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RESISTANCE AND STIFFNESS OF BLIND BOLT LAP JOINTS IN COLD-FORMED STEEL STRUCTURES

NOŚNOŚĆ I SZTYWNOŚĆ POŁĄCZEŃ ZAKŁADKOWYCH NA ŁĄCZNIKI JEDNOSTRONNE W KONSTRUKCJACH Z KSZTAŁTOWNIKÓW GIĘTYCH

Abstract

The paper summarises the existing results of the authors' own research in the range of design of lap-joints with blind fasteners Huck BOM of cold-formed steel profiles. Formulae for their resistance and stiffness have been proposed with reference to the Eurocode EC3. Investigations are part of the research, which aims to develop the structural system of lightweight steel halls. The aim of this article is a comprehensive presentation of basic issues related to the design of bar structures with such connections.

Keywords: experimental and analytical investigations, flexible lap-joints, strength and stiffness, cold-formed steel, blind fasteners

Streszczenie

W artykule zebrano wyniki dotychczasowych badań autorów w zakresie projektowania zakładkowych połączeń kształtowników giętych na łączniki jednostronne Huck BOM. Zaproponowano formuły do obliczania ich nośności i sztywności z odniesieniem do zapisów Eurokodu EC3. Badania są elementem programu, który ma na celu opracowanie systemu konstrukcyjnego lekkich hal stalowych. Celem artykułu jest kompleksowe przedstawienie podstawowych zagadnień związanych z projektowaniem konstrukcji prętowych z badanymi połączeniami.

Słowa kluczowe: badania doświadczalne i analityczne, podatne połączenia zakładkowe, nośność i sztywność, kształtowniki gięte, łączniki jednostronne

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1. Introduction

Sustainable development of steel construction is manifested in the pursuit of rational shaping of lightweight structures, which are easy to prefabricate, transport and install. For this reason, members with cold-formed sections are increasingly used around the world [1, 2]. Their favourable geometric parameters make that they are an interesting alternative to the much heavier hot rolled sections. A properly designed and manufactured cold-formed structure may be 25% to 50% lighter compared to a building erected using the traditional technique, while shortening the installation time by up to 30% [3]. The worldwide interest in this issue is provided, among others, by a series of conferences titled "Thin Walled Structures", which took place, successively, in Glasgow (1996), Singapore (1998), Krakow (2001), Loughborough (2004), Brisbane (2008), Timisoara (2011) [4, 5] and Busan (2014) as well as many papers relating to this topic at the Eurosteel 2014 conference, e.g. [6–10].

The range of cold-formed sections offered by Polish manufacturers is very wide and includes members with open and closed sections and lengths, respectively, up to 14 m and 18 m [11]. They can be made of galvanised steel plates, which ensure appropriate durability and aesthetics.

Currently, single-storey steel buildings designed entirely with cold-formed profiles, constructed by the Swedish company [12], are in high demand in the domestic market. The main bearing systems are frames with lattice girders and laced or uniform columns (Fig. 1).

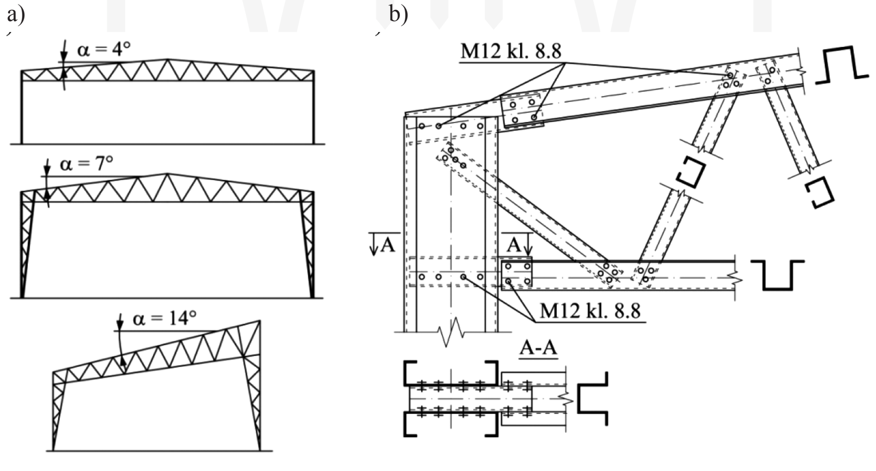

Fig. 1. Swedish steel building system [12]: a) selected geometries of portal frames; b) exemplary structure of joints in frame corner

The span and height of the bays can reach approximately 39 m and 12 m, and the width of the multi-bay building may even exceed 100 m. Connections of members in nodes of the trusses and field splices of trusses and columns are made using galvanised M12 class 8.8 bolts, which, together with the nuts, meet the requirements of the ISO8992:1996 standard. Bolts in connections are tightened in a controlled manner; according to the manufacturer's catalogue, these joints are prestressed. An example of a design solution of the frame corner is illustrated in Fig. 1b.

It can be stated that the technology of lap-joints in the contemporary design solutions tends to use – as a connector between the members – mostly ordinary bolts and prestressed bolts [13]. Various types of screws, nails and blind rivets with a diameter of less than 6.0 mm, due to the low load-bearing capacity, are used mostly to connect members of roof and wall cladding.

Cold-formed steel structures are included in the provisions of Eurocode [14] and popularised in manuals [2], but their use is still limited above of all due to the lack of specific guidelines for effective and safe design of connections, and insufficient number of experienced designers. The authors often met and continue to meet with queries from the industry for contact with designers experienced in this type of structures. For these reasons, the authors of the article have taken experimental and analytical studies aimed at developing a structural system of lightweight steel buildings with cold-formed sections, which would be competitive to similar structures offered and constructed in the country by foreign producers.

The aim of the article is to provide designers with comprehensive information containing relevant issues related to the behaviour of flexible lap-joints in bar structures, their bearing capacity and stiffness, developed on the basis of own research – analytical and experimental. The presented material may encourage the design of structures with cold-formed rectangular hollow sections using the tested connectors of the BOM type.

