$		$a_{Fbb} / f_u d_0 t$		
M16.4/2 $w = 2$	M16.4/0 $w = 0$	BOM-S.4 BOM-KSW.4	[(1)/(3)-1]·100%	[(2)/(3)-1]·100%
1	2	3	4	5
2.37 ¹⁾ 2.31 ²⁾	2.18 ³⁾	2.00 ⁴⁾	18.5 15.5	9.0

¹⁾ test average (cf. Tab. 2), ²⁾ $k_1 a_b$ acc. to EC3, ³⁾ test average (cf. Tab. 4), ⁴⁾ see Fig. 10a

A five identical specimens BOM-KSW.4 (cf. Table 1) were loaded until the failure (Fig. 12), which shows that the deformation capacity of the BOM fasteners is comparable to M16 bolt connections. At the final stage of the test, at displacements exceeding 18 mm, a slight increase in load was observed, which is associated with a significant tilting of the fasteners (cf. Fig. 5). This caused that considerable part of the load were transferred by tension in the connectors.

4.2. Comparison of strength and stiffness of tested connections

To compare the bearing capacity of the individual types of fasteners, the ratio of the a_F parameter and the product of f_u , d and t is summarized in Table 5.

It can be assumed that the value of load causing plasticizing in test specimens with M16 bolts with washers under the nut may be about 19% higher compared to the analogous value for connections with BOM fasteners, while in the case of specimens without washers the maximum load can be higher by about 9%. These differences are mainly due to the relatively small diameter of the “head” of BOM fasteners which results in low pull-trough resistance. In the case of the M16 bolt the average of the diameter inscribed and described on its head is 26 mm, while the diameter of the “head” of the BOM R16 fastener is about 21 mm (cf. Fig. 1d). It should also be noted that, according to the producer’s data [3], the sleeve of which the fastener’s “head” is formed is made of mild low carbon steel.

Table 6 summarises the initial stiffness values of connections in tested specimens. In the case of specimens BOM-S.4 the initial stiffness turned out to be about twice as high as for M16.4, wherein both types of specimens were made with steel S235 (cf. Table 1). In the case of BOM-KSW.4, where S355 were used the initial stiffness was almost three times greater.

Table 6.
Initial stiffness of connections in tested specimens

Specimen	Initial stiffness [kN/mm]
1	2
M16.4	14.1 ¹⁾
BOM-S.4	27.9 ²⁾
BOM-KSW.4	40.9 ²⁾

¹⁾ acc. to eq. (2) for $m = 1$, ²⁾ product of a_{Fbb} and b_{Fbb}

Comparing the value of stiffness calculated for BOM fasteners as the product of a_{Fbb} and b_{Fbb} with the value of $S_{\delta,1}$ according to formula (2) for $m = 1$ (cf. Fig. 11 and 12) also in this case the stiffness of connections with blind fasteners turned out to be about twice as high as the value predicted by the formula developed for bolts.

The relatively high initial stiffness of the connections with BOM fasteners results mainly from the lack of slip in the blind bolt joint where the fastener sleeve tightly fills the hole during installation (cf. Fig. 1e). It should also be emphasized that the connections with BOM fasteners are characterized by much smaller dispersion of results in comparison to M16 bolt connections. However, this differences could be probably significantly smaller in the case where M16 bolts with partially threaded shank would be installed in fitted holes or holes enlarged by only 1 mm in relation to the bolt diameter.

5. EFFECT OF JOINT STIFFNESS ON THE STRUCTURAL RESPONSE OF FRAME

The results of static analysis of the frame illustrated in Fig. 1 were described in detail in [2]. The calculations were carried out using Robot Structural Analysis software. Combinations of actions determined on the basis of [25] included the self-weight of the structure, snow load based on [26] and wind

