Net section fracture assessment of steel bolted joints with shear lag effect

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Abstract. Bolted connections are willingly used in steel structures because of their easiness of fabrication and assembly, but often they are the weakest component in the construction. In case of tensile lap connections, fracture of net cross section usually determines a joint capacity. Additionally, possible eccentricities can affect the distribution of stresses in the cross section and hence its load capacity. Analysis of fracture is a completely different issue compared to well-known and established problems of stability or plastic resistance. Paper relates to steel angle tension members connected by one bolt. It starts from the description of experimental investigations which results were used for hierarchical validation of computational models. Choice between two types of material models (elastic-plastic and Gurson–Tvergaard–Needleman) and building of FE models, representing different degrees of complexity, were described. Paper ends with parametric study taking into account influence of the edge distance from the centre of a fastener hole to the adjacent edge of angle. The paper’s aim is to verify and present the methodology for fracture prediction in steel angle tension members, which can be next extended for bolted joints with larger number of bolts and different geometrical configurations.

1 Introduction

Resistance of elements made of structural steel is based on such ultimate limit states as plastic capacity of cross section, loss of local or global stability and also fracture of cross section in tension. Analysis of fracture, especially prediction of ductile fracture using micromechanics-based models, is from physical point of view a completely different issue compared to well-known and established problems of stability or plastic resistance. So, available works on fracture resistance are mostly limited to accidental design situation (exceptional conditions such as explosion, impact or the consequences of localized failure) or to seismic design situations [1-3]. Despite this fact, methodology developed in these areas can be exploited in certain class of resistance problems in persistent design situations. Fracture is dominating failure mode in case of the net cross-section in tension. Its resistance is strongly influenced by existence of holes and openings and also by shear lag effect, which is defined as non-uniform tensile stress distribution in a member or connecting element in the vicinity of a connection [4-6].

Paper relates to steel angle tension members connected by one bolt and to prediction of their ultimate resistance. It starts from short description of experimental investigations which results were next used for hierarchical validation of computational models. In next stage choice between two types of material model (elastic-plastic and Gurson–Tvergaard–Needleman) was described. In further part, creation of finite element

models is discussed, concerning two its types, representing different degrees of complexity. Paper ends with parametric analysis taking into account influence of the edge distance from the centre of a fastener hole to the adjacent edge of angle.

The main aim of the paper is to present and verify the methodology for fracture prediction in steel angle tension members, which can be next extended for bolted joints with larger number of bolts and different geometrical configurations.

2 Experimental investigation

2.1 Single plates with drilled holes

The first stage of the experimental investigation included elements in the form of single plates with holes fabricated by drilling. Generally ten specimens were tested and six additional standard coupons were used to obtain material characteristics. Seven specimens had one hole located symmetrically, two of them had double holes and one had eccentrically located hole (Fig. 1). The diameters of holes d_0 varied in the range from 12 to 50mm (Table 1). The plates had the same dimensions of cross-section ($t=6\text{mm}$, $b=70\text{mm}$) and length ($l=570\text{mm}$). They were made of steel with nominal grade S355. The specimens were tensioned until fracture, with displacement control manner. Displacements were measured by optical extensometer.

Fig. 1. Geometry of single plate specimen (dimensions in mm).

Table 1. Summary of single plate specimens.

Specimen	Nominal diameter [mm]	N _{EX} [kN]	N _{FEA,1} [kN]	N _{FEA,2} [kN]
W1	12	200.3	196.9	194.5
W2	18	182.0	175.8	174.9
W3	24	163.2	155.2	155.0
W4	30	141.3	136.6	136.2
W5	38	115.5	108.9	109.0
W6	42	101.9	95.6	95.2
W7	50	70.5	67.6	67.7
W8	2x12	202.7	196.2	197.0
W9	2x12	166.3	156.3	159.9
W10	24	148.9	146.2	147.3

2.2 Angles connected by one leg to gusset plates

The next stage of the experimental testing included equal leg angles connected by one bolt to the gusset plates, as is shown on Figure 2. The specimens were made of three different sizes of angles, each of them were made of steel with nominal grade S235. Bolts class 8.8, with diameters within the range from M12 to M22, were placed with different distance e_2 from the edge. Bolts were fully threaded. Utilisation of fully threaded bolts becomes now a common practise, because of one bolt size can be universally used for larger number of connections.

