Load–deflection behaviour of thin-walled plates with a single bolt in shearing

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ABSTRACT

This paper presents an experimental, numerical and analytical study of the behaviour of thin-walled plates connected by a single bolt under shear. Eighteen tests were carried out to provide detailed data of load–deflection and load–strain curves for validation of the finite element simulation model. The validated finite element model was then used to perform a comprehensive set of parametric studies to investigate the effects of different design parameters on the connected plate behaviour, including initial stiffness, ultimate resistance and maximum deformation at the ultimate resistance. It was found that the stiffness and ultimate resistance could be predicted accurately by using existing methods. The analytical study therefore focused on developing a method to calculate the maximum plate deformation (hole elongation) at the ultimate resistance. Based on the parametric study results, methods of calculating the ultimate deformation were proposed, based on different failure modes of the connection.

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1. Introduction

Cold-formed thin-walled steel has been used in many areas of civil engineering construction. In cold-formed thin-walled steel structures, bolted connection is often used. Currently, design codes for cold-formed thin-walled steel structures (e.g. EN 1993-1-3) may be used to obtain stiffness and load carrying capacity of connections. However, there is no method to evaluate the complete load–deflection curve, in particular, the deformation capacity of connections. The current status is acceptable if the designer is only interested in structural strength under normal condition or the loading condition in the structure does not change. However, when a structure is under accidental loading such as fire, the load carrying mechanism may change or the loading condition in the structure may change.

For example, in sandwich panel construction, catenary action may be activated to enable partially damaged structure to sustain the applied load [1]. The ability of a structure to develop catenary action depends on the tensile capacity and deformation capacity of the connection [2]. Also, when a beam–column structural connection is exposed to fire, forces in the connection vary throughout the fire exposure. Knowing only the load carrying capacity of the connection components is no longer adequate and it is necessary to have detailed load–deformation behaviour of the components to quantify connection behaviour.

The objective of this research is to develop an analytical method to quantify the complete load–deflection behaviour of bolted thin-walled steel plates in bolt shear, illustrated in Fig. 1. This paper will deal with one single bolt, but the resulting load–deflection behaviour will be able to be used in the so-called component based method [3] to deal with multiple bolts. In the component based method, a connection is split into many single individual components which are treated as springs with specified load–deflection behaviour. These “springs” are then connected in series or parallel ways to represent the connection. The component based method combines flexibility and simplicity and is now firmly established as the preferred method of analyzing hot-rolled connection behaviour and is included in EN 1993-1-8 [3].

Despite bolted connector being ubiquitous in thin-walled connections, a review of past research studies by the authors revealed very limited information on the load–deflection characteristics of this component. Rogers and Hancock [4,13] conducted a series of thin-walled steel connection tests to develop a method to calculate bolted connection bearing failure loads for thin-walled G550 & G300 steel sheet connection; Rex and Easterling [5] focused on the initial stiffness of the bearing component; Kim and Kuwamura [6] developed a FE model to simulate the bearing behaviour of thin-walled stainless steel bolted connections, focusing on the failure loads under different failure modes without providing information on displacement quantification.

Because of this lack of load–deflection behaviour, the authors conducted a series of 18 tests to obtain experimental results to allow the authors to validate their numerical models. The validated numerical model will then be used to conduct an extensive

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Nomenclature

A_n	net cross-section area
d	bolt-hole diameter
e_1	end distance
e_2	edge distance
k	initial stiffness

F_t	net-section failure load
F_s	end pull-out failure load
$F_{b,Rd}$	bearing failure load
f_u	ultimate tensile stress
p_1	spacing of bolt-rows in load transfer direction
t	plate thickness

parametric study to develop a component behaviour database from which an analytical method can be derived to predict the complete load–deflection behaviour. This paper will present the experimental results, validation of the finite element modelling using the commercial software ABAQUS [7] and parametric study results, and the development and validation of an analytical model.

2. Test arrangement

In total, 18 tests were conducted and Table 1 lists the main parameters of these tests. These tests used 1.5 mm thick plates and 12 mm bolts with 14 mm bolt-holes. The tests were designed to investigate the effects of different end/edge distance combinations

and their effects on failure modes. Tensile coupon tests were carried out according to BS EN 10002-1:2001 [8]. Fig. 1 shows the experimental set-up with indication of the locations of displacement and strain measurement. The displacement transducer was attached on the plate to track the movement of the bolt head due to bolt-hole elongation. Two thick plates were placed on two sides of the thin-walled steel plate to prevent curling. Fig. 2 shows a test in progress.

3. Validation of finite element modelling

The commercial software Abaqus was used to simulate the tests. This section describes the main points of the simulation and compares the simulation and test results.

Fig. 1. Bolted connection test set-up.

Table 1
Main parameters of tests.

