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ISSUES OF ALTERNATING LOAD IN DESIGN OF COLD-FORMED STEEL FRAMES WITH LAP JOINTS

The paper raises the issues of alternating loads in designing of cold-formed steel frames with blind bolt lap joints. Based on own research and information found in the literature pointed out the need to develop the procedures for calculating such connections, taking into account their actual behaviour, i.e. according to proper hysteresis loops. Presented also the method of determining of nonlinear force-displacement (F-δ) and moment-rotation (M-ϕ) characteristics describing the behaviour of a single-cut connections of cold-formed sections with blind fasteners of the type BOM [1], loaded in one direction. The proposed formulas are based on previously unpublished research results and allow for determination of mentioned dependencies on the basis of selected physical parameters of such connections. The curves of the relationships F-δ and M-ϕ obtained from the proposed formulas were compared in graphs with experimental curves obtained during the tests of elements in which connections has been loaded in both one direction and alternately. As a conclusion, the predicted directions for further research are presented.

Keywords: cold-formed steel frames, lap joints, blind fasteners, alternating load, semi-rigid joints, stiffness of joints

1. Introduction

Lap joints with mechanical fasteners in cold-formed steel frames are characterized by a significant degree of flexibility, which was repeatedly ascertained by the national [2, 3, 4, 5, 6] and foreign [7, 8] studies. For this reason, in the static calculations of such structures, rigidity of the joints with connections loaded by axial forces in bars and bending moments on their ends, can be taken into account, preferably, on the basis of experimentally

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obtained force-displacement and moment-rotation relationships, which changes non-linearly under load. It should be noted, that in the previous attempts of design of frames ignores the fact that the wind load may act alternately, from two opposite directions. Then the effects of variable actions will be imposed on the effects of existing permanent load and the effects of pre-existing variable load cycles [9]. The behavior of a given joint in a frame structure will be described by proper hysteresis loops, and its calculations will require to develop appropriate procedures, including incremental load and deformation analysis [10]. Then, the internal forces in the respective bars and displacements in the joints may significantly differ from the case in which the horizontal wind load acts only in one direction [11]. It was estimated that the differences between internal forces in the frame with rigid and semi-rigid joints may then exceed at least 20% [12]. If, however, additionally takes into account the impact of alternating action of the wind, further changes in forces have to be expected, reaching also 20% [11]. In such cases the use of linear relationships describing the rigidity of the joints – proposed in EC3 [13] and [14] may be too simplistic because, the calculation results may not reflect the actual behavior of the structure. Therefore, to describe the behavior of the alternately loaded structure, it is necessary to provide an experimentally verified method of prediction of hysteresis loops for connections in a complex load state and to create a procedure for calculating them, taking into account the relevant criteria of bearing capacity and serviceability.

The paper presents a method of determining the nonlinear $F–\delta$ and $M–\phi$ characteristics based on the selected physical parameters of the tested connections loaded in only one direction: the actual diameter of the fastener d_0, equal after installation to the diameter of the hole, thickness t of the connected sheets and their ultimate tensile strength f_u. Proposed formulas are modified comparing to [15], because additional unpublished results of tests have been taken into account. The range of the study includes joints whose parameters are within the ranges: d_0 = (9,0÷14,3) mm, t = (3,0÷5,0) mm, f_u = (350÷550) MPa. Curves of the relationships $F–\delta$ and $M–\phi$ obtained from the proposed formulas were compared on the graphs with the experimental curves obtained during the tests of the elements in which connections were in the complex state of load acting either in one direction or alternately.

2. Tests of relationship F-δ

The physical relationship between the force F_1 shearing a single connector and the mutual displacement δ of the connected sheets were determined experimentally by testing of axially loaded elements of type "I" (Fig. 1a), in which the sheets of the cold-formed sections with a thickness of 3, 4 and 5 mm were connected by blind fasteners of the type BOM.

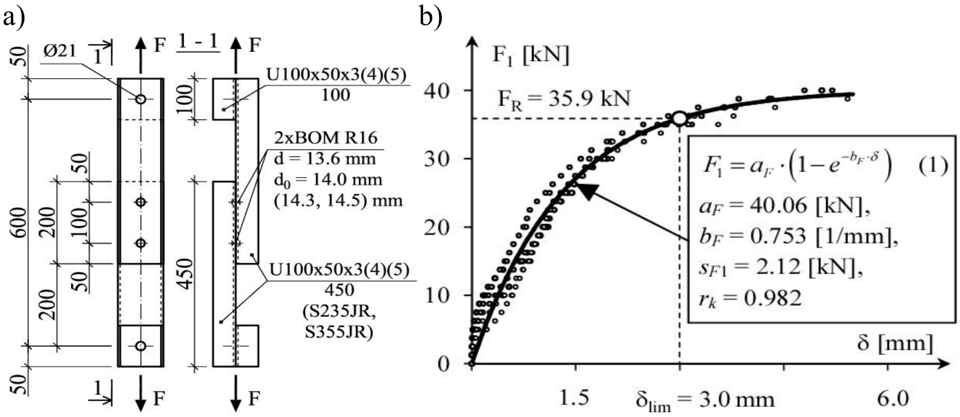

Fig. 1. Testing of F_1-δ relationship: a) test element „I", b) diagram of the relationship F_1-δ in test elements group S4