The test results and precise description of specimens and adopted testing method are included in [7]. Eight specimens, for which computer analyses were conducted, are described in Table 2. Similarly to single plates with holes, angle specimens were tensioned until fracture, with displacement control and monitoring of force and displacement. Reference points used by optical extensometer to measure displacements are shown in Figure 2.

Fig. 2. Geometry of bolted angle specimen.

Table 2. Summary of selected angle specimen.

Specimen	Cross-section	Bolt/ e_2	N _{EX} [kN]	N _{FEA} [kN]
J60/18/24	L60x6	M18/24	93.0	86.4
J60/20/27	L60x6	M20/27	83.8	87.8
J60/20/31	L60x6	M20/31	130.9	116.4
J60/22/27	L60x6	M22/27	105.6	93.4
J80/22/29	L80x6	M22/29	133.6	113.2
J80/22/32	L80x6	M22/32	132.1	122.4
J80/22/36	L80x6	M22/36	149.3	139.6
J80/22/39	L80x6	M22/39	177.6	157.5

3 Validation and verification of FE models

3.1 Choice of material modelling

Elements of hierarchical verification and validation were used during development of computational models built by means of FE package ABAQUS [8].

First of all choice between two types of material models (elastic-plastic and Gurson–Tvergaard–Needleman) was done. In order to verify ability of each material model to predict failure process of elements, results from single plates with drilled holes were utilized. Additional results to supplement material modelling were obtained from coupon tests (cut from the same plate that the elements with drilled holes from the first tested series, and from angles legs in second series). Such coupon tests were prepared, tested and their results were interpreted according to EN 10002-1 [9].

The results of the mentioned tests were used to create computer simulations of elements and to calibrate elastic-plastic (EP) and the Gurson–Tvergaard–Needleman (GTN) material model.

3.1.1 Elastic-plastic material model

All FE models were developed using the package ABAQUS in which material behaviour may be represented by a multi-linear stress-strain curve in terms of true stress and true plastic strain calculated from following relationships:

$$\sigma_{true} = \sigma_{nom}(1 + \epsilon_{nom}) \quad (1)$$

$$\epsilon_{true,pl} = \ln(1 + \epsilon_{nom}) - \sigma_{true}/E \quad (2)$$

The true stress and strain were evaluated from the standard tensile tests. The elastic behaviour was defined by Young's modulus and Poisson's ratio, equalling $E=210000$ MPa and $\nu=0.3$.

3.1.2 Gurson–Tvergaard–Needleman material model

To compare relatively simple elastic-plastic material model with more sophisticated one, which properly control the fracture process, the GTN material model

available in ABAQUS software was implemented in the next step. This type of material is classified as porous material and takes into account the influence of microstructural damage on the load capacity and material strength. Damage of the microstructure occurs in the form of voids, which are initiated on the inclusions present in the material. The destruction process takes place through the growth and merging of voids through localized plastic deformation, which is described in [10]. The Gurson-Tvergaard-Needelman yield condition is expressed as follows:

$$\Phi = \left(\frac{\sigma_e}{\sigma_0}\right)^2 + 2q_1 f^* \cosh\left(q_2 \frac{3\sigma_m}{2\sigma_0}\right) - (1 + q_3 f^{*2}) = 0 \quad (3)$$

where: Φ - non-dilatational strain energy, σ_e - effective stress according to the HMM hypothesis, σ_0 - yield stress of the material, σ_m - hydrostatic pressure (mean stress), f^* - modified void volume fraction, q_i - Tvergaard's parameters describing the plastic properties of the material.