Test ID	Number of replicate tests	Bolt diameter (mm)	Bolt hole diameter d (mm)	End distance (mm)	Edge distance (mm)
D14-14-28	3	12	14	14 (1d)	14 (1d)
D14-21-42	3	12	14	21 (1.5d)	21 (1.5d)
D14-20-80	3	12	14	20 (1.43d)	40 (2.86d)
D14-28-80	3	12	14	28 (2d)	40 (2.86d)
D14-70-40	3	12	14	70 (5d)	20 (1.43d)
D14-70-80	3	12	14	70 (5d)	40 (2.86d)

3.1. Material properties

It should be noted that the data attained from tensile coupon tests are engineering stress and strain. They should be transferred into true stress and true strain according to the following formulas:

$$\sigma_t = \sigma_n(1 + \varepsilon_t) \quad (1)$$

$$\varepsilon_t = \ln(1 + \varepsilon_n) \quad (2)$$

3.2. Element types and mesh size

The ABAQUS simulation model used C3D8R element, which is a three-dimensional, reduced integration solid hexahedral brick element with 8 integration nodes. This element is suitable to be used in both linear and non-linear analysis at large strain and deformation. The reduced integration gives good control on hourglass effect and reduces calculation time. Using brick elements gives detailed information on failure mode, failure load, strain and stress results.

Fig. 2. A test in progress.

A mesh sensitivity study was carried out to determine the best mesh size. Mesh size of $\frac{1}{4}$ plate thickness was found to be sufficient and was applied to places in the structure where a fine mesh was required, i.e. the area around the bolt-hole. For example, Table 2 compares the simulation results using different mesh sizes for one of the tests by Kim and Kuwamura [6] and one of the authors' own tests, using different mesh sizes. The difference in connection failure load is very small, less than 2%. Fig. 3 shows a typical finite element mesh used.

3.3. Geometric simplification

The tested thin-walled steel plate was much more flexible and weaker than the bolt used. In fact, in all tests the bolt showed no visible deformation after the tested plate failed. Therefore, in the simplification, the bolt was modelled using rigid hollow shell elements which did not deform during the entire simulation. This considerably reduced the element number in simulation models and simulation time.

3.4. Comparison between simulation and test results

Three duplicate tests were conducted for each arrangement. All three tests were similar so only the mean results are used in this paper. Table 3 compares the recorded and simulated plate failure loads. Fig. 4 compares the observed and simulated failure modes. Fig. 5 compares the recorded and simulated plate load–deflection relationships. The plate deflection was the bolt hole elongation. Fig. 6 presents a selection of recorded and simulated load–strain results.

The results in Table 3, Figs. 4 and 5 confirm that the finite element model was able to accurately predict the failure mode, failure load and load–deformation curves of all the tests.

Fig. 3. Typical mesh for plate.

Table 2
Results of mesh sensitivity study.

Finite element size (width*length)	No. of elements	Increase in mesh size (%)	Simulation time (s)	Test strength P_e (KN)	Simulation strength P_s (KN)	P_s/P_e
<i>Test SB2-4 of Ref. [6]</i>						
$t/2*t/2$	7188	0	1603	85.62	92.17	1.077
$t/3*t/3$	15,015	109	5006		90.95	1.062
$t/4*t/4$	25,527	255	8961		90.57	1.057
<i>Authors' test D14-70-40</i>						
$t/2*t/2$	5833	0	633	13.65	13.99	1.025
$t/3*t/3$	9709	66	3025		13.75	1.007
$t/4*t/4$	15,325	163	6221		13.53	0.991

Table 3
Comparison of test and simulation results for connection failure load.

Test ID	End distance (mm)	Edge distance (mm)	Recorded failure load (kn)	Simulated failure load (kn)	Recorded failure mode	Simulated failure mode
D14-14-28	14	14	7.41	6.49	End pull-out	End pull-out
D14-20-80	20	40	12.00	10.92	End pull-out	End pull-out (see Fig. 4)
D14-28-80	28	40	15.96	14.43	End pull-out	End pull-out
D14-21-42	21	21	11.58	10.88	End pull-out	End pull-out
D14-70-40	70	20	13.65	13.46	Net-section	Net-section (see Fig. 4)
D14-70-80	70	40	19.52	19.48	Bearing	Bearing (see Fig. 4)

D14-70-40

Net section failure

D14-20-80

End pull-out failure

D14-70-80

Bearing failure

Fig. 4. Comparison of test and FE simulated failure modes.

Fig. 5. Comparison of test and simulation load-displacement results for all tests.

The results in Fig. 6 show that the finite element model accurately simulated all the load-strain relationships except for one case (end pull-out strain at point 1 and 2) which was caused by strain gauge failure due to large deformation of the plate at the strain gauge area, as shown in Fig. 7.

From the above comparisons, it can be accepted that the FE model is sufficiently accurate and can be used to investigate the behaviour of this type of structure for the development of an analytical method.