Table 7.
Nodal forces in frame for various types of joint model

Bar/Node (cf. Fig. 1)	Force	Type of joint model				Differences	
		Rigid	Semi-rigid		Nominally pinned	([4]/[3]-1) ·100%	([5]/[3]-1) ·100%
			BOM R16	BOM R16/M16			
1	2	3	4	5	6	7	8
B4/N1	M_y [kNm]	17.5	5.3	3.7	0.0	-70	-79
	F_x [kN]	100.7	100.7	100.7	100.7	0	0
	F_z [kN]	-46.0	-31.1	-26.8	-37.7	-32	-42
B37/N10	M_y [kNm]	-12.6	-3.1	-2.0	0.0	-75	-84
	F_x [kN]	234.0	143.9	119.0	208.7	-39	-49
	F_z [kN]	-66.8	-49.2	-47.3	-57.4	-26	-29
B29/N14	M_y [kNm]	-21.3	-43.1	-45.7	-28.2	102	115
	F_x [kN]	-193.3	-99.3	-73.3	-173.2	-49	-62
	F_z [kN]	-48.9	-53.5	-53.9	-33.9	9	10

action according to [27]. The loads were collected for a frame spacing 4.5 m. The effect of the semi-rigid joints on the structural behaviour of the frame was included using the option of non-linear releases for bars. The relationship between the axial force F_x and the corresponding displacement δ_x as well as the transverse force F_z and displacement δ_z (cf. Fig. 1c) in the nodes of the frame were adopted in the form of the exponential function (3). The relationship between the bending moment M_y and rotation angle ϕ in the joints were determined assuming that the centre of rotation in the joint is located in the centre of gravity of the group of fasteners, then:

$$M_y = \sum_{i=1}^m r_i \cdot a_F (1 - e^{-b_F \cdot r_i \cdot \phi}), \quad (5)$$

where r_i – is the radius connecting the axis of the i -th fastener with the centre of rotation of the group of fasteners (cf. Fig. 1b and c).

Calculations of the structure were made in several iterative steps, where each change in the geometry of the joints resulted in a change in their stiffness and the values of internal forces in the frame members. In each step the load capacity of the frame members according to [28] was checked. Based on the finally obtained values of forces, 4 to 10 fasteners were adopted in the joints of the frame. The bearing resistance of the BOM fasteners was checked according to the formulas proposed in [4] for a $\delta_{lim} = 3$ mm deformation criterion, while the bearing capacity of the M16 bolts was verified on the basis of [10].

Table 7 summarizes the values of the maximum internal forces for the design combination of loads in selected frame nodes (see Fig. 1a) for various types of joint models. The results of calculations obtained on

the assumption of rigid joints are given in column 3. Column 4 shows the results obtained assuming that all joints in the frame nodes are made using BOM fasteners, therefore the parameters of the exponential functions (3) and (5) were taken as $a_F = a_{Fbb}$ and $b_F = b_{Fbb}$ according to Fig. 10. Column 5 gives the results for the frame, where it was assumed that joints with both side access will be made using M16 bolts. In this case for the joints at the column base (node N1), bottom chord to column (node N10) and in the diagonal members of the column (cf. Fig. 1a and c), the parameters of exponential function were modified, assuming $a_F = a_{F,b}$ and $b_F = b_{F,b}$ according to formula (4a, b), keeping the same geometry and number of connectors in the joint. For the other joints, the characteristics appropriate for BOM fasteners were retained. Column 6 shows the results for nominally pinned joints.

Columns 7 and 8 show the differences in the values of internal forces in relation to the frame with rigid joint model. Changes in the value of internal forces are significant. For example, the bending moment M_y in nodes N1 and N10 decreased by over 70%, while in the node N14 of the upper chord increased by about twice. In the case where BOM fasteners were replaced by M16 bolts in selected nodes, this resulted in further changes of the internal forces by several percent.

The effect of the joint type on the displacement values of the frame nodes for characteristic combinations of actions is also significant (Table 8). In the case of semi-rigid joints with BOM fasteners the horizontal displacement at the frame corner (cf. Fig. 1a, node N4) and vertical deflection in the middle span of the girder (cf. Fig. 1a, node N36) may be about

Table 8.
Nodal forces in frame for various types of joint model

Node	Displacement	Type of joint model				Differences [%]		Limit displacement [mm]
		Rigid	Semi-rigid		Nominally pinned	([4]/[6]-1) ·100%	([5]/[6]-1) ·100%	
			BOM R16	BOM R16				
1	2	3	4	5	6	7	8	9
N4	Horizontal [mm]	2.1	5.0	6.1	3.6	39	69	35
N36	Vertical [mm]	27.9	49.8	53.8	33.9	47	56	96

twice as high as for the frame with rigid joints and also about 39÷47% higher than the values established for the frame with nominally pinned joints (cf. Table 8, column 7). This is due to the fact that the semi-rigid joints reduces the shear stiffness of the lattice frame. These differences are even larger if part of the frame joints would be made using M16 bolts (cf. column 8).

