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DESIGN ASSISTED BY TESTING OF COLD FORMED STEEL TRUSSES

BY

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The paper presents the experimental programme developed in the Laboratory of Civil Engineering Faculty of the "Politehnica" University of Timişoara, Romania, in order to establish the real behaviour of bolted connections in cold formed steel trusses. First, the semi-rigid behaviour of cold formed steel truss joints is demonstrated by means of tests of typical T joints. A formula for the axial rigidity of single lap joint is determined, and, based on this formula, theoretical models are proposed for the rotational rigidity of cold formed steel truss bolted joints. In the third step of the experimental programme, a cold formed steel truss is tested, in order to observe the structural behaviour of joints and to validate the theoretical assumptions. A numerical analysis of the tested structure is also performed, and comparisons with the experimental results are given.

1. Introduction

Cold-formed steel trusses are frequently used in industrial and residential buildings, mainly as roof structures. The truss members are joined with bolts and screws, or using multiple press joined or "Rosette" type connections. For medium and large span trusses, bolted connections are usually recommended. Concerning the joints behaviour of this type of trusses, usually they are with eccentrical connections, and this feature must be taken into account in the global analysis. The use of 2, 3 or 4 bolts on each flange of the diagonal members, and accounting for their slenderness, is supposed to modify the assumption of pinned joints, generally accepted in case of trusses. The real behaviour of joints, in this case, is semi-rigid with partial moment resistance, which has as effect a favourable reduction in the buckling length of diagonals, but in the same time, due to the rigidity and eccentricities of connections, it induces supplementary bending moments in members. In order to estimate the performance of bolted joints in cold-formed steel trusses, an extensive research programme was developed in the Laboratory of Steel Structures of the "Politehnica" University of Timişoara.

2. Experimental Evidence of Joint Semi-rigidity

To evaluate the bending moment – rotation curve, ten T joint specimens were tested. The results of this phase of the experimental programme were presented in detail by Dubina and Zaharia ([2],...,[4], [10]). For chord, lipped channel profiles of 140 mm height, with thicknesses of 3 and 4 mm were used. For diagonal, 80 mm height lipped channel profiles were used with thicknesses of 2, 3 and 4 mm. The mechanical characteristics of the steel for profiles are corresponding to OL52 steel type, according to Romanian standards. The tested specimens are shown in Fig. 1, and the testing arrangement, in Fig. 2.

Two inclinometers, I_1 and I_2, were placed on the diagonal, in order to measure its rotation, one on the axis of the connection, and the second on the face of the chord.

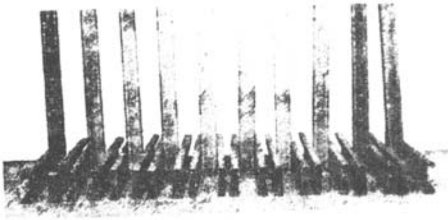

Fig. 1.- T joint specimens.

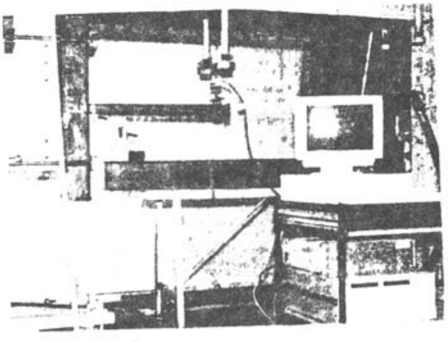

Fig. 2.- T specimen in testing.

Fig. 3 shows a typical experimental bending moment – rotation curve, for one of the tested joints, compared with the Eurocode 3 boundary for rigid full resistant beam-to-column connection in a braced frame [6].

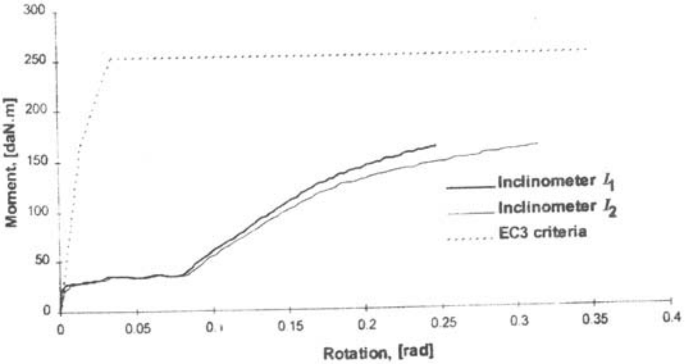

Fig. 3.- Experimental bending moment *vs.* rotation curves.

