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An analytical and numerical assessment of the load capacity of the K-joint of flat steel trusses

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ABSTRACT:
The study assesses the load capacity of the K-joint of flat steel trusses made from hollow sections. Two cases were considered: an unreinforced joint and a joint with reinforcement in the form of a pad welded to the belt. Analytical calculations were made for the analyzed cases, based on which, the load capacity of the considered joint was determined (before and after strengthening). A numerical model of the analyzed connection was prepared, and then the stress and strain values in the joint were determined. The obtained results were compared with the results of the analytical calculations. It has been shown that the analytically determined joint load capacity (as the maximum allowable load that does not damage the joint) is less than the allowable load capacity obtained on the basis of the numerical calculations. Estimation of the load capacity of the joints made from hollow sections, based on an analytical approach, allows for the safe design of welded truss contacts, however, in some cases it can lead to an underestimation of the load capacity of the joint.

KEYWORDS:
truss girders; joints resistance; K-joint

1. Introduction

Truss structures made of circular hollow sections (CHS), square hollow sections (SHS) and rectangular hollow sections (RHS) are widely used in steel construction as, for example, truss girders or roof purlins. They are characterized by a relatively low weight compared to elements made of hot-rolled, open sections (I-sections, channel sections). However, a certain limitation in their use is their higher purchase price. To improve the economic competitiveness of tubular lattice elements, the labor costs associated with their manufacture must be reduced. To this end, it is necessary to improve and automate the process of cutting and welding as well as shaping the joints to eliminate or minimize the use of gusset plates and ribs. Therefore, several basic solutions of typical node geometry have been developed and implemented (Fig. 1), which have good structural, technological and economic properties [1].

Designing truss elements made from hollow sections consists of checking the required load-bearing conditions for individual bars (top cord, bottom cord and webs) and the load-bearing capacity of welds (in the case of welded elements), as is the case of cutters with open sections. In addition, it is also necessary to check the load capacity of the nodes. This is due to the way internal forces are transmitted in the nodes. These forces from the walls of the lattice bars are transferred to the walls of the strips in plane or contact surfaces, which may cause a local loss of load capacity in the profile walls within the node, despite the sufficient cross-sectional capacity of individual bars and welds. Typical modes of failure for square or rectangular sections joints are shown in Figure 2.

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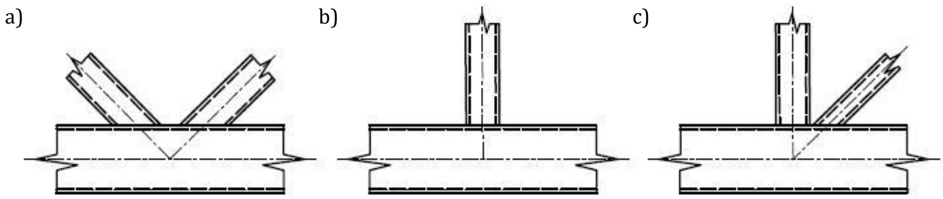

Fig. 1. Types of joints in hollow sections lattice girders made on SHS or RHS sections: a) K-joint, b) T-joint, c) N-joint

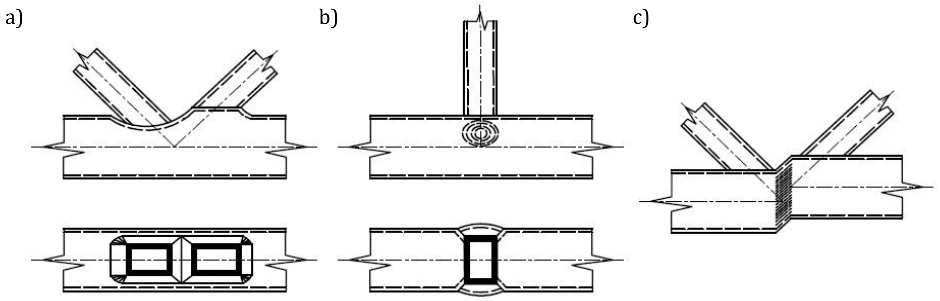

Fig. 2. Failure modes for joints between SHS and RHS members [2]: a) chord face failure (plastic failure of the chord face) or chord plastification (plastic failure of the chord cross-section), b) chord side wall failure (or chord web failure), c) chord shear failure