2. Shaping of joints in lattice structures

In cold-formed structures, an important issue are joints of members in the nodes. The requirements related with the use of welds in the case of thin plates with a thickness of 3, 4 and 5 mm, residual stresses [15] and the use of zinc coating tend to look for different methods of fastening. Choosing the right solution – in terms of practical use in the construction of steel structures – was preceded by studies of different types of fasteners [16, 17]. The most rational among sequentially tested by the authors self-drilling and self-tapping screws and blind bolts proved the lap joints using modern blind fasteners HUCK BOM *Blind, Oversize, Mechanically locked* (Fig. 2a) [18, 19], which received Technical Approval of Building Research Institute [20]. Their main advantages are the possibility of joining walls of sections with only one side access, tight filling of the hole by the sleeve of the connector after installation (design diameter of the fastener is equal to the diameter of the hole $d = d_0$ Fig. 2b) and high shear strength, corresponding to bolt class 12.9 [21]. The BOM fasteners are widely used, among others, to fasten subway wagon chassis [22] and for bridge repair [23]. Installation of the fastener is done using special hydraulic or pneumatic tool in just a few seconds and a worker can learn this procedure after short training [18, 19]. Correctness of the installation is assessed visually or by means of a special stencil. The technology of these connections is described in more details in [24] and [25].

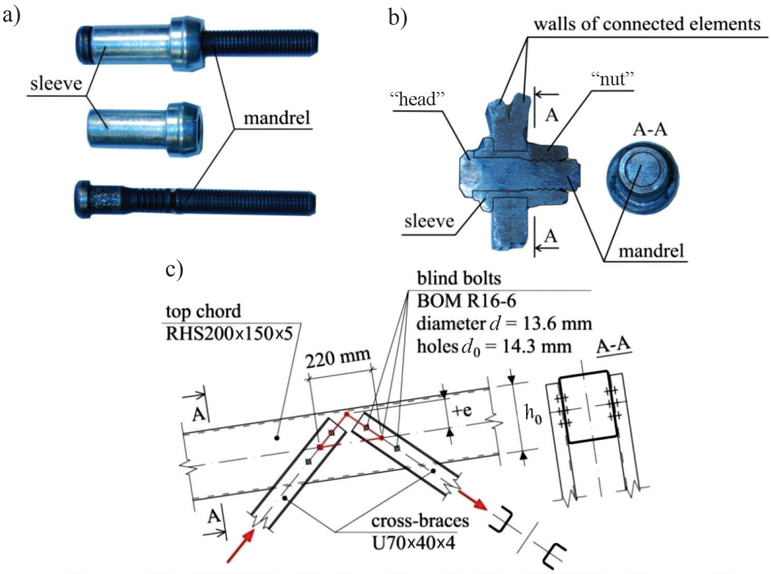

Fig. 2. Single-cut joints with BOM blind fasteners [18–20]: a) BOM R16-6 fastener, b) cross-section of the fastener after installation, c) structure of the truss joint

The use of blind fasteners enables the design of bar members with hollow sections, while the introduction of eccentricity at intersections allows for the assembly of the lattice structure without gusset plates. The joint of the web members with the upper chord of the lattice frame is illustrated in Figure 2c. In considered single-cut connections, the BOM fasteners will be subjected in the joints, besides the shearing force, also to specified tension and bending. The proposed technology allows for easy and quick erection of the structure of the individual members on the building site. The use of hollow sections enables the design of e.g. lattice frame with a span of 24.0 m and self weight not exceeding 20 kg/m^2 [26].

3. Experimental tests of single cut joints

3.1. Axially loaded test elements

In the single-cut joints, after application of the load, their deformations resulting from the permanent mutual displacement of the connected plates, due to plastic deformation of the material in the place of bearing of the fastener against the walls of bolt hole, were observed. The magnitude of these deformations undertakes to treat these connections definitely as semi-rigid [27–29]. Blind bolts of the BOM type 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 [30].

The behaviour of the single-cut joints has been studied experimentally, among others, on an example of axially loaded test elements "I" (Fig. 3), in which the walls of cold-formed channel sections made of steel S235 or S355 with the same thickness 3, 4 and 5 mm, were connected by two BOM R16 fasteners. Taking into account the results of similar studies [29], the analysed results for a total of fifty-five elements, that were divided for eleven different groups of connections [30].

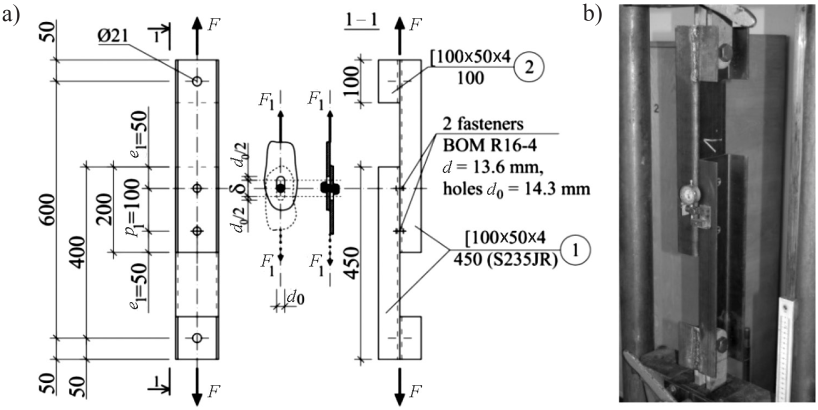

Fig. 3. Axially loaded test element “I”: a) structure and dimensions, b) view of the element anchored in the testing machine

Figure 4 shows an exemplary diagram of the relationship between the shearing force $F_1 = 0.5F$ acting on a single fastener and mutual displacement δ of connected plates in full range of the load until failure of the joint. Green curve “A” represents the behaviour of the connection of plates with a thickness of 3 mm, and the orange curve “B” – plates with a thickness of 4 mm. In both elements, profiles made of the same steel grade S235 and BOM R16 fasteners were used. 0.3 mm difference in the diameters of the holes in the tested elements is in the range of tolerance recommended by the producer [18].

