Research on AM non welded N RHS truss joints – resistance criteria

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ABSTRACT: This paper presents N type RHS plug & play truss non-welded connections, made using AM technology. The Abaqus finite element three-dimensional models were created where the three-dimensional C3D8R, 8-node linear brick element with reduced integration were used. The mesh was densified in the area of maximum deformation and the boundary conditions correspond to realistic data from experiment set-up. A contact interaction between elements was assumed. Material properties were taken as the average values of the coupon tests. True stress-strain relationship were defined. Nine numerical models were created and validated by the experimental tests. Due to use of hierarchical validation in the performed simulations an appropriate level of accuracy was obtained. Failure mechanisms in FEM models and experimental tests seems to be similar. The criteria of joints load resistance are proposed such as permissible displacement of chord flange and Mann-Kendal (M-K) criterion. Finally, some conclusions are given.

1 INTRODUCTION

Fabrication and assembly of the typical steel connections requires considerable time and generation high costs. The use of modern techniques which belongs to AM as: 3D and CNC laser cutters or 3D printers made possibility to develop a new type of joints. These joints which are easy to make and install are the one of the possible answer for the strong need of manufactures to reduce the overall costs of steel structures. This knowledge related to demountable connections of steel trusses requires more extensive research. Such studies on plug & play connections are shown, among others, in the works [Brekelmans, Bijlaard (2000), Bijlaard, Breckelmans (2007), Szlendak, Oponowicz (2011, 2013), Szlendak, Szpyrka (2018), Szlendak (2019)].

In Figure 1 the new concept of steel truss N type connection, which is studied herein, is presented. The socket in the flanges of RHS chord was made using Advanced Manufacturing (AM) technology (3D industrial laser cutting). In the slots of this socket the compressed RHS branch was inserted. The tension bracing contains of two elements. First of it contains two anchor blocks produced with the 3D printer and second is the round steel bar. Twisting nuts on the treaded ends eliminate clearances between the round bar of tension bracing and anchor blocks. This allows transmit stress to the top parts of anchor blocks and through they to the down parts up to the truss chord member. Concept of non-welded N RHS joints was presented in works of [Szlendak (2019) & Szlendak, Szpyrka (2020)]. The joint eliminates welding as the typical technology [EN 1993-1-8 CEN (2005)] to connect the compressed and tension bracing with the RHS chord. Procedure for resistance verification of the N RHS joints was presented in [Szlendak, Szpyrka (2020)]. There the failure phenomena, the joint components and theoretical resistance of tested joints (WN3-WN9) were described. The test results show that the anchor blocks have

Figure 1. View of non-welded N type RHS truss joint using AM technology.

much higher resistance than other components. For the studied N type RHS connections it is possible to eliminate the welding and reach the resistance of joint not less than the welded ones.

2 NUMERICAL MODEL

2.1 Material properties

Material properties were taken as averaged values from the material coupon tests and defined on the basis of the actual stress-strain relationship. For the finite element analysis to simulate realistic behaviour, the material model has to be defined by true stress-strain relationship. The engineering data of material properties were converted to real values by applying equation (1) as follows:

$$\sigma_{true} = \sigma_{eng}(1 + \varepsilon_{eng}); \varepsilon_{true} = \ln(1 + \varepsilon_{eng}) \quad (1)$$

where σ_{eng} - engineering stress; ε_{eng} - engineering strain.

Ductile failure of an elastic-plastic material was defined. Beginning of destruction is assumed after achieving an equivalent plastic deformation. A technique with a centre axis algorithm was used to create a finite element mesh with regular shapes. In the area of maximum deformation, the mesh was compacted.

2.2 Assumptions

For estimation load resistance and deformation of the tested joints have been developed the numerical models. These models were created using Abaqus software [Abaqus CAE]. FEM analysis was also applied to the first generation of N type RHS non-welded joints [Szlendak, Oponowicz (2013)].

The FEM model of joint was built of solid elements and the finite element mesh was made using three-dimensional C3D8R eight-node elements with reduced integration, see Figure 2. The element type used in the model represents geometric and material nonlinearities, large deformations and crack simulations. Boundary conditions correspond to the real conditions carried out in experimental studies. In the numerical model, the 'general' contact was assumed between the surfaces, and the contact character was additionally defined as 'normal behaviour', see [Abaqus CAE]. Friction contact was assumed for the contact surface of the RHS chord face and the lower part of the anchor blocks and moreover for the lower part of the anchor block and the upper part of the anchor block. The friction coefficient was assumed to be equal to 0.15. Nine numerical models of joints have been validated according to experimental tests.

Figure 2. Numerical mesh used in FEM analysis for the N RHS truss joint.

3 COMPARISON OF THE TEST RESULTS WITH FEA AND THEORETICAL ESTIMATIONS

FEM models and results of natural scale experiments show the similar behaviour of joints. One of it could be seen in Figure 3. Concentrations of stresses in the ‘teeth’s’ of anchor block in the place of ‘teeth’s’ contact with the slots of chord are obtained, Figure 4. However, experiments confirmed the lack of failure of anchor blocks ‘teeth’s’ and if it will be needed these anchor blocks can be used again.

4 CRITERIA OF THE CONNECTION RESISTANCE

The resistance of a connection for which FEM models exist can be estimated using different criteria. One of them is the permissible displacement of chord flange of studied joint. The second is the Mann-Kendall (M-K) criterion which detects the mutation of the characteristic parameter with load increase.

4.1 Criterion of permissible displacement

From numerical analyzes displacement maps for the joint chord was presented. Criterion of permissible displacement to be equal to the RHS chord flange thickness was proposed for RHS truss welded joints by Wardenier [Wardenier (1982)]. The similar assumption is suggested by the Authors for the non-welded N RHS truss joints. So, for specimens WN4, WN6

Figure 3. Destruction of the RHS webs for the joint WN8: during experiment (left), simulation by FEA (right).