Numerous experimental studies [3] and numerical analyses [4] are carried out to determine the load capacity and displacement of steel structural elements. They also concern the load capacity of the nodes in lattice elements made of closed sections. In [5], the authors presented a new methodology for designing X-type nodes made of RHS profiles with the same section width, for which the buckling load of webs of chord is critical. The solution they propose allows the obtaining of more accurate results compared to previous methods and extends the scope of possibilities in assessing the load capacity of walls, whose slenderness (height to thickness ratio) does not exceed 50. An analysis of the same type of node but made of circular hollow sections made of high strength steel was carried out in [6]. Based on the performed analytical and numerical calculations as well as experimental research, a design guide was developed, which is a valuable supplement to the dimensioning algorithms used so far for these type of nodes. In [7], the authors analyzed the work of a K-joint made from the CHS profile with a gusset plate welded to the chord, to which cross-braces were attached using screws. A computational formula, confirmed by experimental tests, allowing the determination of the load capacity of the node was presented. Typical pipe constructions are supplemented with elements made of high-strength pipes (HSS).

The authors of [8] reviewed the latest solutions using HSS pipes and conducted a preliminary assessment of the current principles of designing welded joints in these elements, at the same time indicating the scope of their application. A certain alternative to welded pipe components can be N-type "key-lock" welded nodes, where internal forces are transferred by the pressure and shear of the adjoining profile walls joining the node [9]. Properly shaped ends of the cross-braces are the "key" and a hole with a strictly defined geometry cut out at the waist is the "lock". The whole structure is connected by a bolt passing through the cross-braces and through the belt. The conducted experimental research and performed numerical analysis confirmed the possibility of eliminating welding in this type of node. It has been shown that the load capacity of the N-key-lock contact is comparable to the load capacity of welded "T" truss nodes from RHS pipes. One way to increase the load capacity of tubular trusses is to use CFT girders whose belts are filled with concrete. In [10, 11], the authors conducted an analysis of unstressed and prestressed girders made of round pipes, and in [12] there was a fatigue assessment of the Y-node of a girder made from rectangular pipes, indicating possible forms of damage and a method of checking the load capacity. The subject of the fatigue strength of innovative lattice bridge structures was discussed in [13]. Attention was drawn to the fact that the existing design recommendations based on research from the nineties contained in [14] do not take into account some of the structural details used in currently designed structures. Research projects have been discussed, thanks to which, the scope of application of currently used dimensioning algorithms should be extended.

Computational procedures have been developed for the most commonly used solutions in the field of lattice tubular structures [2]. This load-bearing capacity is defined as the maximum axial force that can occur in the checking rod so that the node does not break. Factors affecting the load capacity of welded tubular nodes are: node geometry, cross-sectional dimensions of rods connecting to the node (e.g. slenderness of the belt walls and cross-braces, ratio of cross-sectional height/width of cross-braces to height/width of the cross-section of the belt), inclination angles of the cross-braces to the belt, possible eccentric connection of the grating bars in the node as well as the stresses occurring in the belt cross-section [1].

The calculation procedures used in the process of designing steel truss structures contain some simplifications and generalizations, which in certain cases, cause some discrepancies between the design and actual values. In this work, an attempt was made to estimate the scale of these discrepancies, using the example of a welded K-joint, assessing its load-bearing capacity using an analytical approach in accordance with [2] and numerical analysis performed using the Idea StatiCa program.

2. Analyzed K-joint

The subject of the analysis is a K-joint with a chord of RHS pipes and with cross-braces made of SHS pipes. Two variants of the node were considered: before strengthening and after strengthening with a plate, welded to the upper wall of the chord (Fig. 3).