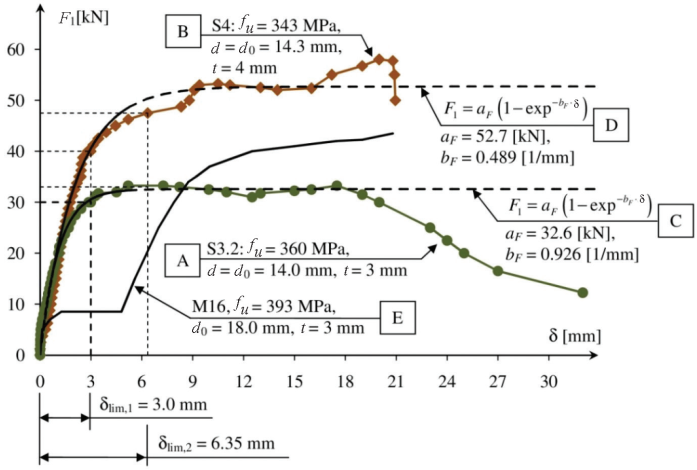

Fig. 4. Relation F_1–δ in axially loaded test elements “I”

The behaviour of the joints "A" and "B" have been described by exponential curves, plotted on a graph with a dashed line and marked, respectively, by the letters "C" and "D". On the graph, the values of limit displacements $\delta_{\mathrm{lim},1} = 3.0$ mm acc. to European Recommendations [31] and $\delta_{\mathrm{lim},2} = 6.35$ mm acc. to [32] are shown, which are proposed there as a reliable criteria for determining the bearing capacity for this kind of connections. Load values corresponding to a displacement of 3.0 mm are within the range of the elasto-plastic deformation of the joint, and for 6.35 mm are within the range of significant plastic deformation, and are close to the characteristic bearing resistance calculated as for blind rivets according to [14] without the partial safety factor γ_{M2}. The design bearing resistance $F_{b,Rd}$ determined on the basis of experimental tests of five identical elements following the procedure proposed in [31], for $\gamma_{M2} = 1.25$, is equal to: 19.8 kN – in the case of connection of plates 3 mm thick and is equal to 26.3 kN – for connection of plates 4 mm thick.

The curves in Fig. 4 can be compared with the curve "E" according to [33], which represents the behaviour of the bearing type connection category A according to [15], wherein plates that were 3 mm thick were connected using M16 bolts installed in a hole with a diameter $d_0 = 18$ mm. It is worth to note the considerable slip in the joint of about 4 mm, caused by clearance existing between the bolt shank and the wall of the hole, which appears at the load of about 25% of maximum capacity and which is not noted when using BOM fasteners loaded in only one direction.

It is worth to emphasise the high capacity for plastic deformation of the tested connections – their failure occurred at the displacements exceeding 20 mm. The tilt of the axis of fastener relative to the contact plane was then almost 90°, which is associated with significant plastic deformation of connected plates in vicinity of holes (Fig. 5). Then, the fastener, in addition to shearing, is subjected to substantial tension and bending. In the case of joint of plates 3 and 4 mm thick, failure of the connection occurred by pulling out the fastener through a highly deformed hole, while for joint of 5 mm thick plates – by tearing the fastener sleeve.

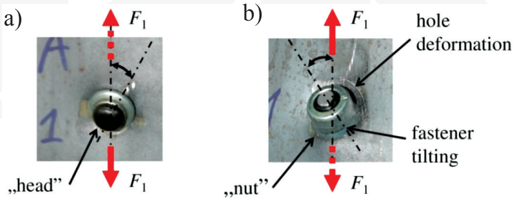

Fig. 5. Hole deformation and fastener tilting observed during tests, view from: a) "head", b) "nut" side

3.2. Test elements loaded axially alternately

In the actual structures, e.g. loaded by wind, forces in joints may act alternately in two opposite directions. Then, the behaviour of the given joint in the bar structure is described by proper hysteresis loops [34]. Due to the above reason, an additional investigation was conducted with properly designed test elements loaded alternately. Fig. 6 shows a graph illustrating a hysteresis loop of relationship $F_1 - \delta$ in two identical test elements of the type „In" [27]. Comparing their envelopes with the shape of exponential curve "F", of which parameters have been established as for the elements loaded only in one direction, significant differences can be observed. Their possible causes are alternating plastic deformations in the places of bearing of the fasteners against walls in the holes. The changes in the structure of the material associated with these deformations may result in an increase of the connection stiffness. Moreover, the characteristic is small, almost zero stiffness of the joint observed when changing the direction of the load at a given level, as well as the growth of permanent deformations in their following cycles. Then, there is a need to reckon with specified clearances in given joint, which need to be taken into account in the static analysis of the structure. The question also arises on how to determine the bearing capacity in this case, having in mind that, in the Recommendations [31], the considered loads are acting only in one direction.

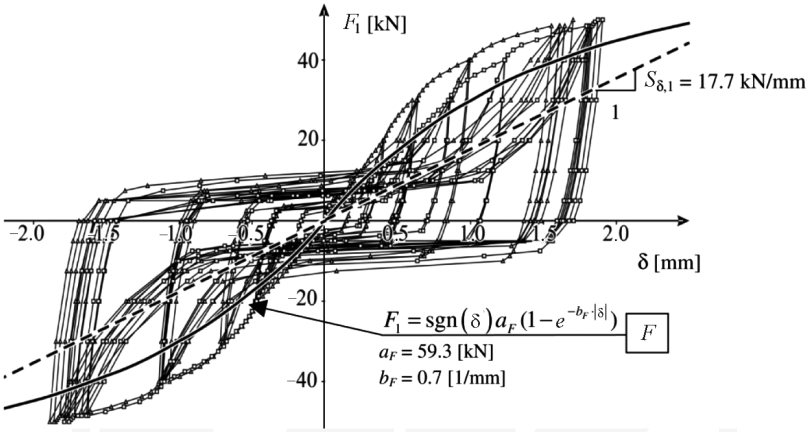

Fig. 6. Relation F_1–δ in alternately loaded test element “In”

In the graph in Fig. 6, a straight dashed line is also applied, inclination of which corresponds to the translational stiffness $S_{\delta,1}$ = 17.7 kN/mm. It was calculated based on the formulae proposed in [35], which were derived on the basis of stiffness coefficients for basic joint components listed in [15]. It can be stated that this straight line safely describes the behaviour of the tested joints, including the “from the bottom” characteristic dispersion of the test results.

3.3. Eccentrically loaded test elements

In the nodes of any arbitrary bar structure with lap-joints (cf. Fig. 2c), in addition to the axial force, the bending moment and shear force may also occur. To see how the joints with BOM fasteners behave in such complex load conditions, eccentrically loaded elements “V” with 2, 3, 4 and 5 fasteners (Fig. 7) have been tested [28, 36, 37].

