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INFLUENCE OF LOCAL PLASTIC BUCKLING OF A JOINT ON THE CARRYING CAPACITY OF THIN-WALLED TRUSSES

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***Abstract**. The use of cold-formed structural members in steel structures increases rapidly and companies offer wider range of shapes of cross-sections possible to use in design practice. One of the biggest disadvantage of this type of the members in design is a lack of information of their real behaviour under load i.e. mainly about possible local buckling effects which can considerably decrease capacity of a whole compression member or even a whole structure. To illustrate this problem there were shown the results of experimental and numerical researches of a truss joint in which local plastic buckling of a wall of the compression member have decisive influence on its behaviour and carrying capacity.*

1 INTRODUCTION

The use of cold-formed structural members in steel structures increases rapidly and companies offer wider range of shapes of cross-sections possible to use in design practice. Those shapes assure not only a better usage of a material but also make steel structures lighter and more economical than those made from hot-rolled sections. Cold-formed structural members are normally used in applications like roof and wall systems of industrial, commercial and agricultural buildings, steel racks for supporting storage pallets, structural members for plane and space trusses, frameless stressed-skin structures, residential framing and steel floors and roof decks. They are usually manufactured by one of two processes i.e. roll forming and brake forming, which have influence on material properties of the latest one. One of the biggest disadvantage of this type of the members in design is a lack of information of their real behaviour under load i.e. mainly about possible local buckling effects which can considerably decrease capacity of a whole compression member or even a whole structure. The use of thinner material and cold-forming processes result in special design problems not normally encountered in hot-rolled construction. In addition, welding and bolting practises in thinner sections are also different, requiring design provisions unique to thin sheets. The thickness of individual plate elements of cold-formed sections are normally small compared to their widths, so local buckling may occur before section yielding. However, the presence of local buckling of an element does not necessarily mean that its load capacity has been reached [1]. To illustrate above mentioned problems, in the next chapters, there were shown the results of experimental and numerical researches of a truss and in particular its joint in which local plastic buckling of a wall of the compression member have decisive influence on its behaviour and carrying capacity. The elements of the truss were manufactured by roll forming.

2 ANALYSED STRUCTURE

The object of investigation was the truss made from cold – formed sections (Fig 2 and Fig.3b) and in particular its joint (Fig. 3a). The truss consists of two types of cross sections i.e. Z and Sigma (Fig. 1a-c) which are produced by roll forming. Z profiles were made form steel S420 while Sigma from S355. The material properties of flat steel i.e. f_{yb} and f_u were determined on basis of tension tests of real elements. The influence of roll forming on material properties of cross sections i.e. yield strength of corners f_{yc}, was taken into consideration according to Karren's proposal [2]. The material properties of flat steel as well as those calculated for corners were set in Tab. 1. Z profiles are designed to be a compression and tension members of truss while sigma as bottom and top chords. In case of compressed ZV bar the Z profile was reinforced by two flat stiffeners (Fig 1b). All the elements are connected together in welded joint (Fig. 3a). The system of joining elements requires a special preparation (deformation) of ends of the members (Fig. 3c) and can cause unstable behaviour of walls of compressed member (local buckling). It forced to investigate the behaviour of joint as well as the determination of bending moment – rotation characteristic and its influence on capacity and rigidity of whole system (truss).

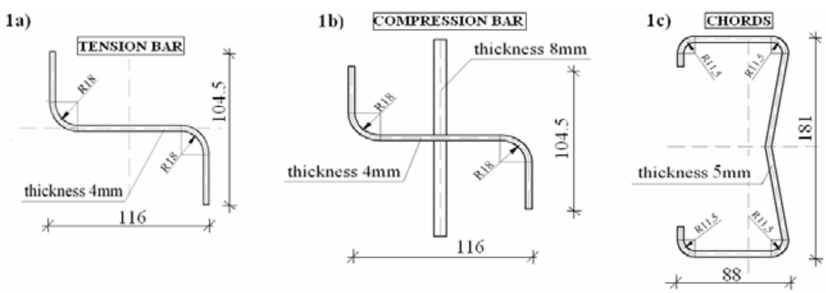

Figure 1: Cross-sections of truss members.