4. Parametric study and development of analytical load-deflection curve

4.1. Parametric study

In order to develop an analytical model to predict the load-deflection behaviour of thin-walled steel plates loaded by a single bolt in shear, an extensive set of parametric studies were performed

Fig. 6. Comparison of recorded and simulated load-strain curves.

to establish a comprehensive database of results. Table 4 lists the parameters investigated, intended to assess the effects of the following parameters: bolt-hole size, end distance, edge distance and ultimate strain of steel. In total 56 simulations are performed.

4.2. Determination of key values in analytical load-deflection curve

The analytical load-deflection curve is assumed to be linear-elastic-plastic, as shown in Fig. 8. Therefore, three values are required to determine the analytical curve: initial stiffness, strength and deformation capacity.

4.2.1. Initial stiffness

Eurocode 3 provides the following equation for calculating bolt bearing initial stiffness:

$$k = 24n_b k_b k_t d f_u \quad (3)$$

where k_b is a factor that considers the effect of end distance and bolt row spacing and $k_b = \min\{k_{b1}, k_{b2}, 1.25\}$ with $k_{b1} = 0.25e_1/d + 0.5$, $k_{b2} = 0.25p_1/d + 0.375$, $k_t = 1.5t_j/d_{M16}$ which is a reduction factor for steel plate thickness and d_{M16} : nominal diameter of a M16 bolt.

This formula is intended for use with hot-rolled steel connection. However, close agreement between the test, simulation and analytical calculation results in Table 5 suggests that it can also be used to predict initial bearing stiffness for cold-formed thin-walled steel connections.

4.2.2. Strength

There are three possible failure modes: net section tensile fracture, end pull-out and bearing failure.

The net section tensile fracture capacity is

$$F_t = A_n f_u = (2e_2 - d) t f_u \quad (4)$$

In an earlier version of Eurocode 3 [9], the end pull-out capacity was calculated using

$$F_s = te_1 f_u / 1.2 \quad (5)$$

And the bearing resistance was calculated using

$$F_{b,Rd} = 2.5dt f_u \quad (6)$$

but $F_{b,Rd} \leq te_1 f_u / 1.2$

In the latest version of Eurocode 3 [10], the above two equations are combined to give the following single equation:

$$F_{b,Rd} = 2.5\alpha_b k_t f_u dt \quad (7)$$

where k_t is 1 if there is no net section failure. α_b is taken as the smaller value of $e_1/3d$ (end pull-out) and 1 (bearing).

In the Australian/New Zealand [11] and North American design standards [12], the end pull-out resistance formula is similar, only the reduction factor 1.2 is excluded, i.e.

$$F_s = te_1 f_u \quad (8)$$

Table 6 compares the ABAQUS simulation results with predictions for connection strength from the different prediction methods. It appears that for end pull-out, the New Zealand/Australian standard of not including a modification factor of 1.2 gives better results.

From the comparisons for initial stiffness and load carrying capacity under different failure modes, it can be confirmed that the existing design calculation methods for these two quantities are sufficiently accurate.

Fig. 7. Damaged strain gauges at point 1 and 2 of Test D14-20-80.

4.2.3. Deformation capacity

The main focus of the analytical load–deflection develop is to determine the connection deformation at the ultimate capacity.

Here the connection deformation refers to elongation of the bolt hole. Due to symmetry, bolt hole elongation is the tensile deformation of half of the bolt hole circumference plus any compressive pile up in front of the bolt, as indicated in Fig. 9. Therefore, to calculate the bolt-hole elongation, it is necessary to obtain the tensile strain distribution around the bolt hole and the compressive strain distribution in front of the bolt.

4.3. Tensile strain distribution

After detailed investigation of strain distributions around the bolt hole based on the parametric study results, it was found that

Fig. 8. Assumed analytical load–displacement curve.

Table 5

Comparison of initial stiffness from test, FE simulation and Eurocode 3 calculation.

Test ID	K_1	K_2	K_3	K_2/K_1	K_3/K_1
D14-14-28	10,156	9366	11,290	0.92	1.11
D14-20-80	12,222	14,709	12,945	1.20	1.06
D14-28-80	11,297	15,774	15,053	1.40	1.33
D14-21-42	12,580	15,785	13,171	1.25	1.05
D14-70-40	13,820	16,167	18,816	1.17	1.36
D14-70-80	14,032	16,258	18,816	1.16	1.34

K_1 : initial stiffness from test.

K_2 : initial stiffness from ABAQUS simulation.

K_3 : initial stiffness from Eurocode 3 calculation.

Table 4

List of parameters in parametric study.