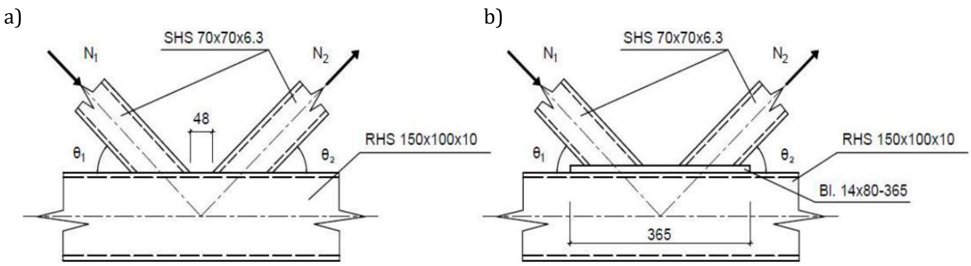

Fig. 3. Geometry of the K-joint analyzed: a) before strengthening, b) after strengthening

Node parameters adopted for calculations:
- inclination angles of the braces: $\theta_1 = 47°$, $\theta_2 = 45°$,
- forces in braces: $N_1 = 185$ kN, $N_2 = 200$ kN,
- steel grade: S235, $f_y = 235$ MPa
- welds between braces and plate: fillet welds thickness 4 mm

3. Calculation results

3.1. Analytical calculations

Analytical calculations were carried out in accordance with [2]. For the analyzed node (due to the geometry and profiles used) it is required to check the possibility of chord face failure. Because the load bearing conditions calculated for the unreinforced node (Fig. 3a) were not met, chord reinforcement was used (Fig. 3b) and recalculations were performed. The calculation results for each of the braces are shown in Tables 1 and 2.

Table 1
Results of analytical calculations - load capacity of unreinforced node

Brace type	Load in brace N_i [kN]	Node load capacity $N_{i,Rd}$ [kN]	Load capacity condition $N_i/N_{i,Rd}$ [%]
Compressed brace	185.00	167.45	110.48
Tension brace	200.00	173.23	115.45

Table 2
Results of analytical calculations - load capacity of reinforced node

Brace type	Load in brace N_i [kN]	Node load capacity $N_{i,Rd}$ [kN]	Load capacity condition $N_i/N_{i,Rd}$ [%]
Compressed brace	185.00	328.27	56.36
Tension brace	200.00	339.53	58.90

The load capacity of the unreinforced node is exceeded by 10.48% for the compressed brace and by 15.45% for the tension brace. After welding the reinforcing plate, the node's load capacity increased by 96%. Such a significant increase in load capacity is caused by the adopted geometry of the reinforcing plate. According to [1], as a result of chord reinforcement, the node's load capacity should increase significantly. Therefore, the thickness of the reinforcing plate was assumed to be 40% greater than the wall thickness of the chord. Therefore, in order for the analyzed contact to be considered correctly designed in accordance with [2], it is necessary to make the reinforcement.

3.2. Numerical calculations

Numerical calculations were made using the Idea StatiCa program using FEM. Equivalent stress values in diagonals and waist were determined for the inferior zone in the unreinforced node (Fig. 4). The maximum stress value is 233.2 MPa and is smaller than the design value of the yield strength of steel from which the components of the node were made, i.e. 235.0 MPa. The stress concentration zone occurs in the upper wall of the chord, in the area of contact with the braces and in the upper corners of the chord profile. The deformation of the profile walls at the joint is negligible. The maximum value of relative plastic deformation is 0.04% and occurs in the upper corners of the chord profile, in the zone between the braces (Fig. 5). The areas of stress and strain concentration are in the same places as in the potential failure modes adopted in accordance with [2] in the analytical calculations (Fig. 2a). Thus, according to the numerical analysis carried out, the load capacity of the node in question is sufficient, there is no need to strengthen it.