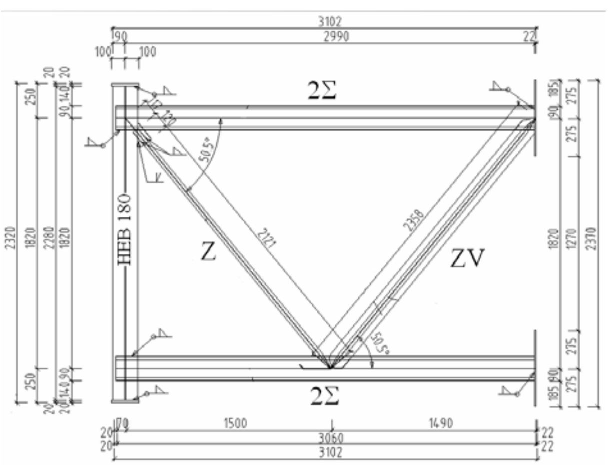

Figure 2: Geometry of truss made from cold-formed sections.

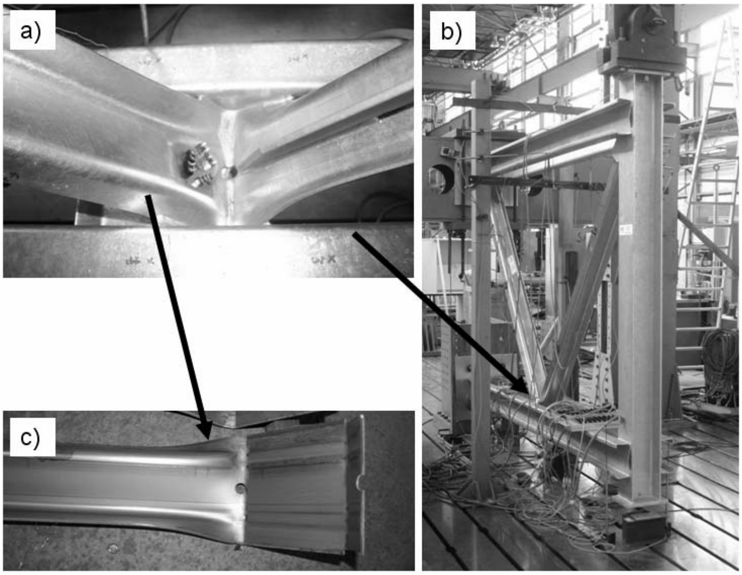

Figure 3: Welded truss joint (a), truss (b), and end of bar (c)

Table 1: Material properties of cross-sections

Section	f_{yb} [MPa]	f_u [MPa]	E [GPa]	f_{ya} [MPa]	f_{yc} [MPa]	A [cm^2]
Z	426	525	210	448	579	8
ZV	426	525	210	448	579	19.2
Σ	359	473	210	398	528	18.5

Z-tension bar, ZV-compression bar, Σ-chord, E- Young's modulus, f_{ya} f_{yb}, f_{yc}- average, basic and corner yield strength respectively, f_u- ultimate tensile strength, A- area of cross-section.

3 EXPERIMENTAL INVESTIGATION

3.1 Description

The experimental research was focused on describing the behaviour of the joint in particular local buckling of wall of compressed Z profile and associated additional effects. There were carried out three experiments in which the analysed structure was truss cutting containing joint (Fig. 4a). To produce required internal forces in particular elements of the truss cutting, special frame system was designed (Fig. 4b). The frame system consisted of three bars one horizontal and two diagonal made from C profiles connected together with use of bolts. The connections between particular elements of the frame were designed to be a "perfect" hinges to avoid problems with additional stiffness of whole system i.e. truss cutting + frame. During the experiments the measured quantities were vertical and horizontal displacement of joint (Fig. 5b and Fig. 8a) as well as load *P* and movements of supports *UR1* and *UR2* (Fig. 5a). The concentrated load *P* was realized by hydraulic press and was located directly above the end of compression bar *ZV*. The load position was thought to produce equal internal forces both in compression and tension bars. Moreover in every element there was applied appropriate layout of gauges to determine real stress states in cross-sections (Fig.6). On the basis of strain measurements the exact internal forces in individual members were calculated and compared at every load increment. Furthermore the visual inspection of welds was done before and during the experiments.