From the tests, for all specimens, it was concluded that the rotational flexibility is mainly due to the bearing work of the bolts, considering both the elastic and plastic deformations of the bolt holes. The differences introduced by the local deformations of connected members (the values corresponding to inclinometer I_2) were generally small. Consequently, the rotational rigidity of the joint can be evaluated if the axial rigidity of the relevant single lap bolted connection in shear is known. If the initial rotational slippage is neglected, then, according to Eurocode 3, all tested joints can be classified as semi-rigid and partial moment resisting. In fact, the triangulated shape of truss, which is geometrically and kinetically stable, and the presence of the axial forces in connected members prevent, or limit, at least, the initial rotational slippage in joint. In order to provide the evidence of this assumption, a cold-formed steel truss is tested in the third step of this experimental programme.

3. Axial Rigidity of Single Lap Joint

Experimental studies in order to calibrate a formula for the flexibility of single lap bolted connection of two thin plates were already performed at the University of Salford by Zadanfarrokh and Bryan [9]. The formula calibrated by these authors gives the axial flexibility of a single lap connection in terms of plate thicknesses and considering the threaded portion of the bolt into connection. The Salford formula was calibrated for a M16 bolt and a 2 mm clearance of the bolt hole. In case of specimens tested at Timişoara, M12 bolts with 1 mm clearance of the bolt hole, as used in Romanian practice, were considered. This part of the experimental programme was aimed to calibrate a formula for the axial rigidity of single bolt lap joints, subjected to shear, depending of plate thickness and bolt diameter, considering the practical case of threaded portion of the bolt into connection, and 1 mm hole clearance. A complete description of this part of the experimental programme is given by Zaharia [10], [11].

The formula of the axial rigidity of single lap bolted joints was calibrated using the Annex Z [1] of Eurocode 3 is presented below [10], [11]:

$$K_{\text{axial}} = 6.8\frac{\sqrt{d}}{\left(\dfrac{5}{t_1}+\dfrac{5}{t_2}-1\right)}, \ [\text{kN/mm}], \tag{1}$$

with a partial safety factor $\gamma_R = 1.25$, in which d is the nominal diameter of the bolt and $t_{1,2}$ – the thicknesses of joined plates. The ranges of validity of this formula are the bolt diameter between M8...M16 and the thickness of plates between 2...4 m.

4. Computation Models for Rotational Rigidity of Truss Joints

The computation scheme for the rotational rigidity of a diagonal-to-chord joint, with two bolts on each flange of the diagonal, is shown in Fig. 4. The rotational rigidity of the joint, $K_{\text{nod},t}$, can be expressed in terms of total bending moment and corresponding rotation, θ, as [10], [11]:

$$K_{\mathrm{nod},t} = \frac{M_{\mathrm{tot}}}{\theta} = \frac{2kda}{\dfrac{d}{0.5a}} = ka^2 = \frac{6.8a^2\sqrt{d}}{\dfrac{5}{t_1} + \dfrac{5}{t_2} - 1}, \quad [\mathrm{kN.mm/rad}], \tag{2}$$

where

$$F = kd \quad \text{and} \quad \mathrm{tg}\theta \cong \theta = \frac{d}{0.5a}. \tag{3}$$

In the previous formulas, a is the distance between the two bolts. The partial safety factor to be used is the same as for formula (1), $\gamma_R = 1.25$.

Table 1 shows a comparison between the theoretical and experimental values of rotational rigidities obtained from the first part of the experimental programme on T joints, $K_{\mathrm{nod},t}$ and $K_{\mathrm{nod},e}$, respectively. A good correlation between the experimental results and the characteristic values of the rotational rigidity can be observed. The average ratio between the theoretical characteristic values and the experimental ones is 1.036 and the correlation coefficient is $\rho = 0.982$. Considering the design theoretical value of the formula, $K_{\mathrm{nod},d} = K_{\mathrm{nod},t}/\gamma_R$, it can be observed that all theoretical values are in the safe range. Similar models may be established for 3 or 4 bolts truss joints [10], [11].