Rys. 1. Zależność F_1-δ : a) próbka do badań „I", b) wykres zależności F_1-δ próbki z grupy S4

Fig. 1b shows example of envelopes of paths of static equilibrium F_1–δ in the five identical test elements, in which the sheets made of steel with f_u = 343,0 MPa and thickness t = 4,06 mm were connected by means of the two fasteners BOM R16-4 installed in the holes with a diameter d_0 = 14,3 mm. On the diagram the value of the limit displacement δ_{lim} = 3,0 mm has been marked, for which according to [16], corresponds the bearing resistance of a single connector F_R = 35,9 kN. Relationship F_1–δ can be described by an exponential function (1) (see Fig. 1b), and its parameters can be associated with the physical parameters of the tested joint as shown in [15].

Table 1. Physical parameters of tested elements of the type "I"

Tabela 1. Fizyczne paramety próbek badawczych typu "I"

No	Group	Number of tests	Fastener type	f_u 1) [MPa]	d_0 1) [mm]	t 1,2) [mm]	t/d_0
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	S3.1	5	BOM R10-4	352,5	9,0	3,18	0,35
2	S3.2	3	BOM R16-4	368,0	14,3	3,17	0,22
3	S4	5	BOM R16-4	343,0	14,3	4,06	0,28
4	S4OC	5	BOM R16-4	364,6	14,0	4,03	0,29
5	S5	5	BOM R16-6	402,3	14,5	4,86	0,36
6	W4	6	BOM R16-4	444,7	14,3	4,05	0,28
7	W5	5	BOM R16-6	423,5	14,0	4,97	0,36
8	K4 3)	6	BOM R16-6	537,2	14,0	4,01	0,29
9	KSW3	5	BOM R16-4	469,0	14,0	3,00	0,21
10	KSW4	5	BOM R16-4	521,7	14,0	4,00	0,29
11	KSW5	5	BOM R16-6	520,3	14,0	5,00	0,36

1)average measured value for group of test elements, 2)actual average core thickness of the material, 3)acc. to [17]

In this paper included new results obtained for joints of the sheets with the steel grade S355JR, and results of the similar investigations conducted by Słowiński [17] in the elements with a slightly different structure. Total of fifty five tests results have been analyzed, in eleven different groups of the joints, the parameters of which are summarized in the table 1.

Fig. 2 shows the graphs which illustrate the relationship between the physical parameters measured in the construction of the tested joints and the parameters of the exponential function (1) obtained on the basis of the tests of elements "I". The inclusion of more test results obligate to modification of the proposals put forward in [15]. In the formula determining there the value of a_F currently omitted coefficient $z = (390/f_u)^{0,5}$, which according to [7] should be used for $f_u \geq 390$ MPa; consideration of this coefficient resulted, for some new elements, a substantial increase in scatter. In [15] the value of b_F determined according to the initial translational stiffness of the connection, which would be a characteristic value for the given joint. New research results did not confirm this assumption; it turned out that this method requires experimental determination of the stiffness for each group with slightly different physical parameters. Finally, it was decided to join the value of b_F with the ratio of the thickness t of the thinner of the connected sheets to the diameter of the hole d_0, that expresses the influence of tilt of the fastener observed in single-cut connections on the stiffness of the joint. Due to the considerable dispersion of the value of b_F specified for individual elements, and still insufficient number of the tests decided initially to adopt two different values of this parameter equal to 1.4 [1/mm] for $t / d_0 < 0.25$ and 0.7 [1/mm] for $t / d_0 \geq 0.25$ (see. Fig. 2b).