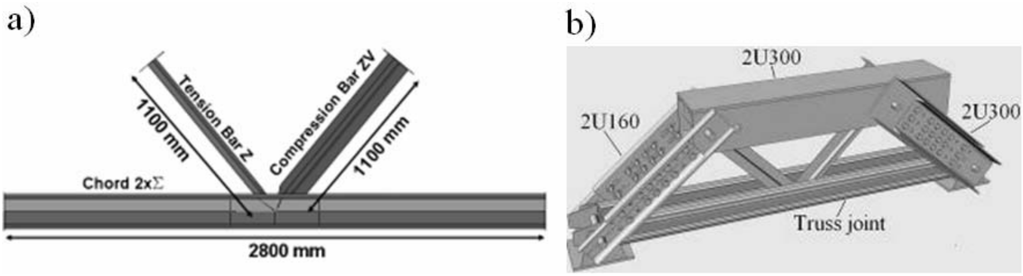

Figure 4: Dimensions of truss cutting containing joint (a) and frame system (b).

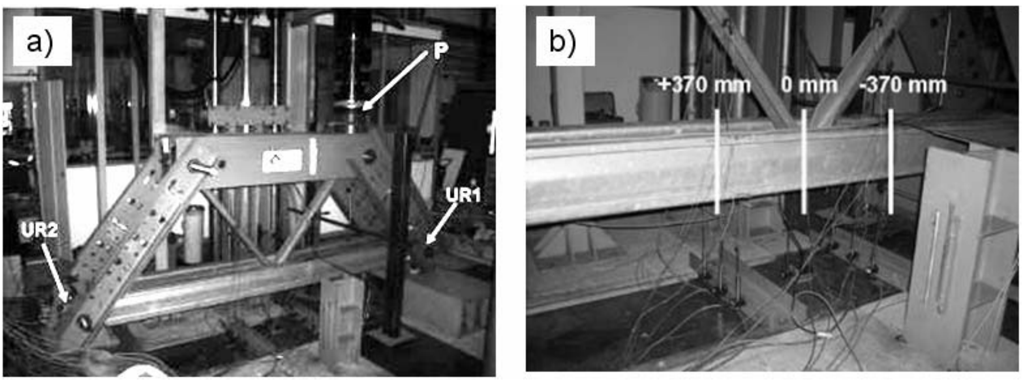

Figure 5: View of experimental area (a) and measurement system of vertical displacements of joint (b)

3.2 Results

As it was mentioned above the basic point of the research was to describe the phenomenon of local plastic buckling of the wall of compressed member. The shape of deformation of buckled wall was presented in Fig. 10. This effect appeared at external load P = 840 kN that corresponds to normal force in compression member N_{DD} = 285.15 kN (Tab.2). The normal force N_{DD} (calculated according to gauge measurements) amounted 84% of design capacity of cross-section N_{DDmax1} = 336 kN within the joint (cross section without stiffeners) and 35% of design capacity of cross-section in the middle of the bar N_{DDmax2} = 806 kN. The appropriate internal forces corresponding to selected external load levels were set in Tab. 2. On Fig. 6 there were presented tables containing values of normal stresses in individual measurement point for every cross-section. It can be seen that the normal stress distribution within cross-sections is nonlinear, that can be a result of existence of interaction between normal forces, bending and torsional moments. The excessive rotation of compression bar due to local buckling caused rotation of the rest of the members i.e. chord and tension element.