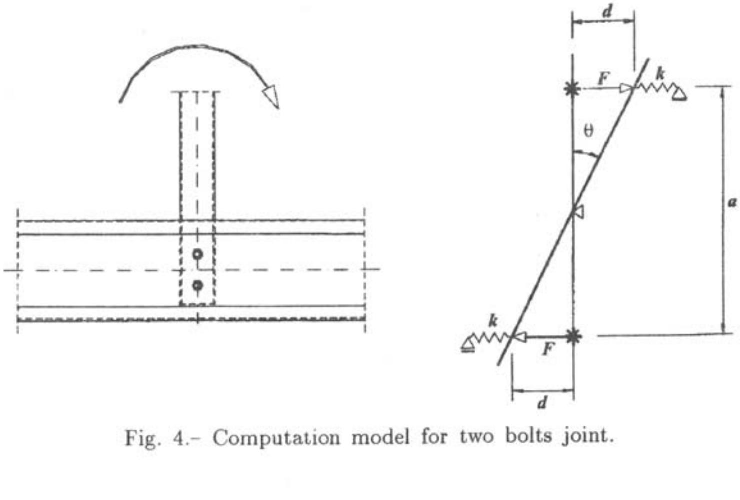

Fig. 4.- Computation model for two bolts joint.

Table 1

Comparison between Experimental and Theoretical Values of Joint Rigidity

Node	t_1 mm	t_2 mm	$K_{\text{nod},e}$ kN.mm/rad	$K_{\text{nod},t}$ kN.mm/rad	$K_{\text{nod},t}/K_{\text{nod},e}$	$K_{\text{nod},d}/K_{\text{nod},e}$
1	3	2.05	10,130	9,830	0.971	0.777
3			10,270		0.958	0.766
2	3	3	12,480	13,083	1.047	0.838
4			11,110		1.177	0.942
5	4.05	2.05	10,560	11,418	1.080	0.864
8			10,968		1.041	0.833
6	4.05	3	15,320	16,057	1.048	0.838
9			15,490		1.037	0.830
7	4.05	4.05	21,189	20,779	0.981	0.785
10			20,361		1.021	0.817

5. Test on Truss Structure

In order to prove that the initial rotational slippage observed in case of tested joints, is not significant when the joint is working in the truss structure, and to validate the theoretical assumptions introduced above, a full-scale test of a truss specimen was performed [10], [11]. The dimensional characteristics of the experimental model are shown in Fig. 5. All connections are made with M12, 8.8 grade bolts. As for the case of T connections tests, the mechanical characteristics of the steel for profiles are corresponding to OL52 steel type, according to Romanian standards. Fig. 6 shows the experimental device. The load was introduced by means of a 500 kN QUIRI actuator. The load introduction was controlled in terms of displacements, with a rate of 2.5 mm/min. Two inclinometers measured the global

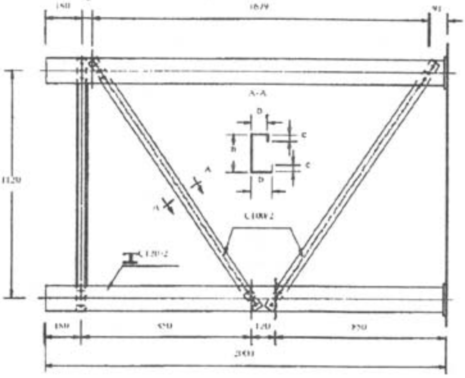

Fig. 5.- Experimental model.

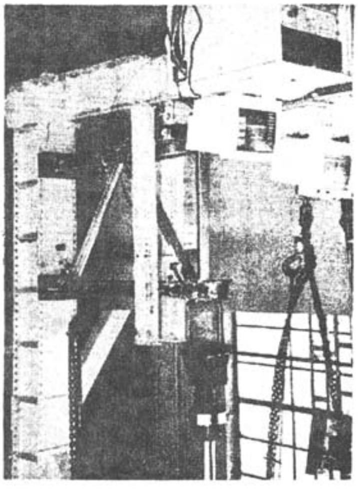

Fig. 6.- Experimental device.

rotation of the diagonals. In order to measure the axial slippage in connections, two LVDT displacement transducers were placed on the axis of each diagonal. Four potentiometric displacement transducers were used to control the displacements in structure.