Bolt size (mm)	Bolt hole size d (mm)	End distance e_1	Edge distance e_2	Thickness t (mm)	Ultimate strain of steel
8	10	1d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		2d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		3d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		4d	1d, 1.5d, 2d, 2.5d	1.5	0.35
12	14	1.5d	1d, 1.5d, 2d, 2.5d	1.5, 3	0.35
		2d	1d, 1.5d, 2d, 2.5d	1.5	0.25, 0.35
		3d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		4d	1d, 1.5d, 2d, 2.5d	1.5	0.35
18	20	1d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		2d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		3d	1d, 1.5d, 2d, 2.5d	1.5	0.35
		4d	1d, 1.5d, 2d, 2.5d	1.5	0.35

Table 6
Comparison between simulated strength and predictions using different design standards.

Model	End (mm)	Edge (mm)	Failure mode	N_t (kN)	B_1 (kN)	S_1 (kN)	S_2 (kN)	S_3 (kN)	S_1/S_3	S_2/S_3
D14-17.5-56	17.50	28.00	E	20.16	16.8	7	8.40	9.18	0.76	0.92
D14-21-80	21.00	40.00	E	31.68	16.8	8.40	10.08	11.40	0.74	0.88
D14-28-80	28.00	40.00	E	31.68	16.8	11.20	13.44	14.43	0.78	0.93
Model	End (mm)	Edge (mm)	Failure mode	N_t (kN)	B_1 (kN)	S_1 (kN)	S_2 (kN)	S_3 (kN)	N_t/S_3	
D14-21-28	21	14	N	6.72	16.80	8.4	10.08	7.39	0.91	
D14-35-35	35	17.5	N	10.08	16.80	14	16.80	10.96	0.92	
d14-56-35	56	17.5	N	10.08	16.80	22.4	16.8	11.03	0.91	
Model	End (mm)	Edge (mm)	Failure mode	N_t (kN)	B_1 (kN)	S_1 (kN)	S_2 (kN)	S_3 (kN)	B_1/S_3	
d14-35-56	35	28	B	20.16	16.80	14	16.80	15.80	1.06	
d14-42-56	42	28	B	20.16	16.80	16.8	16.8	16.61	1.01	
d14-56-49	56	24.5	B	16.80	16.80	22.4	16.8	15.53	1.08	

Note: S_1 : End pull-out failure load, Eurocode 3 formula; S_2 : End pull-out failure load, New Zealand/Australian Standard formula; S_3 : Simulated failure load; N_t : Net-section failure load; B_1 : Bearing failure load; E : End pull-out failure mode; N : Net-section failure mode and B : bearing failure mode.

the tensile strain distribution around the bolt hole may be assumed to be multi-linear between five key points, as shown in Fig. 9. The strain at points D and E may be assumed to be 0.

The tensile strain values at points A, B and C are dependent on the connection failure mode. As explained in the previous section, there are three pure failure modes: net section tension failure, end pull-out and bearing failure. For strain calculations, the following three mixed failure modes should also be considered to avoid a step change in strain values at the critical points: net section tension/end pull-out, net section tension/bearing, end pull-out/bearing. Fig. 10 compares the assumed tensile strain distributions around the hole (to be presented in the next section) with the numerical simulation results for different failure modes. The assumed strain distributions can be considered acceptable.

4.3.1. Net section failure

For net section failure, it is assumed that the strain at point C is equal to the ultimate tensile strain of steel. For example, Fig. 11 shows that the ultimate tensile strain of steel was 0.35 (cf Table 4). The strain at points A, B, D and E is zero. Fig. 11 shows the assumed strain distribution around the bolt hole.

Net section failure occurs when: $F_t < F_s$ and $F_t < F_b$. Therefore

$$F_t = A_n f_u = (2e_2 - d) t f_u < F_s = t e_1 f_u$$

$$F_t < F_b = 2.5 f_u d t$$

Re-arranging the above equations gives

$$e_2 < (e_1 + d)/2 \quad (9)$$

$$e_2 < 1.75d \quad (10)$$

4.3.2. Pull-out failure

Pull-out failure happens when $F_s < F_t$ and $F_s < F_b$. Therefore

$$F_s = t e_1 f_u \leq F_t = A_n f_u = (2e_2 - d) t f_u$$

$$F_s \leq F_b = 2.5 f_u d t$$

Re-arranging the above equations gives

$$e_1 \leq 2e_2 - d \quad (11)$$

$$e_1 \leq 2.5d \quad (12)$$

When end pull-out happens, it is assumed that the strain at point C, D and E is zero but the strain at B reaches $\varepsilon_B = \varepsilon_t + \mu \varepsilon_r$, where ε_t is the ultimate tensile strain of steel, μ Poisson's ratio (0.3) and ε_r is the radial compressive strain due to bearing. It is assumed that $\varepsilon_r = 1.0$. Therefore, in Fig. 12, the tensile strain at point B is $0.35 + 0.3 \times 1.0 = 0.65$.

The tensile strain at point A equals to the ultimate tensile strain of the steel material, e.g. 0.35 in Fig. 12.