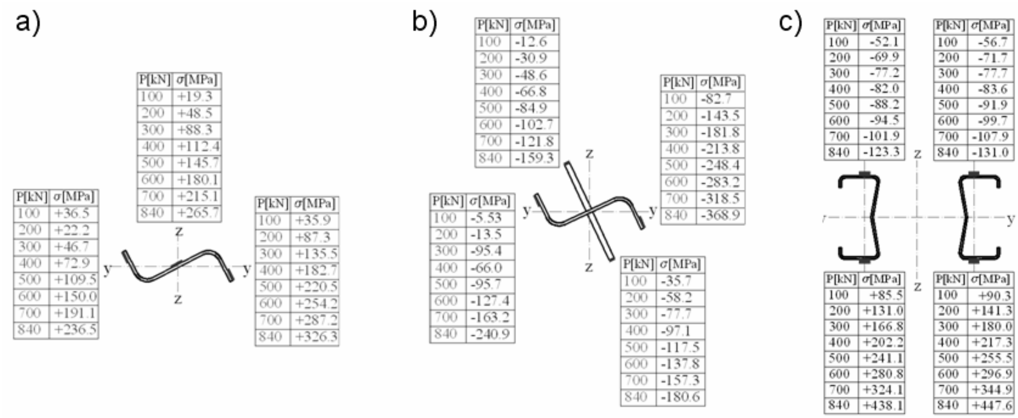

Figure 6: Layouts of gauges and stresses in tension bar (a), compression bar (b) and chord (c)

Table 2: Internal forces in individual members

P [kN]	N_{ZD} [kN]	N_{DD} [kN]	N_G [kN]
100	16.75	40.85	30.95
200	42.15	74.15	60.40
300	70.00	104.50	88.65
400	98.20	134.65	117.35
500	126.85	165.95	146.40
600	155.85	197.65	177.35
700	184.95	230.35	212.40
840	220.95	285.15	229.00

P-external load, N_{ZD}-tension force, N_{DD}-compression force,
N_G-tension force chord (sigma profile)

3.2 Bending moment – rotation curve

To determine basic characteristic of joint i.e. bending moment-rotation curve, a system of measurement points of vertical displacements was applied. The layout of those points was presented on Fig. 7. On the basis of those measurements and with use of 4^{th} order interpolating function, the deflection curve *u(x)* was build for selected load increments. Using well-known equations (1) and (2) representing dependences of bending moment and rotation on deflection, the values of these latest were determined. The bending moment-rotation curves were presented on Fig. 7b.

$$\varphi(x) = \frac{d}{dx} u(x) \tag{1}$$

$$M(x) = -EI \frac{d^2}{dx^2} u(x) \tag{2}$$

where: *u(x)*-deflection curve, *M(x)*-bending moment curve, φ*(x)*-rotation curve, *EI*-bending stiffness of chord.

It can be seen that bending moment - rotation characteristic is linear in a large part of curve. The design moment resistance of a joint $M_{j,Rd}$ was estimated at value 58 kNm and corresponds to rotation of joint ϕ_{Rd} = 0.21 deg. The elastic range of behaviour of joint is characterized by two values i.e. bending moment $M_{j,Ed}$ = 36 kNm and rotation ϕ_{Ed} = 0.11 deg. The slope of the curve in this area described the initial stiffness of a joint $S_{j,ini}$ = 327 kNm/deg. EC-3 part 1.8 [3] allows to classify the joint by stiffness (p. 5.2.2) and by strength (p. 5.2.3). According to these points the joint was classified as a semi-rigid and partial strength. Taking into consideration method of classification of joints, which is contained in table 5.1 of EC-3 [3], the type of joint model was classified as a semi-continues model.