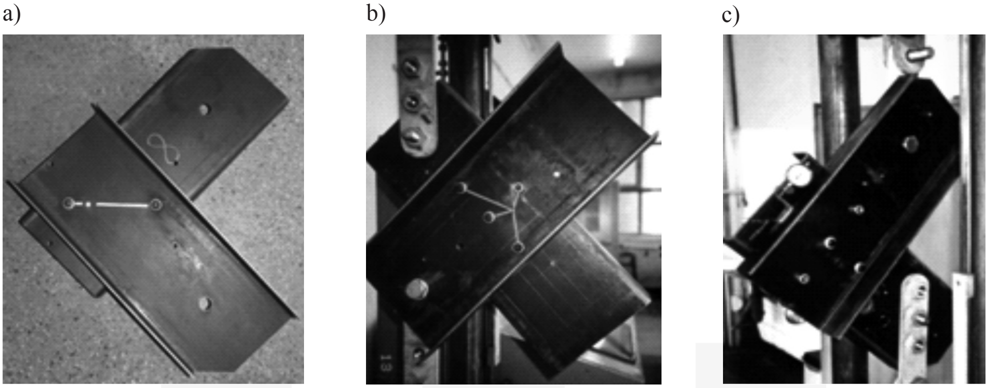

Fig. 7. Eccentrically loaded test elements with: a) 2-bolt joint, 4-bolt joint, 5-bolt joint

Fig. 8a shows a structure of the element with three connectors [28]. In Fig. 8b, white stripes marked the position of the so-called instantaneous centre of rotation.

Fig. 9 shows a graph of the relation between the bending moment $M = F \cdot e$ (see Fig. 8) and the mutual angle of rotation ϕ of the connected members [28].

Points plotted on the graph in the colours green, blue and orange correspond to the envelopes of paths of static equilibrium in three identical test elements as shown in Fig. 8. The curve "G" was obtained by solving the appropriate system of equilibrium equations, which may describe the behaviour of any arbitrary single-cut joint in a complex state of load [27, 4]. Design bending resistance $M_{j,Rd}$ = 5.67 kNm corresponds to reaching of the bearing capacity by the most loaded connector No. 3 (cf. Fig. 8a). Inclination of the dashed line corresponds to the initial rotational stiffness of the joint $S_{j,\text{ini}}$ = 236 kNm/rad, which was calculated based on the formula given in [35].

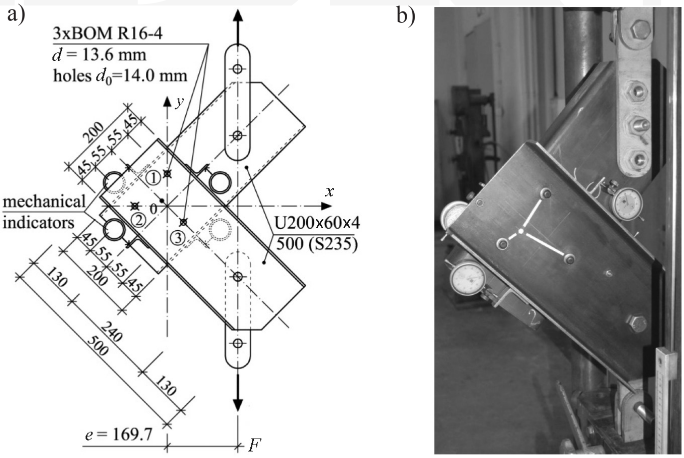

Fig. 8. Eccentrically loaded test element „V" with 3-bolt joint: a) geometry of the element, b) element anchored in testing machine

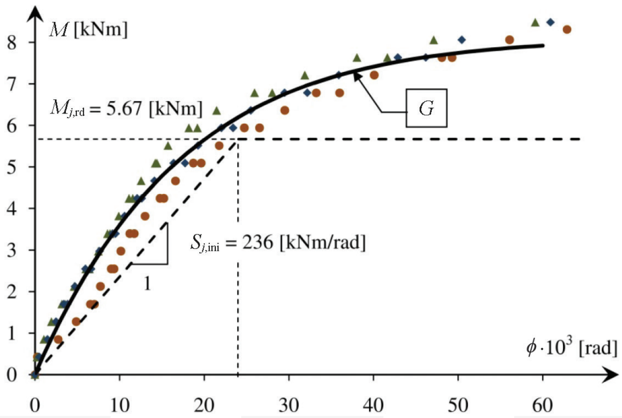

Fig. 9. Relation M-ϕ in eccentrically loaded test element "V" with a 3-bolt joint

3.4. Test elements in alternating bending

In the case of test elements in alternating bending, a similar behaviour of the joints as in elements alternately loaded axially was observed. For example, Fig. 10 shows the hysteresis loops of relation M–ϕ in two identical elements with 8-fastener joint [27, 36].

[27] contains the results obtained for identical test elements "X" with 4-fastener joint. Fig. 11 shows the hysteresis loops obtained in the two elements at the load level $M = \pm 10.86$ kNm, which does not exceed the resistance of the connection yet.

The shape of the curves shows a large difference in the stiffness of both joints, as well as certain permanent deformations (clearances) existing in the tested connection. It should be underlined that both elements were tested at different load cycle programs. Curve 1

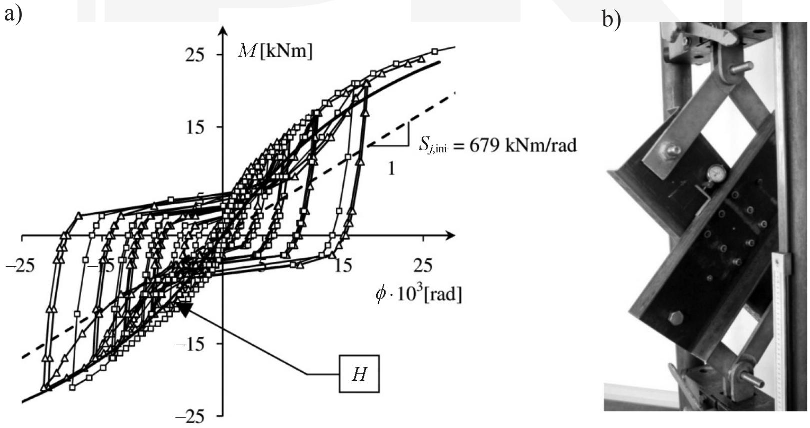

Fig. 10. Test element „X" with 8-fastener joint in alternating bending: a) relation M-ϕ, b) view of the element anchored in the testing machine