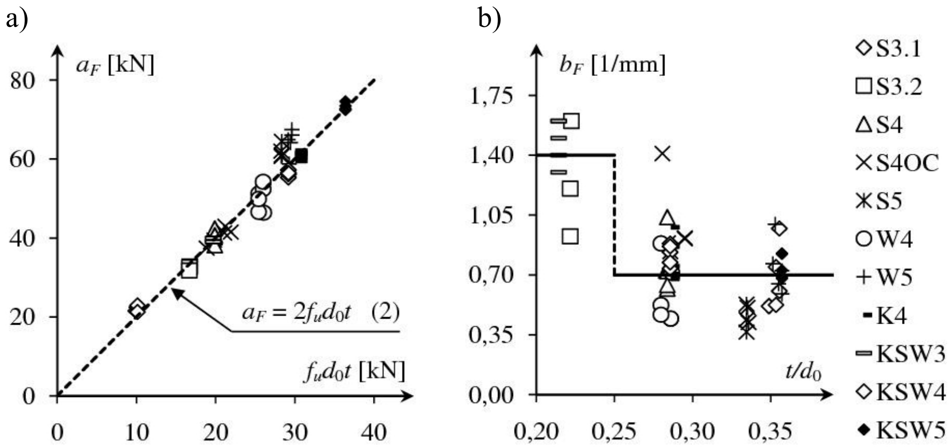

Fig. 2. Relationships between physical parameters of tested joints and values of the parameters of exponential function describing the F_1-δ relation: a) relation a_F - $f_u \cdot d_0 \cdot t$, b) relation b_F - t/d_0; compare in [15]

Rys. 2. Zależność między fizycznymi parametrami badanego połączenia i funkcji wykładniczej opisującej zaleność F_1-δ: a) zależność a_F - $f_u \cdot d_0 \cdot t$, b) zależność b_F - t/d_0 [15].

Figures 3÷6 show the graphs F_1–δ, on which the points lying on the envelopes of the paths of static equilibrium obtained in the experimental tests of selected groups of the joints can be compared with the exponential curves, determined on the basis of the proposed relations. In the graphs broken dashed lines correspond to the translational stiffness $S_{\delta,1}$ calculated according to the formulas proposed in [14], which were developed on the basis of the stiffness coefficients of the components of the joint specified in [18]. Horizontal part of the dashed line corresponds to the design resistance $F_{b\,Rd}$, determined by [16].

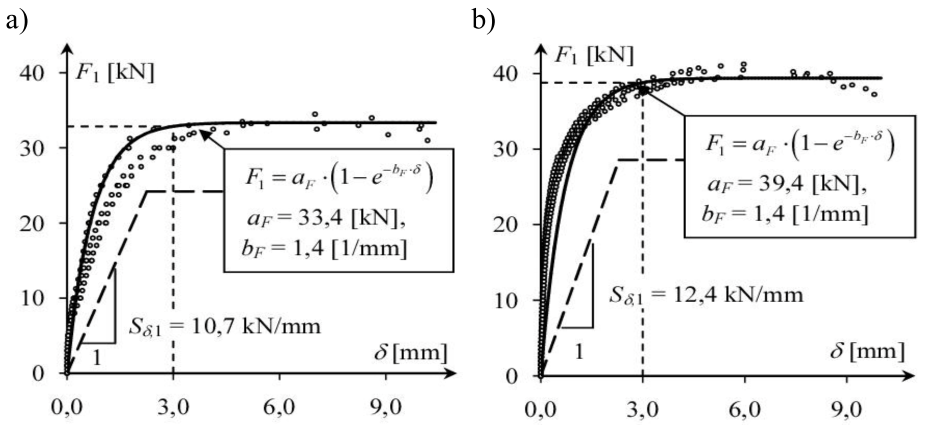

Fig. 3. Comparison of the actual and theoretical relations F_1-δ in groups: a) of test elements S32, b) of test elements KSW3

Rys. 3. Porównanie rzeczywistej i teoretycznej zależności F_1-δ grup: a) próbka badawcza S32, b) próbka badawcza KSW3

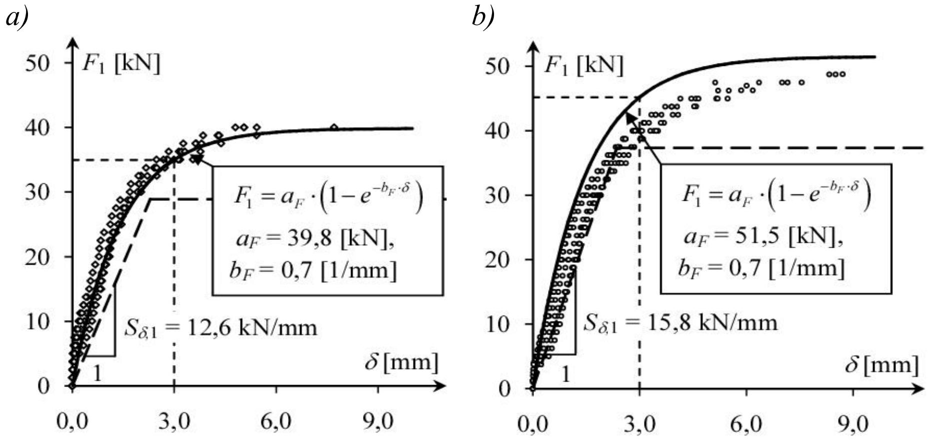

Fig. 4. Comparison of the actual and theoretical relations F_1-δ in groups of test elements "I": a) S4, b) W4,