It should be noted that the horizontal displacements of the columns and the vertical deflection of the girder do not exceed the limit values, equal according to [28]: 1/150 of the column height and 1/250 of the girder span (cf. Table 8, column 9). However, in the case of joints with M16 bolts the formulas describing the stiffness of these joints do not take into account the possibility of slips, which can significantly increase the deformation of the structure.

6. CONCLUSIONS

M16 bolts and blind fasteners BOM R16 are connectors with a different structure, however, based on the obtained results, some relevant conclusions can be presented.

A similar form of failure was identified for both types of connections. In the first stage of loading, plastic deformation of the connected walls was observed in the vicinity of the fasteners, associated with the elongation of the holes and the tilting of the fasteners. When the tilt reached about 45 deg, a slight increase in load was observed, which in this state was partially transferred by tension in the fastener. At the final stage of loading both types of fasteners were pulled through strongly deformed holes (cf. Fig. 4 and Fig. 5).

The number of washers had a considerable effect on the value of the maximum force transferred by connections with M16 bolts. The bearing resistance of connections without washers may be 10% lower, while connections with washers under the nut and bolt head may be up to 30% higher, when comparing with the value of characteristic bearing resistance according to Eurocode [10] (cf. Tables 2 and 4). Only in the case of connections with washers under the nut

the values obtained from the tests were close or slightly higher (up to 6%) in relation to the value obtained on the basis of the EC3 (cf. Table 3).

The ultimate bearing capacity of connections with M16 bolts turned out to be higher than the analogous connections with BOM R16 fasteners. For joints without washers, the difference is about 9% when the washers are installed under the bolt nuts, the difference is 19% (cf. Table 5). When the washers are installed under the nut and head of the bolt, the difference may exceed 50%.

In the range of permissible load, BOM fasteners are characterized by high translational stiffness, which can be even twice as high as the stiffness of analogous bolted connections (cf. Table 6). In addition, blind fasteners are characterized by the lack of initial slippage and significantly smaller dispersion of static equilibrium paths. This is primarily the result of a tight filling of the hole by the sleeve of the fastener during installation process. In the case of M16 bolts installed in standard holes with a diameter of 18 mm, a large initial slip may be expected. In the most unfavourable case, the value of the slip can reach even about 4 mm (cf. Fig. 3).

The static calculations results of the exemplary frame, in which both the translational stiffness and the rotational stiffness of the joints were taken into account, indicate a significant effect of the behaviour of tested connections on the response of the structure. In the case of the frame with BOM fasteners, differences in the values of internal forces in the most loaded nodes can reach almost 100% compared to the frame with rigid nodes. These differences can increase by at least few more percent if joints with both side access would be made with M16 bolts (cf. Table 7). The values of displacements of the lattice frame with semi-rigid joints are higher even comparing to the frame with nominally pinned joints. This is possible because the translational stiffness of the joints has been neglected for the frame with pinned connections. Assuming that the joints will be made only with BOM fasteners differences reach 47%, while in the frame with both BOM fasteners and M16

bolts displacements can increase to 69%. However, in each of the considered cases the designed frame met the criteria of the serviceability limit state (cf. Table 8). It should be also emphasized that the force-displacement and moment-rotation characteristics adopted for M16 bolt joints do not take into account the slip that may occur in these joints. As shown in [5] and [29], slippage may have a significant impact on the behaviour of structure with bolted shear connections. In the case of multi-nodal structures, as lattice frame in Fig. 1, slips can cause excessive deformations even under the self-weight. The behaviour of such structures loaded alternately, e.g. by wind, may also raise some concerns, and require appropriate consideration in the static calculations of the bearing structure [21].

The presented results should be treated as the initial ones for further tests of connections with various numbers and configurations of fasteners, various thicknesses and steel grades of connected plates, also in the complex state of loading with bending moment and shear force, as well as in alternating loads. It is also necessary to determine the effect of slips in M16 bolt connections in standard holes on the structural response of various types of frames. The results of tests on bolted connections with a partially threaded shank and holes 1 mm larger than the bolt diameter would be valuable. It can be expected that in the range of permissible loads the behaviour of such joints will be more comparable with the BOM fasteners.

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