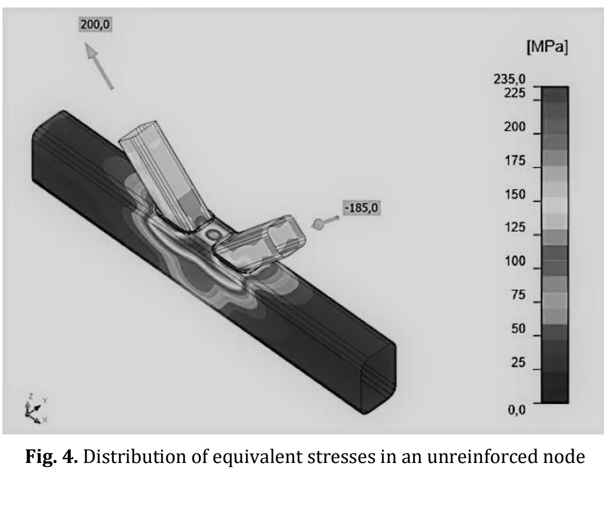

Fig. 4. Distribution of equivalent stresses in an unreinforced node

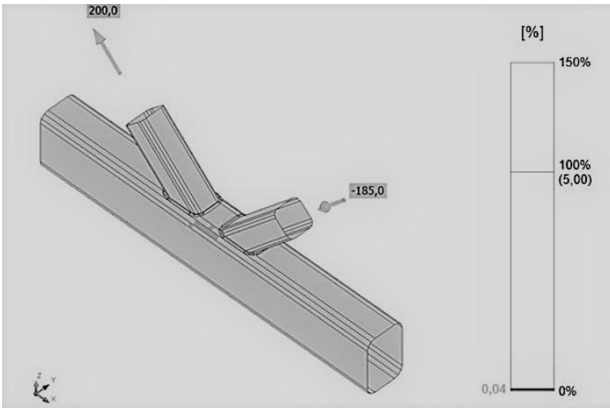

Fig. 5. Distribution of plastic deformations in an unreinforced node

Since the results of the numerical calculations made for the unreinforced node have shown that both stresses and strains do not exceed the permissible values, there is no need to carry out numerical analysis of the node with the reinforcing plate (in the reinforced node the actual values of stress and deformation will be even smaller).

4. Conclusions

The calculation methods used cause some discrepancies in the results. In the case of the analytical approach in accordance with [2] - in the absence of a reinforcing plate - the node's load capacity was exceeded by a maximum of 15%. The same node subjected to numerical analysis behaved correctly (maximum stresses and deformations did not exceed permissible values). These differences result from the different methods used to assess the load capacity. In the analytical approach, the failure modes (FM) method is used, while in the numerical analysis the component based finite element method (CBFEM) is used.

The numerical model of the analyzed connection more accurately reflects its behavior during load transfer. The stress and strain values obtained are close to real world values. The analytical model contains some simplifications and generalizations, the purpose of which is to develop universal design algorithms applicable to various geometrics and material variants of the contacts analyzed.

Estimation of the load capacity of nodes made of hollow sections based on an analytical approach allows for the safe design of welded truss connections. In some cases, however, it may lead to an underestimation of the node's load capacity and, consequently, to the need to strengthen it, which would not be necessary when using numerical modelling, which accurately reflects the designed connection.

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Analityczna i numeryczna ocena nośności węzła typu K płaskiej kratownicy stalowej

STRESZCZENIE:
W pracy dokonano oceny nośności węzła typu K płaskiej kratownicy stalowej, wykonanej z kształtowników zamkniętych. Rozpatrywano dwa przypadki: węzeł niewzmocniony oraz węzeł ze wzmocnieniem w postaci nakładki dospawanej do pasa. Dla analizowanych przypadków wykonano obliczenia analityczne, na podstawie których określono nośność rozpatrywanego węzła (przed i po wzmocnieniu). Sporządzono model numeryczny analizowanego połączenia, a następnie wyznaczono wartości naprężeń i odkształceń w strefie przywęzłowej. Otrzymane wyniki porównano z wynikami obliczeń analitycznych. Wykazano, że określona analitycznie nośność węzła (jako maksymalne dopuszczalne obciążenie niepowodujące zniszczenia węzła) jest mniejsza niż dopuszczalna nośność uzyskana na podstawie obliczeń numerycznych. Szacowanie nośności węzłów wykonanych z kształtowników zamkniętych w oparciu o podejście analityczne pozwala na bezpieczne projektowanie styków kratownic spawanych, jednak w niektórych przypadkach może prowadzić do zaniżenia nośności węzła.

SŁOWA KLUCZOWE:
kratownice stalowe; nośność węzłów; węzeł typu K