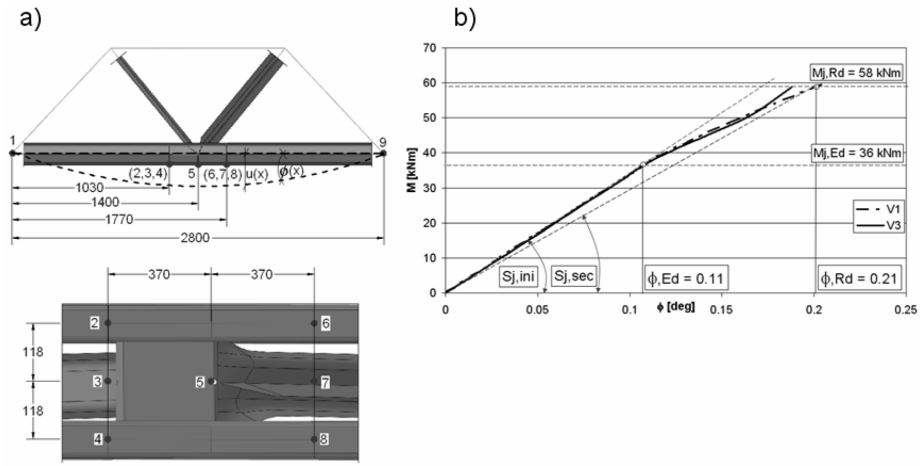

Figure 7: Measurement points for displacements (a), bending moment-rotation curve (b)

4 NUMERICAL MODEL

4.1 Global Analysis

Integral part of discussed study was a numerical model. The model was built and calibrated according to experimental research. The main structures i.e. truss cutting was modelled with use of 4-node shell finite elements (S4R) and the frame with beam elements (B2D3). In the nodes in which the beam elements were joined there were created hinges to assure correct behaviour of system consisting of frame and truss cutting. The discretized model was presented in Fig. 8. Assumptions taken during the numerical calculations were as follows: program and version: ABAQUS 6.8.2 [4]; bilinear material law for steel i.e. perfect elastic-plastic behaviour with a nominal slope of the yielding landing; geometrical imperfections and also residual stresses were not considered; materially non-linear analysis (MNA); both shell (S4R) and beam (B2D3) finite elements were used to discretize model; loads and boundary conditions were defined in appropriate coordinate systems; convergence criteria – force. The numerical solution stayed consistent with empirical results. All of the phenomena noticed in experiments appeared in FEM simulations i.e. local plastic buckling of wall of compressed element and its excessive rotation around the longitudinal axis (Fig. 9) as well as damage of welds along and across the joint. Moreover the capacity of whole system obtained in FEM calculation (P_{FEM}) stays in good adequacy with experimental one (P_{EXP}) i.e. P_{EXP} = 840 kN, and P_{FEM} = 835 kN. The experimental load-displacement curve included all geometrical imperfections caused by inaccuracy of the frame system. After a careful analysis of the numerically obtained results, the authors decided only to compare load capacities and not to include the experimental curve.