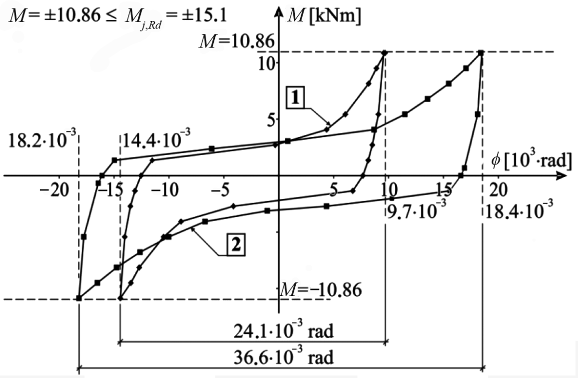

Fig. 11. Hysteresis loops in two identical test elements with 4-bolt joint with different load history

describes the behaviour of the connection, which first took over the load increases in the positive half cycles, and then in the opposite direction. While curve 2 corresponds to the growth of the load carried out alternately, once in the positive half cycles direction and next the negative. This may prove a significant influence of the history of alternating load on the behaviour of the tested joints. Issues related to the influence of alternating loads on the behaviour of the tested connections are discussed in more details in [36, 30].

3.5. Journal friction in single-cut joint

In simultaneously bend and shear joint – in the vicinity of each connector – exists friction, which causes a rise of torsional moments $M_{i,\phi}$ that oppose the mutual rotation ϕ of walls of connected members [4]. This phenomenon was tested on the example of test elements "O" with single fastener (Fig. 12a). These elements were tested on a properly constructed test stand (Fig. 12b), which allowed to establish the relationship between the torsional moment $M_{1,\phi}$ and angle of rotation ϕ of connected plates, at various values of shearing force F_1 acting on a single fastener. Relations $M_{1,\phi} - \phi$ have been designated for selected values of shearing force F_1 equal sequentially: 5 kN, 10 kN, 15 kN, 25 kN and 30 kN. For each value of $F_{1,}$ three to five identical test elements were investigated. Results of the investigations have been illustrated in the form of envelopes of paths of static equilibrium on the diagram $M_{1,\phi} - F_1 - \phi$ (Fig. 12c).

The value of the torsional moment $M_{1,\phi}$ increases with increasing shearing force F_1. The surface "K", which describes the physical relationship $M_{1,\phi} - F_1 - \phi$ defined as a product of two exponential functions, whose parameters were fitted to the results of investigations using the least squares method (see. Fig. 12c). Both galvanised and non-galvanised elements were tested, stating higher deformability of galvanised elements. On one galvanised test element, it was observed that the value of torsional moment changes in time, and after five days from the start of the test, it stabilises at about 60% of the initial value. Detailed information on the conduct of the test and its results are given in [4, 28].

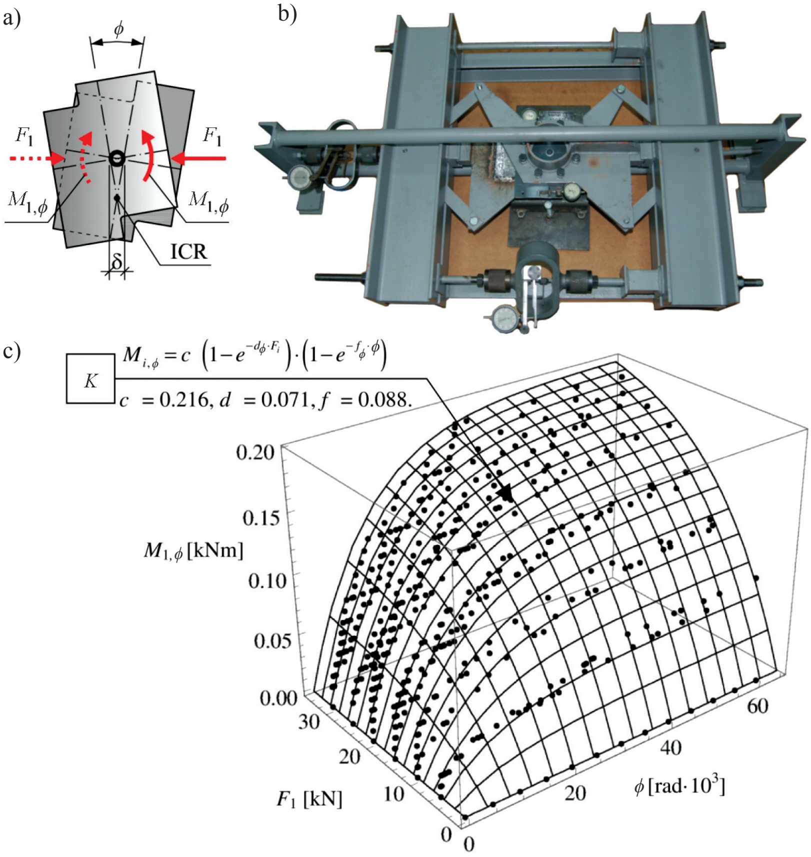

Fig. 12. Tests of journal friction: a) scheme of test element “O” (ICR – instantaneous centre of rotation), b) test stand, c) results of tests and surface describing relation $M_{1,\phi}$–F_1–ϕ

4. Calculation of any arbitrary lap joint in complex state of load

4.1. Scheme of any arbitrary single-cut joint

The method of calculating any arbitrary lap-joint loaded by transverse forces H and V and bending moment M (Fig. 13) are given in [27, 36] and extended in [28, 4], by introducing the torsional moments into the system of equilibrium equations. It was assumed that:

- connected plates with a thickness t_u and t_b are rigid bodies,
- deformations occur only in close vicinity of fasteners,
- initial distances between connectors are preserved,
- components of the load H, V and M are transmitted from the “upper” plate to “bottom” plate in the plane of contact via connectors,
- all the loads grow simultaneously and proportionally.