4.3.3. Bearing failure

Bearing failure happens when $F_b \leq F_t$ and $F_b \leq F_s$. These conditions are met when

$$e_2 \geq 1.75d \quad (13)$$

$$e_1 \geq 2.5d \quad (14)$$

When bearing failure happens, it is assumed that the strains at point C, D and E are zero. The strain at point A is $\varepsilon_B = \varepsilon_t + \mu \varepsilon_r$ owing to combined tension and compression in front of the bolt. For example, in Fig. 13, the strain at point A is $0.35 + 0.3 \times 1.0 = 0.65$. The strain distribution between A and C is linear so the strain at point B is half of that at point A. Fig. 13 shows the complete assumed tensile strain distribution around the bolt hole under bearing failure.

Fig. 9. Positions of critical strain points.

5. Mixed failure modes

In the previous section, strain distributions are given for one single failure mode. One single failure mode occurs when the load carrying capacity under this failure mode is much lower than those of the other two failure modes. However, when the calculated failure loads under two different failure modes are similar, using the above strain distributions would introduce artificial step changes. Modifications are therefore necessary to allow a smooth and gradual transition from one failure mode to another.

It is hard to decide exactly when mixed failure mode or pure single failure mode occurs. In order to determine the critical point strain values, approximate boundaries are assumed based on the simulation results.

5.1. Type I: mixed net-section/end pull-out failure

According to Eqs. (9) and (11), net section/end pull-out failure is determined by the ratio of $e_1/(2e_2 - d)$. When this value is less than 1, end pull-out dominates and when this is greater than 1, net section failure dominates. Also since bearing failure does not happen, therefore, $e_1 < 2.5d$ and $e_2 < 1.75d$. It is assumed that at $e_1/(2e_2 - d) = 1$, the strain values at critical points A, B and C are according to end pull-out failure. The transition period is from when $e_2 = (e_1 + d)/2$ to a reduction in e_2 by $0.25d$ when the strain values at critical points A, B and C are calculated for net-section failure. Within the transition region, linear interpolation is used. Fig. 14 shows the assumed strain distributions at points A, B and C as function of e_2 .

5.2. Type II mixed net-section/bearing failure

For mixed net-section/bearing failure, end pull-out failure does not occur. Therefore, $e_1 > 2e_2 - d$ and $e_1 > 2.5d$. According to Eqs. (10) and (13), the condition $e_2 = 1.75d$ marks the separation of net-section failure from bearing failure. It is assumed that at $e_2 = 1.75d$, the strain distribution is according to bearing failure. Pure net-section failure happens when $e_2 < 0.75d$. During the transition period of $0.75d < e_2 < 1.75d$, linear interpolation can be used. Fig. 15 shows the assumed strain values at increasing e_2 .

5.3. Type III mixed end pull-out/bearing failure

For this mixed mode, net-section failure does not occur. Therefore, according to Eqs. (11) and (13), $e_1 < 2e_2 - d$ and $e_2 > 1.75d$. The boundary between end pull-out failure and bearing failure is at $e_1 = 2.5d$. It is assumed that at $e_1 = 2.5d$, bearing failure starts to control. The transition zone is between $e_1 = 1.5d$ and $e_1 = 2.5d$. At $e_1 = 1.5d$, end pull-out governs and the strain values are according to end pull-out failure. Fig. 16 shows the strain values at the different critical points at increasing e_1 .

5.4. Compressive strain distribution

Compression strain is used to calculate plate pile up, therefore, compressive strain is only considered at point C (directly in front of the bolt). Although compression in front of the bolt will exist in all cases, significant compressive strain occurs under bearing

Fig. 10. Comparison between assumed strain distribution and simulated strain distribution for different failure modes.

or end pull-out failure. This happens when $e_2 > (e_1 + d)/2$ and $e_2 > 1.75d$. It is assumed that when the end distance is at $e_1 = 1.2d$ (minimum requirement of Eurocode 3), end pull-out failure controls and the maximum compressive strain value is equal to the steel ultimate tensile strain. At $e_1 = 2d$, bearing failure governs and the compressive strain reaches 1.0. Linear interpolation applies during the transition phase.

Nevertheless, for plates that experience net-section failure mode, there is some compression strain, although the

compressive strain is reduced compared to the other two failure modes. According to Eqs. (9) and (10), net-section failure occurs when $e_2 < (e_1 + d)/2$ and $e_2 < 1.75d$. Within this failure mode, the numerical simulation results suggest that when $e_2 \leq 0.75d$, the compressive strain equals 0. When $e_2 \geq (e_1 + d)/2$, the edge distance is sufficient to achieve the maximum compressive strain specified in the last paragraph. When the edge distance falls between these two values, linear interpolation can be applied to determine the reduced compressive strain value.

Fig. 11. Assumed tensile strain distribution for net-section failure.