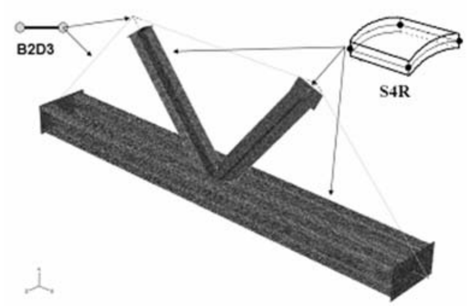

Figure 8: Numerical model of joint

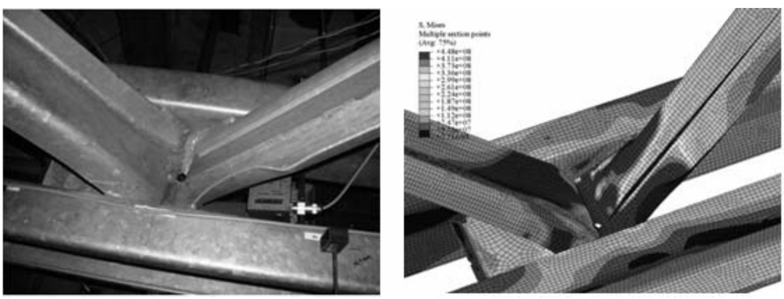

Figure 9: Comparison of results

4.2 Sub-modeling

As it was mentioned in previous chapters, the decisive influence on behaviour of joint and further on whole truss had local buckling of wall of compression element ZV. This phenomenon was investigated more precisely with use of sub-model consisted only of compression element (Fig.10a). The load was applied in appropriate local coordinate system. The boundary condition were designed to represent as accurate as possible the fillet welds joining individual element within the joint. The analysis showed that the compression bar was bale to carry normal compression force F_1 = 352 kN (Fig. 10b) which is 5% bigger than this calculated for cross section without stiffeners F_2 = 336 kN. The increase of this value can be explained by existence of small parts of cross-section of stiffeners inside the joint. It should be mentioned that the bar was not able to carry normal force calculated for cross section with stiffeners i.e. N_{DDmax2} = 806 kN (cf. previous chapter). The difference between numerical and experimental capacities of element i.e. F_1 = 352 kN and F_3 = 285 kN, respectively, can be explained by damage of welds that was observed during the experiment. This excessive rotation of all cross-sections which were included in the joint caused significant decrease of capacity of element.

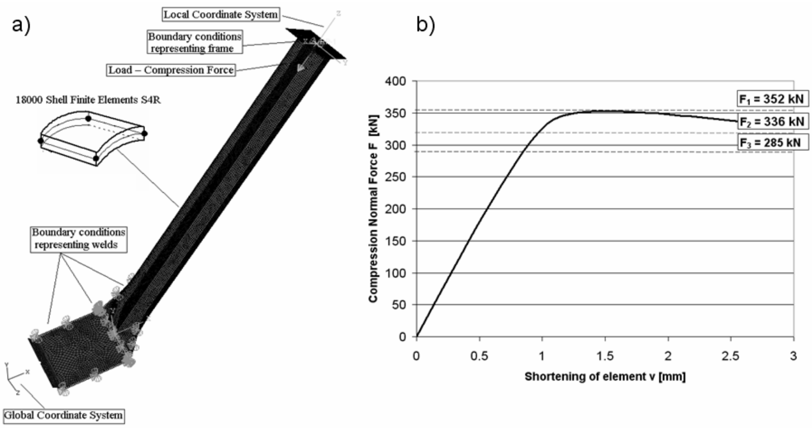

Figure 10: Compression bar: sub-model (a) and statical path of equilibrium of compression member (b)

5 CONCLUSIONS

The object of investigation was the truss made from cold – formed sections and in particular its joint. The experimental research was focused on describing the behaviour of the joint in particular local buckling of wall of compressed Z profile and associated additional effects. It can be seen that the normal stress distribution within the cross-sections is nonlinear, that can be a result of existence of interaction between normal forces, bending and torsional moments. The excessive rotation of compression bar due to local buckling caused rotation of the rest of the members i.e. chord and tension element. The basic characteristic of joint i.e. bending moment-rotation curve was built on the basis of measurements vertical displacements. It can be seen that bending moment - rotation characteristic is linear in a large part of curve. According to rules contained in EC-3 the joint was classified as a semi-rigid and partial strength. Moreover taking into consideration method of classification of joints, which is contained in table 5.1 of EC-3, the type of joint model was classified as a semi-continues model. Integral part of discussed study was a numerical model. The model was built and calibrated according to experimental research. The numerical solution stayed consistent with empirical results. All of the phenomena noticed in experiments appeared in FEM simulations i.e. local plastic buckling of wall of compressed element and its excessive rotation around the longitudinal axis as well as damage of welds along and across the joint. The decisive influence on behaviour of joint and further on whole truss had local buckling of wall of compression element ZV. This phenomenon was investigated more precisely with use of sub-model consisted only of compression element.

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