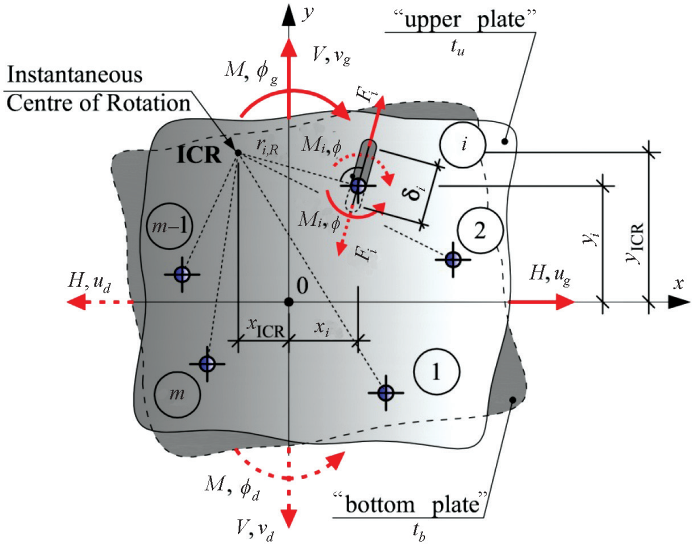

Fig. 13. Scheme of any arbitrary lap joint in a complex state of load

4.2. System of equilibrium equations

The behaviour of the joint describes a system of three equations of equilibrium [27, 36]:

$$H - \sum_{i=1}^{m} \frac{F_i}{\delta_i} \cdot (u - \phi \cdot y_i) = 0, \tag{1}$$

$$V - \sum_{i=1}^{m} \frac{F_i}{\delta_i} \cdot (v + \phi \cdot x_i) = 0, \tag{2}$$

$$M - \sum_{i=1}^{m} \frac{F_i}{\delta_i} \cdot \left[u \cdot y_i - v \cdot x_i - \left(x_i^2 + y_i^2 \right) \cdot \phi \right] + \sum_{i=1}^{m} M_{i,\phi} = 0, \tag{3}$$

and physical equations:

$$F_i = f(\delta_i), \tag{4}$$

$$M_{i,\phi} = f(F_i, \phi). \tag{5}$$

The mutual displacement of connected plates in the axes of individual connectors "*i*" describes the relationship:

$$\delta_i = \sqrt{(u - \phi \cdot y_i)^2 + (v + \phi \cdot x_i)^2}, \tag{6}$$

where the unknowns are the mutual displacements of joined plates u, v, ϕ and displacements δ_i in axes of individual fasteners.

A system of equations can be used to determine the coordinates of the instantaneous centre of rotation in the joint:

$$x_{\mathrm{ICR}} = -\frac{v}{\phi}, \tag{7}$$

$$y_{\mathrm{ICR}} = \frac{u}{\phi}. \tag{8}$$

The presented method of calculation has been verified experimentally, e.g. eccentrically loaded test elements (c.f. curve "G" in Fig. 9).

5. Resistance of single fastener

Tests of axially loaded elements showed that, as the load increases, the joints exhibit substantial plastic deformations (cf. Fig. 4). They are unacceptable, both for the reason of safety (ULS), as well as the serviceability of the structure (SLS). For this reason, as a reliable criterion for the bearing capacity, finally adopted load value corresponds to the limit displacement $\delta_{\mathrm{lim},1} = 3.0$ mm acc. to [31]. This choice is justified primarily by the results of tests of alternately loaded joints (see. Fig. 11) that occur at the nodes of trusses considered by the authors.

Bearing resistance of the BOM fasteners was determined initially on the basis of experimental tests, but in design practice, the appropriate formulae are required, which allow for its calculation, on the basis of physical parameters of the connection. Load capacity corresponding to the specified limit displacement can be determined based on the exponential function describing the relationship F_1–δ (cf. curves „C" and „D" in Fig. 4). Results for fifty-five axially loaded test elements "I" (see. Fig. 3) were analyzed. Searched for the relationship between the measured values of ultimate tensile strength f_u of steel of connected plates, thickness t of plates and diameter $d = d_0$ of the fastener and experimentally determined parameters a_F and b_F of exponential curves (cf. Fig. 4). Previous attempts for determining of those dependencies were published sequentially in [28] and [9]. The adopted dependencies are illustrated in (Fig. 14).

Note the very large dispersion of the value of parameter b_F; for the five theoretically the same test elements, this value can vary almost twice. It is associated with random geometrical imperfections (e.g. tolerance of hole diameter) and related to the technology of the fastener installation, and above all with slipping in the initial phase of load of the connection.

For the previously considered theoretical values of a_F i b_F defined on Fig. 14, and assuming $\delta_{\mathrm{lim},1} = 3.0$ mm, the resistance function may be denoted as:

$$F_R = \alpha_{bb} \cdot f_u \cdot d_0 \cdot t, \tag{9}$$

where:

$\alpha_{bb} = 1.76$ for $t/d_0 \geq 0.25$,
$\alpha_{bb} = 1.97$ for $t/d_0 < 0,25$.

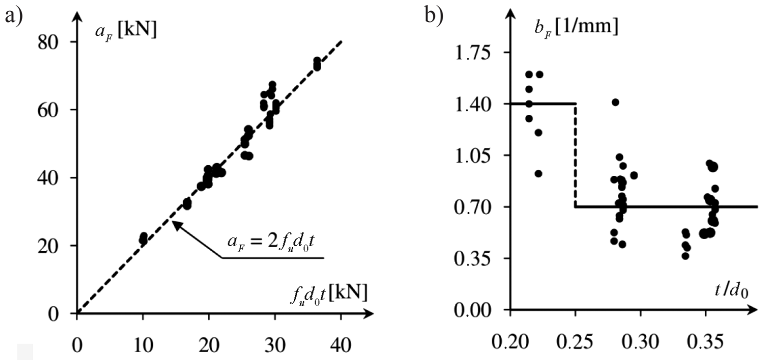

Fig. 14. Relation between physical parameters of the joints and parameters of exponential curves describing relation F_1–δ: a) relation $a_F - f_ud_0t$, b) $b_F - t/d_0$

Formula (9) includes connections of plates made of steel with f_u = (340÷540) MPa, of thickness t = (3÷5) mm and BOM R10 to BOM R16 fasteners installed in the holes with a diameter d_0 = (9÷14.5) mm.