The modified void volume fraction f^* is defined as follows:

$$f^* = \begin{cases} f & \text{for } f \leq f_c, \\ f_c + \frac{\bar{f}_F - f_c}{f_F - f_c} (f - f_c) & \text{for } f_c < f < f_F, \\ \bar{f}_F & \text{for } f \geq f_F, \end{cases} \quad (4)$$

where: f_c - critical void volume fraction at which the void coalescence starts, f_F - void volume fraction corresponding to the complete loss of the material strength, at final separation of the material, $\bar{f}_F = [q_1 + (q_1^2 - q_3)^{1/2}] / q_3$.

When the material is not subjected to the loading and deformation, modified void volume fraction f^* is equal to the initial void volume fraction f_0 , which is a basic GTN material parameter connected to the material porosity. The value of this parameter can be calculated on the basis of the chemical composition (5) [11], where Mn and S are the values of manganese and sulphur inclusions determined from the code [12]. Tvergaard parameters were assumed: $q_1=1.5$; $q_2=1.0$; $q_3=2.25$, which are the standard values for most metal materials.

$$f_0 = 0.054 \left(S\% - \frac{0.001}{Mn\%} \right) \quad (5)$$

Another important parameter of this material model is voids nucleation intensity:

$$A = \frac{f_N}{s_N \sqrt{2\pi}} \exp \left[-\frac{1}{2} \left(\frac{\varepsilon_m^p - \varepsilon_N}{s_N} \right)^2 \right] \quad (6)$$

where: f_N - void volume fraction of the nucleating particles, ε_{mp} - plastic nucleation strain, ε_N - mean plastic nucleation strain, s_N - standard deviation.

The final material parameters that were introduced to ABAQUS program are presented in Table 3.

Table 3. GTN material model parameters.

f_0	q_i	f_N	ε_N	s_N	f_c	f_F
0.0024 (S355) 0.001 (S235)	$q_1=1.5$ $q_2=1.0$ $q_3=2.25$	0.02	0.3	0.1	0.06	0.2

3.1.3 Influence of material modelling

Comparison between force-displacement curves gained from experimental tests and force-displacement curves created on the base of FE models, with elastic-plastic (EP) and GTN material parameters is shown in Figure 3. The referential curves were obtained from tensile tests of standard coupons for steel with nominal grade S355 and S235. It can be seen, that compliance of the results is satisfactory, however there is a slight difference in point, where the curves start to descend.

Fig. 3. Comparison of force-displacement curves for standard tensile coupons obtained from experimental tests and FEA models with EP and GTN material model.

Figures 4 and 5 show similar relationships for specimens with drilled holes. Specimens with holes are characterized by larger degree of stress concentration compared to standard coupons. Specimens were divided into two groups: plates with small holes (where the ratio d_0/b is in the range from 0.15 to 0.45) and with large holes (where d_0/b is in the range from 0.5 to 0.75). The ratio of d_0/b influences on level of stress and strain concentration in tested specimens.

In case of force-displacement curves for specimens with drilled holes, obtained results are characterised by slightly greater disjunction.

In Table 1, with reference to test results, the values of ultimate resistance corresponding to maximum load level obtained in Finite Element analysis are shown. Values of $N_{FEA,1}$ correspond to ultimate resistance predicted by FE analysis with EP material model and $N_{FEA,2}$ come from GTN material model. Tested specimens demonstrated little bit higher resistances than FEA models. Mean value of $N_{FEA,1}/N_{EX}$ and $N_{FEA,2}/N_{EX}$ is almost the same and equal to 0.96. So, both material models show the same degree of accuracy in resistance domain.

Fig. 4. Force-displacement curves for tensile specimens with drilled holes obtained from experimental tests and FE models with EP material model; a) group with small holes; b) group with larger holes.