Fig. 12. Assumed tensile strain distribution for end pull-out failure.

Fig. 13. Assumed tensile strain distribution for bearing failure.

Fig. 14. Strains at different critical points during transition from net section failure to end pull-out failure.

Fig. 15. Strain values at different critical points during transition from net-section to bearing failure.

Fig. 16. Assumed strain values at different critical points for transition from end pull-out to bearing failure.

In order to calculate the bolt hole elongation due to compressive pile up, it is assumed that the compressive strain changes from the maximum value at the bolt/plate contact point to zero at a distance of one bolt diameter

away (or the actual edge of the plate if less), as shown in Fig. 17.

It should be pointed out that some of the low values of edge and end distances may be outside the range of the permitted edge

and end distances by design standards. However, these limits were not enforced so that the proposed analytical mode is generally applicable, including when the end and edge distances fall within the permitted ranges.

Fig. 17. Compressive strain distribution along plate length.

An example is provided in the Appendix to show how to calculate the strains at the various critical locations and the resulting bolt hole elongation.

To validate the above proposed analytical method, a series of parametric studies have been carried out using ABAQUS, covering different end and edge distances. In most simulations, the bolt diameter was 12 mm, the plate thickness 1.5 mm and the steel ultimate tensile strain 0.35. But simulations using other values of bolt diameter (8 and 18 mm), plate thickness (3 mm) and steel ultimate tensile strain (0.25) were also performed to check applicability of the proposed analytical method to different bolt sizes, plate thickness and steel ultimate tensile strain.

Table 7 compares the ABAQUS simulation results and the analytical results. Fig. 18 summarizes the comparison. The agreement

Table 7
Comparison between simulation and proposed calculation displacements.

End-edge distance	Model name	End distance e_1 (mm)	Edge distance e_2 (mm)	Bolt hole d (mm)	Ultimate strain	Thickness t (mm)	Failure modes	FE model displacement (D_1) (mm)	Calculated result (D_2) (mm)	D_2/D_1
1.5d-1d	21-28	21	14	14	0.35	1.5	N/E	4.42	4.02	0.91
1.5d-1.5d	21-42	21	21	14	0.35	1.5	E	7.93	8.67	1.09
1.5d-2d	21-56	21	28	14	0.35	1.5	E	7.29	8.67	1.18
1.5d-2.5d	21-80	21	40	14	0.35	1.5	E	6.97	8.67	1.24
1.5d-1d	21-28	21	14	14	0.35	3	N/E	4.42	4.02	0.91
1.5d-1.5d	21-42	21	21	14	0.35	3	E	8.51	8.67	1.02
1.5d-2d	21-56	21	28	14	0.35	3	E	8.65	8.67	1.00
1.5d-2.5d	21-80	21	40	14	0.35	3	E	7.24	8.67	1.20
2d-1d	28-28	28	14	14	0.35	1.5	N/E	3.58	4.56	1.27
2d-1.5d	28-42	28	21	14	0.35	1.5	E/B	10.40	9.79	0.94
2d-2d	28-56	28	28	14	0.35	1.5	E/B	9.22	9.79	1.06
2d-2.5d	28-80	28	40	14	0.35	1.5	E/B	8.31	9.79	1.18
2d-1d	28-28	28	14	14	0.25	1.5	N/E	3.00	3.29	1.10
2d-1.5d	28-42	28	21	14	0.25	1.5	E/B	8.79	8.96	1.02
2d-2d	28-56	28	28	14	0.25	1.5	E/B	7.26	8.96	1.23
2d-2.5d	28-80	28	40	14	0.25	1.5	E/B	7.32	8.96	1.22
3d-1d	42-28	42	14	14	0.35	1.5	N/B	3.94	4.64	1.18
3d-1.5d	42-42	42	21	14	0.35	1.5	N/B	8.83	8.63	0.98
3d-2d	42-56	42	28	14	0.35	1.5	B	8.07	10.60	1.31
3d-2.5d	42-80	42	40	14	0.35	1.5	B	8.18	10.60	1.30
4d-1d	56-28	56	14	14	0.35	1.5	N/B	3.96	4.64	1.17
4d-1.5d	56-42	56	21	14	0.35	1.5	N/B	9.51	8.63	0.91
4d-2d	56-56	56	28	14	0.35	1.5	B	8.05	10.60	1.32
4d-2.5d	56-80	56	40	14	0.35	1.5	B	7.66	10.60	1.38
1d-1d	d10-10-20	10	10	10	0.35	1.5	N/E	3.83	3.97	1.04
1d-1.5d	d10-10-30	10	15	10	0.35	1.5	E	4.80	3.97	0.83
1d-2d	d10-10-40	10	20	10	0.35	1.5	E	4.35	3.97	0.91
1d-2.5d	d10-10-50	10	25	10	0.35	1.5	E	4.48	3.97	0.89
2d-1d	d10-20-20	20	10	10	0.35	1.5	N/E	3.18	3.26	1.03
2d-1.5d	d10-20-30	20	15	10	0.35	1.5	N/E	8.14	6.99	0.86
2d-2d	d10-20-40	20	20	10	0.35	1.5	E	6.32	6.99	1.11
2d-2.5d	d10-20-50	20	25	10	0.35	1.5	E	5.42	6.99	1.29
3d-1d	d10-30-20	30	10	10	0.35	1.5	N/B	3.09	2.60	0.84
3d-1.5d	d10-30-30	30	15	10	0.35	1.5	N/B	5.35	5.07	0.95
3d-2d	d10-30-40	30	20	10	0.35	1.5	B	4.78	6.30	1.32
3d-2.5d	d10-30-50	30	25	10	0.35	1.5	B	4.48	6.30	1.41
4d-1d	d10-40-20	40	10	10	0.35	1.5	N/B	3.33	2.60	0.78
4d-1.5d	d10-40-30	40	15	10	0.35	1.5	N/B	5.89	5.07	0.86
4d-2d	d10-40-40	40	20	10	0.35	1.5	B	4.70	6.30	1.34
4d-2.5d	d10-40-50	40	25	10	0.35	1.5	B	4.36	6.30	1.44
1d-1d	d20-20-40	20	20	20	0.35	1.5	N/E	9.54	7.93	0.83
1d-1.5d	d20-20-60	20	30	20	0.35	1.5	E	9.16	7.93	0.87
1d-2d	d20-20-80	20	40	20	0.35	1.5	E	7.98	7.93	0.99
1d-2.5d	d20-20-100	20	50	20	0.35	1.5	E	7.74	7.93	1.02
2d-1d	d20-40-40	40	20	20	0.35	1.5	N/E	5.08	6.52	1.28
2d-1.5d	d20-40-60	40	30	20	0.35	1.5	N/E	14.99	13.98	0.93
2d-2d	d20-40-80	40	40	20	0.35	1.5	E	11.18	13.98	1.25
2d-2.5d	d20-40-100	40	50	20	0.35	1.5	E	11.53	13.98	1.21
3d-1d	d20-60-40	60	20	20	0.35	1.5	N/B	4.85	5.17	1.07
3d-1.5d	d20-60-60	60	30	20	0.35	1.5	N/B	13.73	10.14	0.74
3d-2d	d20-60-80	60	40	20	0.35	1.5	B	10.15	12.60	1.24
3d-2.5d	d20-60-100	60	50	20	0.35	1.5	B	10.36	12.60	1.22
4d-1d	d20-80-40	80	20	20	0.35	1.5	N/B	5.04	5.17	1.03
4d-1.5d	d20-80-60	80	30	20	0.35	1.5	N/B	13.95	10.14	0.73
4d-2d	d20-80-80	80	40	20	0.35	1.5	B	10.17	12.60	1.24
4d-2.5d	d20-80-100	80	50	20	0.35	1.5	B	8.86	12.60	1.42