Following the standard procedure [38], in Fig. 15 plotted diagram corresponding to the given there in Fig. D1. Coordinates of points plotted in Fig. 15 correspond: on the vertical axis, the the values of the bearing resistance r_e measured in individual test elements "I"; on horizontal axis, to the values of $r_t = F_R$, which were calculated based on the proposed formula (9) for the actual measured values of f_u, d_0 and t.

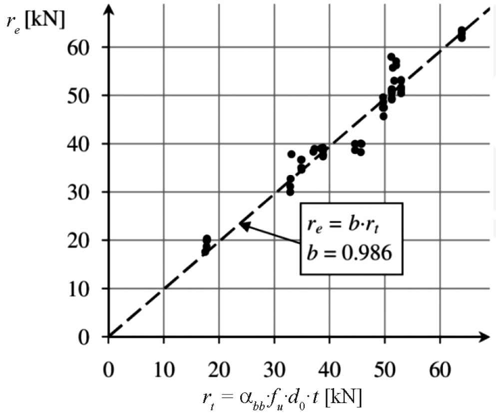

Fig. 15. Comparison of value of the bearing resistance calculated according to formula (9) and test results

The directional factor b = 0.986 of the straight dashed line was matched to the points shown on the diagram by the least squares method. The correlation coefficient of values r_e and $b \cdot r_t$ is 0.955. The proposed formula determines the mean value of the bearing resistance and still requires calibration according to the statistical procedure proposed in [38], in order to determine the characteristic value r_k.

The way of determining the resistance when a shear force acts on the fastener in an alternating manner requires a separate consideration. It may be necessary to introduce an additional correction factor into the resistance formula.

6. Stiffness of tested joints

High flexibility of the tested connections requires proper consideration in the static calculations of bar structures with such joints. Instantaneous translational stiffness $S_{\delta,m,inst}$ in the joint with m number of fasteners for any arbitrary value of deformation δ may be designated as derivative of exponential function describing the relation F_1–δ using the formula:

$$S_{\delta,m,\mathrm{inst}} = m\frac{dF_1}{d\delta} = m \cdot a_F \cdot b_F \cdot e^{-b_F \cdot \delta}, \tag{10}$$

while the rotational stiffness of the joint loaded only by the bending moment according to the formula:

$$S_{j,\mathrm{inst}} = \sum_{i=1}^{m} a_F \cdot b_F \cdot e^{-b_F \cdot r_i \cdot \phi} \cdot r_i^2, \tag{11}$$

where:

r_i – is a ray connecting axis of i-th fastener with the gravity centre of the fastener group,

ϕ – angle of rotation in the joint.

In the case when the connection is loaded simultaneously by the bending moment M and transverse forces H and V, occurring interaction relations between the stiffness assigned to the individual components of load [27, 36]. They can be taken into account by means of reduction factors υ, prepared on the basis of appropriately modified system of equations [39, 40]. These factors can be illustrated for the given joint in the form of the so-called contour plans prepared in a non-dimensional system of rectangular coordinates M/M_{gr} and W/W_{gr}, where W is resultant of shear forces H i V and M_{gr} and W_{gr} are, respectively, defined limit values of the bending moment and resultant shearing force. For example, Fig. 16a shows the contours of stiffness reduction factors for bending υ_M^{III} and shear υ_V^{III} for five fastener joint (Fig. 16b, cf. Fig. 7c), prepared for resultant force W inclined to y axis at an angle $\alpha_W = 0°$.

In [39] and [40] three cases of the limit state in a non-dimensional rectangular coordinate system M/M^{III}_{gr} and W/W^{III}_{gr} were considered. Case I refers to the situation where at least one fastener in the connection is loaded with a force equal to its design load resistance $F_{b,Rd}$; case II – when mutual deformation of connected plates in the place of most loaded fastener reaches the limit value $\delta_{\mathrm{lim},1} = 3.0$ mm; and case III – corresponds to the theoretical limit state when the load of all the fasteners reaches limit values. In [39, 40], the appropriate charts for α_W equal to 15°, 30° and 45° are given.

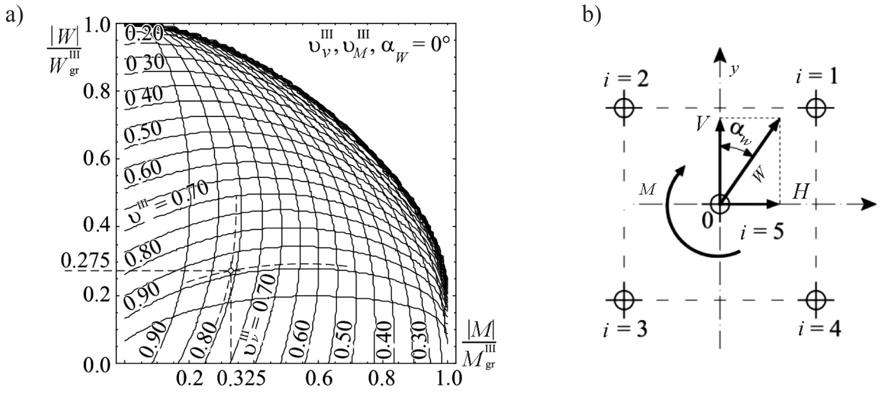

Fig. 16. Stiffness reduction coefficients for 5-bolt joint: a) contours of coefficients υ^{III}_{M} and υ^{III}_{V} when $\alpha_W = 0°$, b) geometry of 5-bolt joint

Preparing a set of contour plans for several typical joints in the future would be a very useful tool in the design of connections in the case of more advanced engineering analysis. In the elementary cases, the method described in [35] may be also used, which is based on the stiffness coefficients of the component parts of the joint shown in section 1–8 of Eurocode 3 [15].

7. Examples of structures

To find out about the rationality of the adopted solutions, the results of experimental and analytical investigations have been used for the design of light lattice frames. For example, the structure of a single storey building with a span of 24 m has been described (Fig. 17), in which the main frames have been spaced at intervals of 4.5 m.