Rys. 4. Porównanie rzeczywistej i teoretycznej zależności F_1-δ dla grup elementów badanych „I": a) S4, b) W4

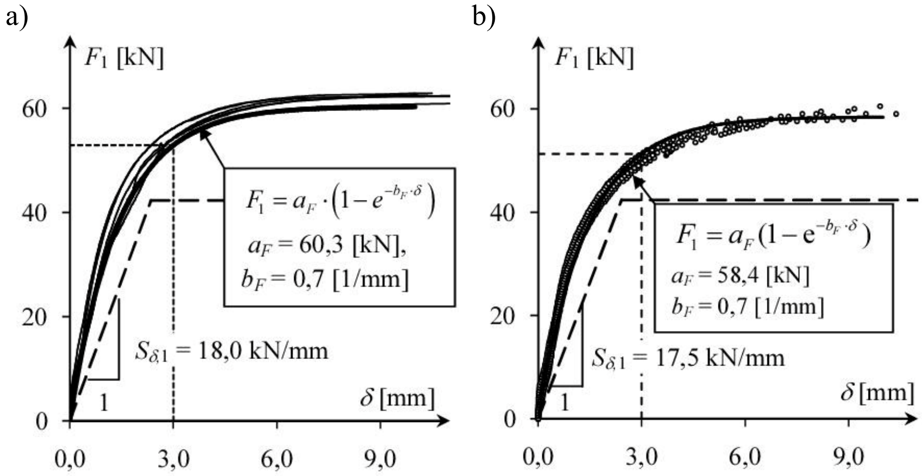

Fig. 5. Comparison of the actual and theoretical relations F_1-δ in groups of test elements "I": a) K4, b) KSW4

Rys. 5. Porównanie rzeczywistej i teoretycznej zależności F_1-δ dla grup elementów badanych „I": a) K4, b) KSW4

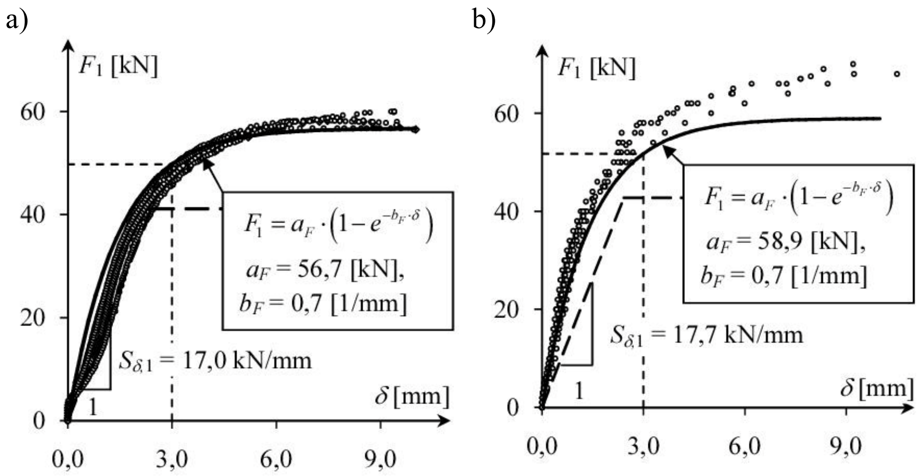

Fig. 6. Comparison of the actual and theoretical relations F_1-δ in groups of test elements "I": a) S5, b) W5

Rys. 6. Porównanie rzeczywistej i teoretycznej zależności F_1-δ dla grup elementów badanych „I": a) S5, b) W5

It should be noted that the stiffness calculated according to the method proposed in the EC3 with a large safety margin describe the behavior of a joints loaded in one direction, covering "from below" the characteristic dispersion of the experimental results.

Fig. 7 shows the graph illustrating the hysteresis loops of the relation F_1–δ in two identical test elements "In" loaded alternately [12], with the same physical parameters as the group of the test elements W5 (cf. Table. 1).