Fig. 18. Summary of comparison between ABAQUS simulation and analytical calculation results for bolt hole elongation.

between these two sets of results is very good, with an average difference of 17.4% and standard deviation of 11.5%.

5.5. Summary of calculation procedure

To sum up, the procedure of calculating the bolt hole elongation at the maximum load is as follows:

Tensile strain

1. Determine the failure mode of the connection by comparing the end distance, the edge distance and the bolt hole diameter. The conditions are:

Net section failure mode

$$e_2 < (e_1 + d)/2 \quad (9)$$

$$e_2 < 1.75d \quad (10)$$

End pull-out failure mode

$$e_1 \leq 2e_2 - d \quad (11)$$

$$e_1 \leq 2.5d \quad (12)$$

Bearing failure mode

$$e_2 \geq 1.75d \quad (13)$$

$$e_1 \geq 2.5d \quad (14)$$

2. Determine whether it is a pure failure mode or a mixed failure mode.

Mixed failure mode happens according to the following conditions.

Mixed net-section and end pull-out failure mode

$$(e_1 + 0.5d)/2 < e_2 < (e_1 + d)/2$$

Mixed net-section and bearing failure mode

$$2.5d < e_2 < 1.75d$$

Mixed end pull-out and bearing failure mode

$$1.5d < e_1 < 2.5d$$

2.1. If it is a pure failure mode, calculate the tensile strain values at the different critical points by referring to Figs. 11–13, respectively.

2.2. If it is a mixed failure mode, calculate the tensile strain values at the critical points by referring to Figs. 14–16, respectively.