The proposed purlinless roof structure has a single-span trapezoidal plate sheeting supported directly on the upper chords of lattice girders. Stability in the longitudinal direction is provided by a steel sheet diaphragm in the plane of the roof slope together with the vertical and wall bracings. The web members have been connected with the chords eccentrically, with the eccentricity of 125 to 250 mm, without gusset plates.

The following actions have been taken into account: self weight, standard snow and wind load. The static-strength calculations of the frame, have been carried out in a few iterative steps. Results for the two cases have been compared:

- the first, when for the joints introduced values of the instantaneous stiffness defined analytically by formulae (10) and (11), taking into account the interaction relationships (see. Fig. 16),
- the second, when the rigidity have been determined based on the bi-linear relationships and determined by the component method (cf. Fig. 6 and 9).

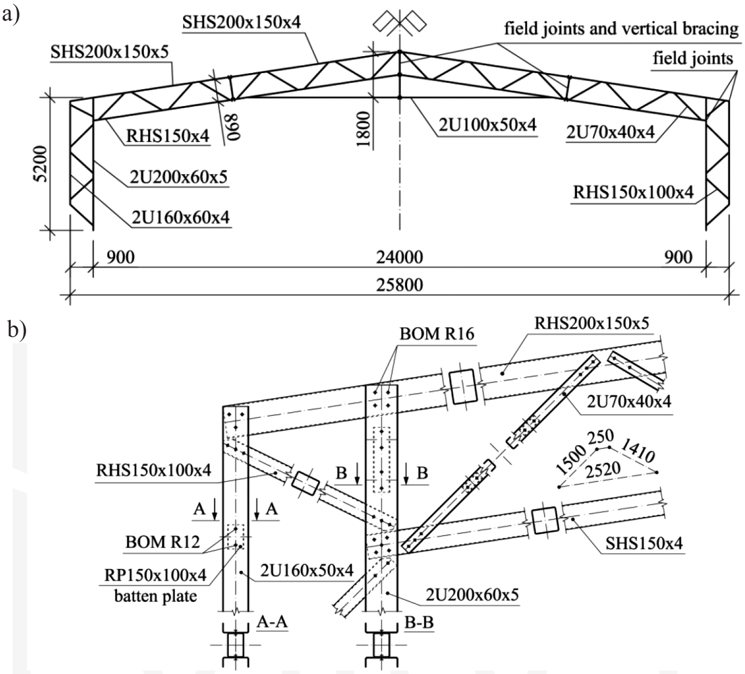

Fig. 17. Latticed frame with a span 24 m: a) geometry of the frame, b) structure of the corner

Figure 18, in the geometric outline of the frame corner, illustrates the diagrams of the bending moments prepared assuming the rigid joints (solid line limiting hatched field) and semi-rigid (dashed line) – when the rigidity determined on the basis of formulae (10) and (11), taking into account interaction coefficients υ_M and υ_W (cf. Fig. 16a), semi-rigid (solid line) – when the stiffness was determined by [35]. On the graph, percentage changes in the value of bending moments have been shown based on calculations for the frame with semi-rigid joints relative to the frame with rigid joints.

As shown in [26], the presented structure meets the appropriate criteria for load capacity and serviceability given in Eurocode 3, and its weight does not exceed 0.2 kN/m^2, which can justify the practical application of the described technology. However, it should be noted that the analysis did not take into account the effects related to the alternating action e.g. of the wind, which causes that the behaviour of the given joint will be described by an appropriate hysteresis loops. The calculation of such a structure requires the development of appropriate procedures, including incremental load and deformation analysis [34]. Then, the internal forces in the respective members and displacement of nodes may vary considerably from the case in which the loads acting in only one direction [41] and the use of linear relationships describing the stiffness of joints – proposed in [35] – may be a too simplified approach. To describe the behaviour of the structure loaded alternately, it is necessary to develop an experimentally verified way of prediction of hysteresis loops for joints in a complex load conditions and to create a procedure for calculating them, taking into account the relevant criteria of load capacity and serviceability [30].

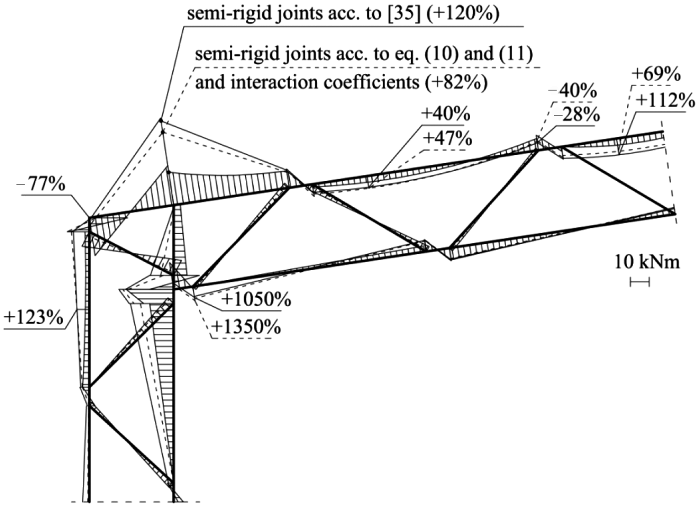

Fig. 18. Diagrams of bending moment in corner of latticed frame (description in text)

8. Conclusions

The presented fastening technology of cold-formed steel sections allows for easy, quick and efficient erection of lightweight and economical structures, which meet the principles of sustainable development. The main issues in the considered structures are values of resistances and stiffness of joints adopted in the static calculations of any arbitrary bar systems, which significantly determine their behaviour.

Characteristic dispersion of results occurring during the tests of elements are caused by the inherent imperfections in the nodes, as well as the load history. It obliges to determine in the future of appropriate safety factors in the design of bar structures with the tested flexible joints.

Received results of the joints tests – on test elements loaded in one direction – are in accordance with the values calculated using the proposed formulae for the bearing capacity and the translational and rotational stiffness of the joints. The bearing resistance formula still requires calibration according to EN 1990 in order to establish the characteristic value.

In the actual structures loaded alternately, much larger permanent displacements occurring in the joints should be considered. They change with the increase and the number of the alternate load cycles, causing specified clearances in the joint.

The intention of the authors of this article is to propose a structural system of lightweight cold-formed steel buildings, which will require the future development of more detailed structural solutions as well as additional studies.

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