Figure 4. Stress concentration in anchor block - simulation by FEA.

and WN8 the permissible displacement is equal to 3 mm; for WN5, WN7 and WN9 4 mm; for WN1, WN2 and WN3 5 mm. The deformation of the chord flange 3 mm thick (specimen WN4) is shown in Figure 5. For above limited deformations of joints the associated with them loads were registered and shown in Table 1.

Results of performed FEA show close agreement with the experimental data. The permissible displacement criterion can be also successfully applied, see Figure 6.

4.2 The Mann-Kendal (*M-K*) criterion

This criterion was described in detail in the doctoral dissertation [Szpyrka, 2020]. The non-parametric Mann-Kendall test is commonly employed to detect monotonic trends in series of data. The null hypothesis, H_0 , is that the data come from a population with independent realizations and are identically distributed. The alternative hypothesis, H_A , is that the data follow a monotonic trend.

A few years ago, the M-K criterion was used to evaluate HBBC connections [Chen, Zhao, Shao, Zhou (2020)]. Studied FEM connection model contain box-column, H-beam, seat angle, top angle and high strength bolts. The state-of-stress of the HBBC connection allows calculating the strain energy values which were received from the connection's FEA simulation. The Mann-Kendall criterion was used to detect the mutation point on the characteristic curves where statistic of test M-K is a function of connection load. The connection failure criterion is defined by the mutation point R on the characteristic curves shown in Figure 7.

The vector or matrix S_j can be used to form the structural stress S_j composed of the strain energy density values of some or all elements to the j -th load value. The criterion is commonly used to detect trend analysis without a requirement for samples form a few abnormal number or to obey some certain distributions. Structural elements are far apart have little spatial relevance or mutual effect, according to Saint-Venant's. Also, the model and material properties have a significant independent content. In order to determine the UF_k-F_j and UB_k-F_j , curves

Figure 5. View of the displacement for the bottom chord of the joint WN4.

Table 1. Resistance of connections - the criterion of permissible displacement and elastic resistance from experimental tests.

Specimen	Resistance according to the criterion of permissible displacement $N_{el,pd}$ – criterion C1 [kN]	Elastic resistance from experimental test $N_{el,exp}$ – criterion C2 [kN]	$N_{el,pd}/N_{el,exp}$
WN1	*	**	-
WN2	*	129.99	-
WN3	*	**	-
WN4	31.20	33.40	0.93
WN5	49.17	47.60	1.03
WN6	51.90	55.80	0.93
WN7	104.60	93.00	1.12
WN8	100.00	110.00	0.91
WN9	*	130.00	-

* No results, the end of analysis before reaching resistance.
** No results, experiment interrupted before obtaining elastic resistance.

Figure 6. Load-deflection diagram for joint WN4 ($\beta=0.4$, $\lambda_0=33.3$).

shown in Figure 7, intersection of which marks the mutation point R , a statistical analysis should be performed, see [Chen, Zhao, Shao, Zhou (2020)]. The energy data (E) obtained from the numerical analysis for the given time should be listed, that E_i is greater than E_j ($1 \leq j \leq i$) from the sequence $(E_1, E_2, \dots, E_n)$. Determine the sign of all data, possible differences $E_i - E_j$, where $i > j$. These differences are $E_2 - E_1, E_3 - E_1, \dots, E_n - E_1, E_3 - E_2, E_4 - E_2, \dots, E_n - E_{n-2}, E_n - E_{n-1}$. Determine the sign of all differences m_i .

$$m_i = \begin{cases} +1, & \text{gdy } E_i > E_j (1 \leq j \leq i) \\ 0, & \text{otherwise} \end{cases}$$

Then define statistical quantity q_k and mean value $E(q_k)$ and variance $v(q_k)$, calculated by the following equations:

Figure 7. The E-F curve example [Chen, Zhao, Shao, Zhou (2020)].

$$q_k = \sum_{i=1}^k m_i (2 \leq k \leq n) \quad (2)$$

$$E(q_k) = \frac{k(k-1)}{4} (2 \leq k \leq n) \quad (3)$$

$$\nu(q_k) = \frac{k(k-1)(2k+5)}{72} (2 \leq k \leq n) \quad (4)$$

Obtain the gradient:

$$UF_k = (q_k - E(q_k)) / \sqrt{\nu(q_k)} \quad (5)$$

Then $UF_k - F_j$ curve can be obtained, where F_j is the load value for which the energy is calculated. In order to obtain the gradient:

$$UB_k = -(q_k' - E(q_k')) / \sqrt{\nu(q_k')} \quad (6)$$

Repeat previous steps for the sequence inverse ($E_n, \dots, E_2, E_1$). Normalize the new q_k' and then obtain $UB_k - F_j$ curve. The intersecting point R of the UF_k and UB_k curves is the state-of-stress mutation point of the $E_j - F_j$ curve. It presents the starting of the failure process of connection or the ending point of the connection's normal working state. Using the described criterion, the resistance of the connections could be determined.

Criterion M-K can be also applied to the plug & play connections studied herein. The results will be presented in subsequent publications.

5 CONCLUSION

The failure models obtained in simulations using FEM and from experimental tests are very similar.

Resistances obtained from the criterion of the permissible displacements were compared with the resistances from the experimental tests. Results vary by a maximum of 12%, so the

consistency of the results looks satisfactory. The permissible displacement criterion can be successfully applied for FEA of such connections to obtain their resistance.

The criterion M-K seems to be valuable to estimate of the resistance of studied connections modelled by FEM, where the mutation point is revealed as the beginning of the failure process.

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