Fig. 5. Force-displacement curves for tensile specimens with drilled holes obtained from experimental tests and FE models with GNT material model; a) group with small holes; b) group with larger holes.

Comparing elongation, results obtained from FE analysis show influence of material modelling. As a reference to displacement capacity comparison between obtained results, point on descending part of the each curve was chosen, which corresponds to plastic resistance of the net cross-section of specimen (Fig. 4b). Global, average proportions are equal to $\Delta_{FEA,1}/\Delta_{EX}=1.17$ and $\Delta_{FEA,2}/\Delta_{EX}=0.93$ for all specimens, where Δ_{EX} corresponds to displacement from test and $\Delta_{FEA,1}$, $\Delta_{FEA,2}$ are displacements obtained in the same way from FE analysis for EP and GTN material model respectively. It can be seen (Fig. 4 and 5), that proportions $\Delta_{FEA,1}/\Delta_{EX}$ and $\Delta_{FEA,2}/\Delta_{EX}$ depend also on ratio of d_0/b . In case of plates with small holes ($d_0/b=0.15\div0.45$) $\Delta_{FEA,1}/\Delta_{EX}=1.29$ and $\Delta_{FEA,2}/\Delta_{EX}=0.96$, while in group with larger holes ($d_0/b=0.5\div0.75$) $\Delta_{FEA,1}/\Delta_{EX}=0.87$ and $\Delta_{FEA,2}/\Delta_{EX}=0.86$.

The greatest accuracy in displacement domain was observed in case of GTN material model and specimens with small holes. In real steel structures rather small proportion of d_0/b is used to keep correct ratio between net section resistance and bolt resistance. So, it can be said that the GTN material model approximates the real behaviour of the material in case of fracture modelling, with good accuracy, considering both resistance and displacement capacity.

The following illustration (Fig. 6) indicates also the proper behaviour of the GTN material model in numerical analyzes. The sequence and initiation and propagation of fracture obtained during FE analyses are identical as observed during the tests.

Fig. 6. Qualitative comparison of specimens with drilled holes fracture (on the left side – FEA models with GTN material, on the right – experimental tests).

3.2 Building of bolted joint FE model

3.2.1 General description

The next step of hierarchical validation of computational model was to build FE model of whole bolted joint with angle element connected by one leg. Such joint is characterised by shear lag effect and large stress concentration caused by eccentricity and existence of bolt hole (net cross-sections). Also load transmission between the angle and the gusset plate occurs by single, fully threaded bolt, which applies a distributed pressure load in the bolt hole, close to net cross section.

Finite element models consisted of four element groups: angle, gusset plate, bolt and washers. Due to the symmetry and to save calculation time, only half of the angle specimen shown in Fig. 2 was modelled. Some part of the gusset plate had blocked displacement in x and y axis direction. The load in z -direction in the form of velocity was also applied to the gusset plate. The end of angle couldn't move in z -direction. Both washers and bolt were located concentrically with holes in angle and gusset plate. The picture below (Fig. 7) presents the view on complete model with finite elements mesh.

Fig. 7. FE model of angle specimen.

Elastic-plastic material properties were implemented for gusset plate, bolt and washers. Material properties of bolts were gained from bolts tensioning experiments. For whole angle members, where fracture was expected, GTN material model was applied with parameters shown in Table 2.

For single plates specimens with holes C3D8I type of element was employed, because of its enhanced bending behaviour. It is defined as a three-dimensional, hexahedral eight-node linear brick with incompatible modes. This element is suitable for complex linear and nonlinear analyses involving contact, plasticity and large deformations, and also has proved to be suitable when simulating lap bolted connections [4,5,13,14]. To model angle specimens, C3D8R element with reduced integration was selected due to reduction of running time. Because of porous material model, dynamic explicit analysis was conducted in both cases.