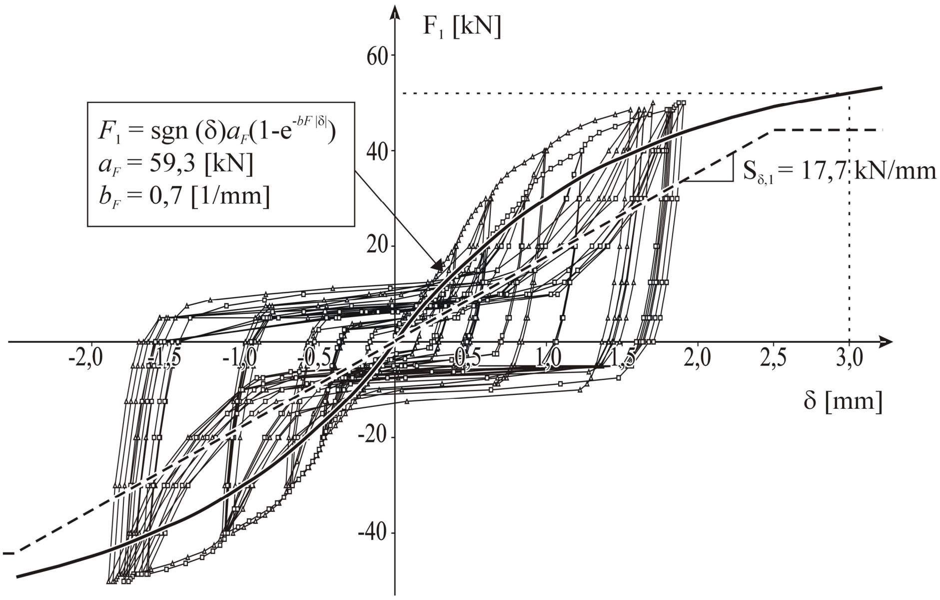

Fig. 7. Comparison of the actual and theoretical relation F_1-δ in two identical alternately loaded elements "In"

Rys. 7. Porównanie rzeczywistej i teoretycznej zależności F_1-δ w dwóch jednakowo naprzemiennie obciążonych elementach „In"

Note that the stiffness observed immediately after the change of the sign of the load is very low, as well as the increase of the permanent deformation in his subsequent cycles. The main question is how to determine the carrying capacity of the connection in this case. It should be noted that in ECCS Recommendations [16], where given the criterion related to the limit deformation δ_{lim} = 3.0 mm, considered only the case of connections loaded in one direction.

Comparing the shape of the hysteresis loops with an exponential curve can be stated, that on the given level of the load deformations in the actual alternately loaded connection are visibly smaller than is apparent from the theoretical predictions for the loads carried in one direction. Here, in each subsequent cycle the load increase in one direction to a certain value, then change the direction until it reaches the same value of opposite sign. Plastic deformations of the sheets in the place of the contact with the connectors, occurring then alternately and changes in the structure of the material of the connected sheets related with this, may cause increase of the stiffness of the connection. Consequently, the impact of load history on the behavior of the connection should be investigated. It would be expedient to make the program of the load of test elements corresponded to the history of the load occurring in a typical bar structure, where the forces reach firstly the values corresponding to the permanent actions and then changing alternately in the specified range as a result of variable actions.

3. Tests of relationship *M*-ϕ

The method of calculation of any arbitrary single-cut lap joint loaded simultaneously by bending moment M and shearing forces H and V is presented in [12]. The system of equilibrium equations proposed there included also the physical relationship between the shear force F_i acting on the i-th connector in the joint and the mutual displacement δ_i occurring in its axis between connected sheets, which is described using exponential function (1) (see. Fig. 1b). Dependencies presented in section 2 were used when formulating the systems of equations that describe the behavior of several joints with different numbers of the connectors. The eccentrically loaded elements "V" and alternately bent element "X" were tested, whose parameters are summarized in Table 2.

Table 2. Physical parameters of tested elements of the type “V” and “X”

Tabela 2. Fizyczne paramety próbek badawczych typu “V” i “X”

No	Group	Number of tests	Fastener type	f_u [1)] [MPa]	d_0 [1)] [mm]	t [1,2)] [mm]	t/d_0
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
1	V33	3	BOM R10-4	350,0	9,0	3,0	0,33
2	V34	5	BOM R16-4	368,0	14,3	4,0	0,29
3	V35	3	BOM R16-6	343,0	14,0	5,0	0,36
4	V4	3	BOM R16-4	364,6	14,3	4,0	0,29
5	X8	2	BOM R16-6	402,3	14,0	5,0	0,36

[1)]average measured value for group of test elements, [2)]actual average core thickness of the material

Figures 8÷11 shows a view of the elements installed in the testing machine, and the graphs, on which envelopes of the paths of static equilibrium M–ϕ obtained experimentally can be compared with the curves obtained on the basis of solution of the appropriate systems of equations. These results can be compared with the two-section dashed lines. First section of the broken line corresponds to the initial rotational stiffness $S_{j,ini}$ of the joint, which was calculated according to the formulas given in [14], developed on the basis of the component method [18]. Horizontal section corresponds to the resistance of the connection, which results from a bearing capacity $F_{b,Rd}$ reached by the most loaded connector.