The load increased until the structure failed due to the flexural instability of the diagonal in compression, in the plane of the truss. A local buckling in the lower chord, due to the shear of the web panel, located between diagonals, was also observed, before the buckling of diagonal was reached. This phenomenon also contributes to the deformability of the joint.

Fig. 7 presents the axial displacements reported by the LVDT transducers. It can be observed the typical behaviour of a thin plate bolted connection in shear. After load corresponding to the initiation of slippage in connection is attained, this can be developed until the hole clearance is consumed. Fig. 8 shows the evolution of the diagonal rotations.

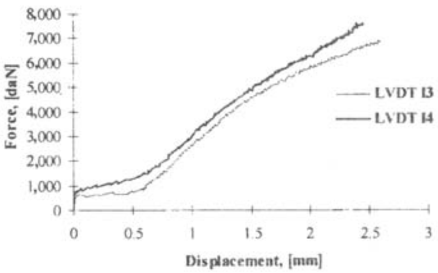

Fig. 7.– Axial displacements of diagonals.

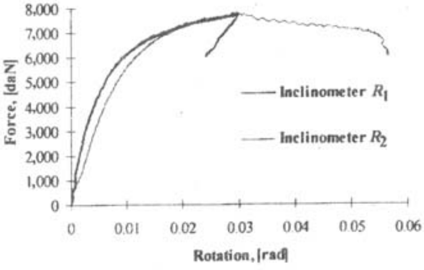

Fig. 8.– Diagonal rotations.

Corresponding to the load range in which the axial slippage occurs, very small rotations are observed only. Until the structure' shake down', the presence of the axial forces and the triangulation effect prevent the developing of significant rotational slippage in connections. Consequently, the rotational rigidity, evaluated without considering the initial slippage, is a real one and can be used in the global analysis, and to evaluate the buckling length of relevant members.

6. Numerical Analysis of Truss

The tested truss was numerically analysed with PEP-micro programme [8], which is a specialized tool for the non-linear inelastic analysis of steel structures with semi-rigid joints. The static scheme of the structure is shown in Fig. 9. The connection eccentricity, L_{exc}, was taken into account by introducing some rigid links at the ends of diagonals. With the purpose of the stability checking of a structure, Eurocode 3 [6] allows for a second order analysis with initial sinusoidal equivalent imperfection of the members. Lipped channels, are classified according to Eurocode 3 Part 1.3 [7] on the buckling curve B, which corresponds to an initial equivalent imperfection, $e_0 = 1/380$. The ultimate load of the member is attained when the yield stress is reached in the external fibber of cross section, accounting for the second order effects – the 'divergence' model. A step by step second order analysis was performed, with a load increment corresponding to 1% of the ultimate load.

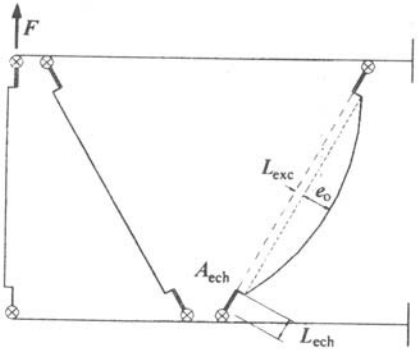

Fig. 9.- Static scheme of the experimental model.

The structure was analysed with and without considering the effect of the axial rigidity of the diagonal connections. The PEP-micro-programme is not able to model this axial rigidity of connections, and, with this purpose, an equivalent finite element was used to simulate this behaviour. The equivalent cross section area of this finite element can be find by equalizing the expression of the axial rigidity of the member in compression/tension with the axial rigidity of connection, resulting:

$$K_{\text{axial}} = \frac{EA_{\text{ech}}}{L_{\text{ech}}}, \tag{4}$$

where K_{axial} is taken from (1).

Fig. 10 compares the experimental load *vs.* displacement curve of this truss, with the theoretical bi-linear ones. The experimental curve shows an initial "structural" slippage, at the load intensity which corresponds to the axial slippage in diagonal connections (Fig. 7). Neglecting this initial slippage, the structural rigidity obtained accounting for both axial and rotational rigidities of connections, K_{axial} and K_{nod}, respectively, is close to the experimental one. Table 2 presents the results of the numerical analysis, in comparison with the experimental ones. The analysis accounting for both axial and rotational rigidity of connections gives differences of 2% in case of ultimate load and 37% for the corresponding displacement. This significant difference in displacement values is due to the initial axial slippage in connections, and to the bolt plastic bearing, which were not considered in the numerical analysis. The comparison between theoretical and experimental initial rigidities, after consumption of slippage, gives differences of 5% only. Without considering the axial rigidity, the difference in displacement would be significantly greater.