To model bolt, C3D8T and C3D6T elements were used. They are, respectively, 8-node thermally coupled bricks with trilinear displacement and temperature and 6-node thermally coupled triangular prisms with linear

displacement and temperature. Triangular prism were used to complete the mesh.

Pretension force was introduced during modelling of bolt. This initial clamp was relatively small, because considered joints were A category according to EN 1993-1-8 [15], in which no preloading and no special provisions for contact surfaces are required. Clamping force has value corresponding to the preloading, which was applied during the assembly of specimens used in the tests. To apply pretension force F_p over bolt, vertical thermal deformation method was employed [16]. In this method, the thermal expansion coefficient is assumed to be unit and the temperature difference ΔT causing preload is calculated from relation:

$$\Delta T = 4F_p / \pi d^2 E \quad (7)$$

Contact between components that are expected to interact with each other was defined using general contact option. The frictional effects between surfaces were also included by incorporating the classical isotropic Coulomb friction model in the contact definition, with a friction coefficient μ equal to 0.2.

3.2.2 Influence of bolt thread modelling

During experimental testing full thread bolts were employed to connect angles with gusset plates. In such case threaded part of the bolts directly bears to internal parts of bolt holes, which can influence local yielding of the plates and global deformability of joint.

To consider influence of bolt detailing during FE analysis on global behaviour of joint, two types of FE models were considered. In first type, shank of the bolt was modelled as smooth cylinder (Fig. 8a). In second type, to imitate the actual connections as faithfully as possible, bolt thread was modelled in the shank (Fig. 8b). In case of the former specimen, the diameter of the cylinder was equal to the nominal diameter of the bolt. In second specimen, the thread geometry corresponded to the standard dimensions of the bolt and its thread. In both models bolt was located concentrically with holes in angle and gusset plate. The purpose of this approach was to check to what extent this influences the results of the analyses.

Fig. 8. Finite element mesh on bolt M20; a) without the thread, b) with the thread.

Figure 9 shows deformation of plates bearing to the bolt and also effective stress on bolt cross section. In

such analysis FE model of J60/20/27 specimen was considered.

Looking at Figure 9, it can be said that modelling of the thread on the bolt shank influence on local behaviour, in vicinity of the bolt. In model skipping the thread, the bolt rotation is noticeable which correspond to observations from experimental testing. In second model, including thread on the shank, the thread inserts into angle and the rotation of bolt is limited.

Fig. 9. Effective stress in bolts; a) without the thread, b) with thread.

But global difference between this two types of modelling is negligible. Force-displacement curves for J60/20/27 specimen, coming from test and from two types of FE analysis (including and skipping the thread on the bolt) are shown in Figure 10. It can be seen that the differences between these both models, in terms of resistance and deformation capacity are insignificant. However, modelling of threaded shank of the bolt has increased calculation time several times. So, for further calculations it was decided to use a bolt model without a thread.

Fig. 10. Force-displacement curves obtained for J60/20/27 specimen and its FE models.

3.2.3 Comparison of FE modelling and test results

The range of FE models of angles connected by one leg to gusset plates is presented in Table 2. Maximum values of tensile force gained from experimental test (N_{EX}) and numerical simulations models (N_{FEA}) are also shown in this Table. The differences between them are in the range of 5% to 15%. It can therefore be concluded that the convergence of results is satisfactory. However elongation of specimens is not identical, as it can be seen

on Fig. 11 and Fig. 12. Generally, deformation capacity obtained from of FE models is noticeably shorter compared to the real ones. But qualitative comparison of behaviour of FE models to real behaviour observed during the test shows high degree of accuracy, in terms of deformations and fracture character (Fig. 13 and Fig. 14).

Fig. 11. Force-displacement curves for J60 test specimens and FEA models.

Fig. 12. Force-displacement curves for J80 test specimens and FEA models.

Fig. 13. Bending deformation of specimen J80/22/36; a) test results, b) FE modelling.