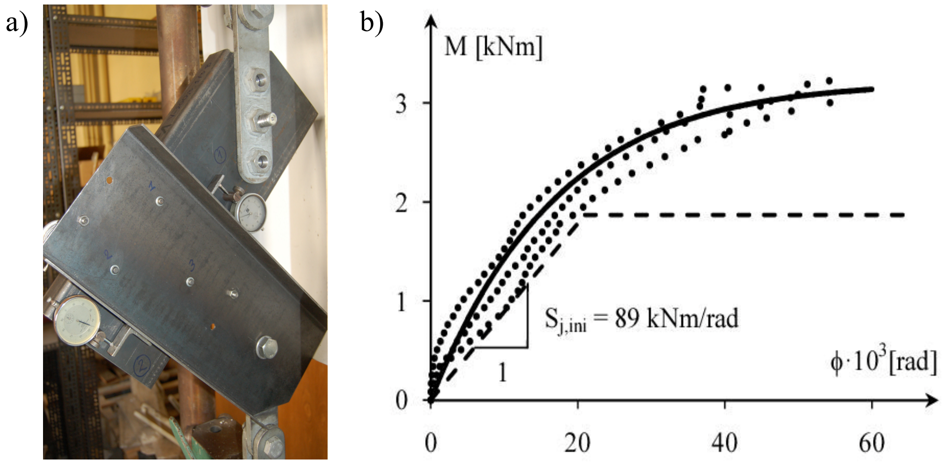

Fig. 8. Tests of eccentrically loaded elements of group V33: a) view of the test element anchored in the testing machine, b) comparison of the actual and theoretical relation *M*-ϕ

Rys. 8. Badanie mimośrodowo obciążonych elementów grupy V33: a) widok próbki zamocowanej w maszynie wytrzymałościowej, b) porównanie rzeczywistej i teoretycznej zależności *M*-ϕ

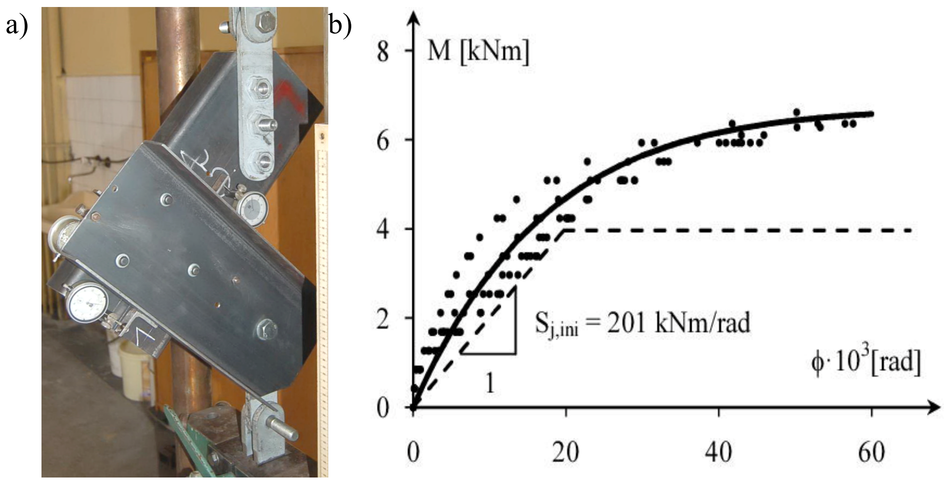

Fig. 9. Tests of eccentrically loaded elements of group V34: a) view of the test element anchored in the testing machine, b) comparison of the actual and theoretical relation *M*-ϕ

Rys. 9. Badanie mimośrodowo obciążonych elementów grupy V33: a) widok próbki zamocowanej w maszynie wytrzymałościowej, b) porównanie rzeczywistej i teoretycznej zależności *M*-ϕ

a) b)

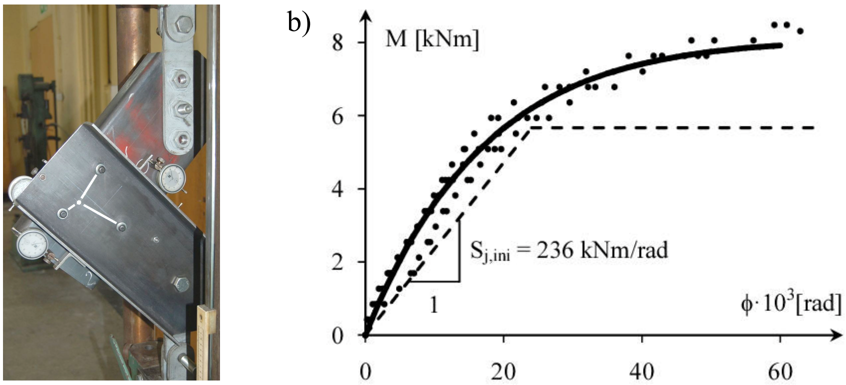

Fig. 10. Tests of eccentrically loaded elements of group V35: a) view of the test element anchored in the testing machine, b) comparison of the actual and theoretical relation *M-ϕ*