Table 2

Results of the Numerical and Experimental Analysis

K_{nod} without K_{axial} (1)	K_{nod} with K_{axial} (2)	Experiment (3)	(1)/(3)	(2)/(3)
Ultimate load, [daN]				
6,650	7,665	7,820	0.85	0.98
Displacement, [mm]				
3.3	9.9	15.8	0.21	0.63
Structural rigidity, [daN/mm]				
2,015	774	734	2.74	1.05

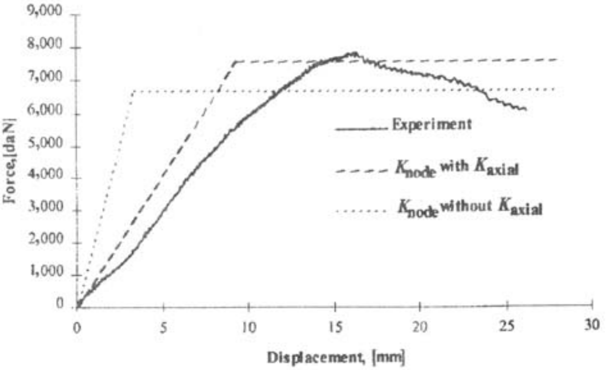

Fig. 10.– Comparison between experimental and numerical analysis.

7. Conclusions

The evidence of the semi-rigid character of cold-formed steel truss bolted joints was provided, by means of tests on T typical joints. The joint deformability is mainly due to the bearing work of the bolts, and consequently, the rotational rigidity of the connection can be determined on the base of the single bolt lap joint behaviour.

In order to evaluate the axial rigidity of a single bolt lap joint, in terms of the thickness of plates and bolt diameter, an experimental programme was carried out. The characteristic and design axial rigidities were calibrated by means of the Annex Z of Eurocode 3. Computation models for the rotational rigidity of the truss joints were established, depending of the axial rigidity of single bolt lap joint. The theoretical model for two bolts joint proves a good correlation of results with the ten tests on T joints.

The test on full-scale truss shown that the initial rotational slippage, observed during the T joint tests, do not appear in structure. The initial slippage on the direction of the diagonal axial efforts contributes only to the ultimate displacement state, without effect on the ultimate load value. The axial rigidity of the connections have also an important influence on the displacement of the structure, but is not significant for the value of the ultimate load. It is recommended, for the global analysis of trusses, and also for the analysis of any other structure built by cold-formed sections with bolted joints, to consider both axial and rotational rigidities of the connections. For displacement analysis, and for computation of the buckling length of the members, the design values of the rotational and axial rigidity of the connections, as proposed in this paper, can be used, while for connection design, the characteristic values are recommended.

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PROIECTAREA ASISTATĂ DE EXPERIMENT A FERMELOR ALCĂTUITE DIN PROFILE METALICE FORMATE LA RECE

(Rezumat)

Se prezintă programul experimental desfăşurat în Laboratorul de Construcţii Metalice a Universităţii „Politehnica" din Timişoara, pentru stabilirea comportării reale a îmbinărilor cu şuruburi în cazul fermelor metalice alcătuite din profile formate la rece. În prima parte a programului experimental s-a demonstrat caracterul semi-rigid al acestor tipuri de îmbinări, prin teste pe îmbinări

în T. Prin teste pe îmbinări cu un singur şurub, s-a determinat apoi o formulă de calcul a rigidităţii la forţa axială. Pe baza acestei formule s-au propus modele de calcul ale rigidităţii rotaţionale a îmbinărilor tipice pentru ferme. În cea de a treia parte a programului experimental s-a realizat încercarea unei ferme la scară reală, pentru a observa comportamentul îmbinărilor şi a valida ipotezele teoretice. În ultima parte a acestei lucrări se prezintă analiza numerică a structurii testate şi se oferă comparaţii cu rezultatele experimentale.