Fig. 14. Qualitative comparison of the way of angle specimens destruction; a) test results, b) FE modelling.

4 Parametric study – ultimate resistance of angles connected by one leg

Validated and presented in previous chapters methodology for fracture prediction in steel angle tension members was utilised to verify design rules from EN 1993-1-8 [15].

EN 1993-1-8 [15] gives formulas for calculating the load capacity of single angles in tension connected by a single row of bolts in one leg. Such elements can be treated as concentrically loaded over an effective net section. For angles connected by only one bolt, the design ultimate resistance should be determined as follows:

$$N_{u,Rd} = 2,0 (e_2 - 0,5d_0) t f_u / \gamma_{M2} \quad (8)$$

where: e_2 – edge distance (Fig. 2), d_0 – diameter of fastener hole, t – thickness of connected arm, f_u – ultimate strength of steel, γ_{M2} – partial factor, equal 1.25 for bolted connections.

The range of parametric study covered the tested group of angle specimens connected by one leg, with angles L80x6 (Table 2). The aim of analysis focused on the influence of edge distance e_2 on the angles behaviour and ultimate resistance. Results from finite element models of joints used in previous chapter were utilized. Two additional FE models were created (with $e_2=33\text{mm}$ and $e_2=37\text{mm}$) to get more accurate relationship between ultimate resistance in relation to edge distance e_2 . The range of parametric study is shown in Table 4.

Table 4. Parametric study results

Specimen	Actual e_2 [mm]	N_{EC3} [kN]	N_{FEA} [kN]	Δ [%]
J80/22/29	28.4	93.1	113.2	21.6
J80/22/32	30.7	107.2	122.4	14.2
J80/22/33	33.0	120.7	131.0	8.5
J80/22/36	34.6	131.9	139.6	5.8
J80/22/37	37.0	143.7	148.4	3.3
J80/22/39	38.9	153.8	157.5	2.4

The ultimate resistances of joints obtained from FE modelling and from test results were compared to ultimate tensile resistance calculated according to the

formula (8). For the needs of comparison, characteristic values of ultimate resistances were calculated from (8) assuming the actual dimensions of the elements, the ultimate tensile strength obtained from the experimental tests and the partial factor equal to $\gamma_{M2}=1.0$. Obtained results are presented in Table 4 and in Figure 15.

Fig. 15. Comparison of ultimate tensile resistance calculated according to Eurocode 3, FEA models and gained from experimental tests.

Obtained results confirmed dependence of ultimate resistance on edge distance e_2 in all considered cases. This is visible in Fig. 15, both for experimental and numerical simulations results. Despite the fact that the actual ultimate strength of steel was taken into account for the calculation, Eurocode formula (8) gives lower values of ultimate resistance of angles connected by one leg for all specimens. Ultimate resistance determined on the basis of finite element modelling including GTN material model is slightly higher (21.6% to 2.4%) compared to results from formula (8). Although, it can be observed that the greater the distance from the edge e_2 , the smaller the difference between the results (Fig. 15).

Fig. 16. Effective true stress along net cross section for different loading level for J60/20/27 specimen (N_u – ultimate resistance of angle connected by one leg).

It can be concluded that the resistance determined on the base of code formula (8) is little underestimated, which gives a reason to further analyses. In such analysis FE modelling with material including damage of the microstructure can be used. Such models can give better insight into process of redistribution of stress along net cross section during increasing loading, (Fig. 16).

5 Summary and conclusions

In this paper net section fracture assessment in steel lap connections with one bolt were conducted basing on experimental tests and computational models. Hierarchical validation was used to achieve appropriate compatibility of numerical simulations with test results. Thanks to application of porous material model, fracture of angle member was simulated. The presented computer models show proper behaviour under load acting, corresponding to real specimens. This allows to carry out further numerical simulations for angles connected to a larger number of bolts and perform parametric analyzes for a larger range of variables.

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