Rys. 10. Badanie mimośrodowo obciążonych elementów grupy V33: a) widok próbki zamocowanej w maszynie wytrzymałościowej, b) porównanie rzeczywistej i teoretycznej zależności *M-ϕ*

a) b)

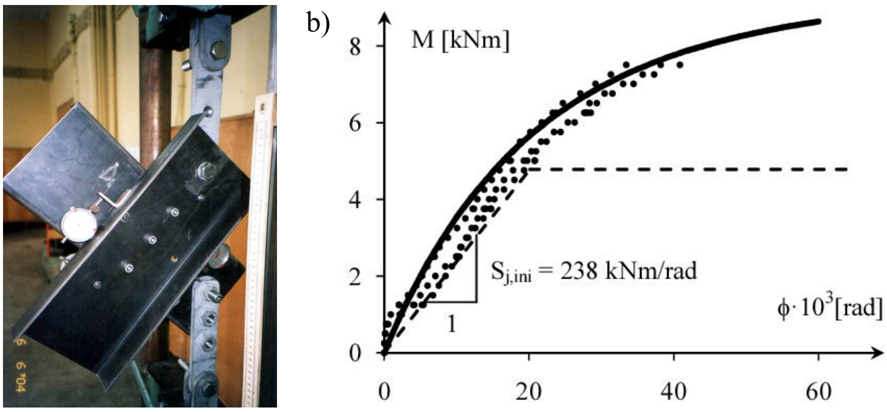

Fig. 11. Tests of eccentrically loaded elements of group V4: a) view of the test element anchored in the testing machine, b) comparison of the actual and theoretical relation *M-ϕ*

Rys. 11. Badanie mimośrodowo obciążonych elementów grupy V4: a) widok próbki zamocowanej w maszynie wytrzymałościowej, b) porównanie rzeczywistej i teoretycznej zależności *M-ϕ*

Similarly as observed in the tests of the elements "In", also here alternately bended joint (Fig. 12) proved to be stiffer than is shown by the theoretical curve *M–ϕ*. This difference is more distinct in the direction of the positive half-cycle of the load, which was performed first. Can also be noted, that the compliance of the course of the hysteresis loops in the two identical test elements "X" is greater than the elements "In" (see. Fig. 7). This may be the result of a larger number of the connectors and thereby lower sensitivity of the 8-fastener joint to the imperfections associated with the technology of their installation and drilling accuracy, ie. their lower deformability.

a) b)

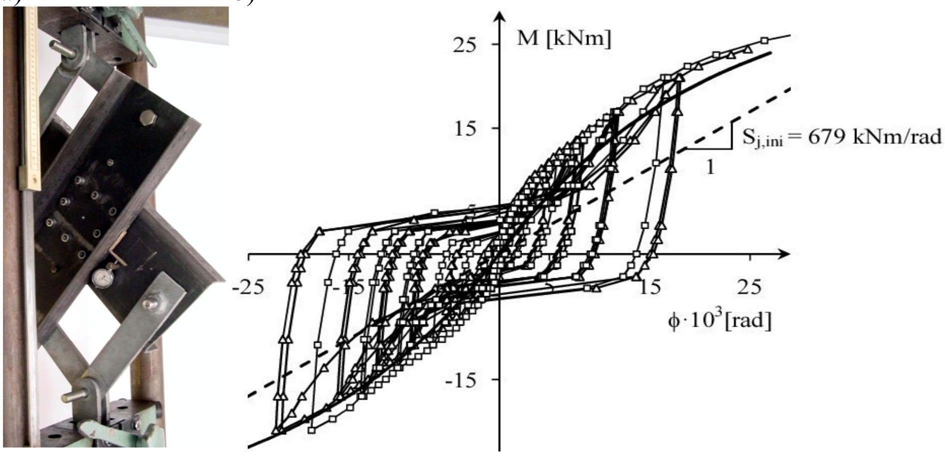

Fig. 12. Tests of alternately bent elements of group X8: a) view of the test element anchored in the testing machine, b) comparison of the actual and theoretical relation M-ϕ

Rys. 12. Badania naprzemiennie zginanych elementów grupy X8: a) widok próbki zamocowanej w maszynie wytrzymałościowej, b) porównanie rzeczywistej i teoretycznej zależności M-ϕ

In [12] contains the results for the identical test elements "X" with the four bolt connection. Fig. 13 shows the hysteresis loops obtained in the two elements at the load $M = \pm$ 10.86 kNm, lower than the resistance of the connection. The shape of the curves indicates a large differences in stiffness of both joints, however it should be emphasized that the both elements were tested at different load cycles programs. Curve 1 describes the behavior of the connection that first took over the load increases towards the positive half cycles, and then in the opposite direction. While curve 2 - corresponds to the load increases realized alternately, once in the positive half cycles direction and next the negative. This may prove a significant influence of the history of the alternating load on the behavior of the investigated joints.

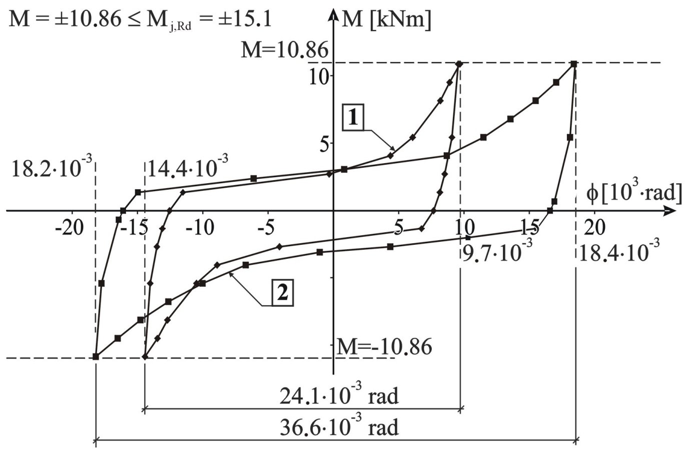

Fig. 13. Hysteresis loops in two identical test elements with 4-bolt joint with different load history [12]

Rys. 13. Pętle histerezy dwóch identycznych badanych elementów z węzłami 4-śrubowymi o różnej historii obciążenia [12]

4. Summary

In the case of the joints loaded in one direction the proposed formulas allow for a relatively precise prediction of the characteristics $F–\delta$ and $M–\phi$ of the investigated connections. The way of determining the b_F parameter (see. Fig. 2b) requires more accurate method, which leads to the additional testing of the axially loaded elements at different ratios t/d_0.

For the joints loaded alternately the determination of the impact of the load history on their behavior in the bar structures with the considered joints need to be taken. There is a need to adopt appropriate depending allowing for describe of the course of hysteresis loops in the joint loaded first by permanent and next by the variable action. May prove useful models specified in [10] or a method proposed in [19] for the single-cut bolted connections of the cold-formed sections.

The further studies should be planned for a wider recognition of the impact of alternating loads on the behavior of a bar structures with joints in a complex load state, in which BOM fasteners are used. The aim of the research is to obtain the method of determining the characteristics of such nodes in the form of appropriate simplified hysteresis loops in order to obtain a basis for the adoption of appropriate criteria for the carrying capacity and deformability of the connections. It will be necessary to develop the design procedures, because most of the available software for engineering calculations does not allow for the incremental load and deformation analysis, which is required when designing the alternately loaded structures.

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PROBLEMY OBCIĄŻEŃ ZMIENNOZNAKOWYCH W PROJEKTOWANIU RAM STALOWYCH Z KSZTAŁTOWNIKÓW ZIMNOGIĘTYCH Z POŁĄCZENIAMI ZAKŁADKOWYMI

Artykuł przedstawia kwestie obciążeń zmiennych w projektowaniu ram z zimnogiętych kształtowników stalowych, łączonych na zakryte połączenia zakładkowe śrubowe. Na podstawie badań własnych i informacji literaturowej wskazano potrzebę udoskonalenia procedury dla obliczania takich połączeń, biorąc pod uwagę ich rzeczywiste zachowanie, t.j. zgodnie z właściwymi pętlami histerezy. Przedstawiono również metodę określania nieliniowej charakterystyki siła - odkształcenie (F- δ) i moment - obrót (M- ϕ) opisujących zachowanie się jednociętych złączy kształtowników zimnogiętych na zakryte łączniki typu BOM [1], obciążone jednokierunkowo. Zaproponowane formuły oparto na wcześniejszych niepublikowanych wynikach badań i pozwalają na określenie zależności na podstawie wybranych parametrów fizycznych takich połączeń. Krzywe zależności F- δ i M- ϕ uzyskane z proponowanych wzorów porównano z krzywymi otrzymanymi z badań doświadczalnych, w których połączenia były obciążone zarówno jednokierunkowo jak i naprzemiennie. Na zakończenie zaprezentowano kierunki dalszych badań

Słowa kluczowe: ramy stalowe z kształtowników zimnogiętych, połączenia zakładkowe, łączniki zakryte, obciążenie naprzemienne, węzły półsztywne, sztywność węzłów

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