Compressive strain

3. The maximum compression strain is 1.0 at $e_1 = 2d$ and equals to the ultimate tensile strain of steel at $e_1 = 1.2d$. Interpolate between these two values for other e_1 values.
4. Multiply the maximum compressive strain by a factor. This factor is 0 if $e_2 \leq 0.75d$. This factor is 1.0 if $e_2 \geq (e_1 + d)/2$. Interpolate if e_2 is between these two limits.
5. Refer to Fig. 17 for the compression strain distribution in front of the bolt hole.

Bolt hole elongation

6. Calculate the total bolt hole elongation with contributions from the tensile elongation around the bolt hole circumference and the compressive pile up in front of the bolt.

6. Conclusions

This paper has presented a comprehensive experimental, numerical and analytical study of thin-walled plate behaviour under shear in a single bolt, emphasizing on bolt hole elongation. The following conclusions may be drawn:

- (1) The experiments successfully revealed the three different anticipated failure modes: net section tension, end pull-out and bearing.
- (2) The general finite element package ABAQUS was successfully applied to simulate these tests.
- (3) Eurocode 3 and the Australian/New Zealand standard can be used to predict plate initial stiffness and strength.
- (4) To predict the maximum bolt hole elongation, the tensile strain distribution around the bolt hole may be considered to be linearly distributed between five critical points. Compressive strain also exists in front of the bolt.
- (5) This paper has proposed a method to calculate the strains at these critical points according to the aforementioned three failure modes and three mixed failure modes.
- (6) Comparisons of the bolt hole elongation between ABAQUS simulation results and analytical calculations using the proposed strain distributions show that the proposed method gives very accurate results.

Appendix. Calculation example

End distance: $e_1 = 1.25d$, edge distance: $e_2 = 1d$, bolt hole diameter $d = 14$ mm, plate thickness: 1.5 mm, ultimate tensile stress of steel $= 320$ N/mm², Poisson's ratio $= 0.3$ and ultimate tensile strain of steel $= 0.35$.

Tensile strains

End pull-out load: $te_1f_u = 1.5 \times (1.25 \times 14) \times 320 = 8.4$ kn

Net-section load: $t(2e_2 - d)f_u = 1.5 \times (2 - 1) \times 14 \times 320 = 6.7$ kn

Bearing failure load: $2.5dtf_u = 2.5 \times 14 \times 1.5 \times 320 = 16.8$ kn

Therefore, the failure mode is net section failure.

Furthermore, since $(e_1 + 0.5d)/2 < e_2 < (e_1 + d)/2$, i.e. $0.875d < e_2 < 1.125d$, the failure mode is mixed net-section/end pull-out.

For pure end pull-out failure mode (when $e_2 = 1.125d$):

Fig. 19. Tensile strain distribution around bolt hole.

The tensile strains are

$$\varepsilon_{AO} = 0.35, \varepsilon_{BO} = 0.65, \varepsilon_{CO} = 0$$

For pure net-section failure mode (when $e_2 = 0.875d$):

The tensile strain are

$$\varepsilon_{AO} = 0, \varepsilon_{BO} = 0, \varepsilon_{CO} = 0.35$$

Interpolation according to Fig. 14 for the tensile strains at $e_2 = 1d$

$$\varepsilon_C = 0.35 - \frac{0.35 - 0}{1.125d - 0.875d} \times (1d - 0.875d) = 0.18$$

$$\varepsilon_B = 0 + \frac{0.65 - 0}{1.125d - 0.875d} \times (1d - 0.875d) = 0.33$$

$$\varepsilon_A = 0 + \frac{0.35 - 0}{1.125d - 0.875d} \times (1d - 0.875d) = 0.18$$

Fig. 19 shows the tensile strain distribution around the bolt hole.

The total bolt hole elongation due to tensile strain can be calculated as

$$\begin{aligned} D_T &= \frac{\pi R}{4} \varepsilon_C + (\varepsilon_B + \varepsilon_C) \frac{\pi R}{4} \frac{1}{2} + (\varepsilon_A + \varepsilon_B) \frac{\pi R}{4} \frac{1}{2} \\ &= 5.5 \times 0.18 + 0.51 \times 2.75 + 0.51 \times 2.75 \\ &\Rightarrow D_T = 3.80 \text{ mm} \end{aligned}$$

Compressive strain

Since the failure mode is net-section, two linear interpolations are necessary.

First, calculate the maximum compressive strain.

At $e_1 = 1.2d$, the maximum compressive strain is

$$\varepsilon_{AC} = 0.35$$

At $e_1 = 2d$, maximum compressive strain is

$$\varepsilon_{AC} = 1.0$$

Therefore, maximum compressive strain at $e_1 = 1.25d$ is

$$\varepsilon_{AC} = 0.35 + \frac{1 - 0.35}{2d - 1.2d} (1.25d - 1.2d) = 0.39$$

Second, find the multiplication factor for edge distance e_2 :

The lower bound is defined by

$$e_2 = 0.75d, \varepsilon_{AC} = 0$$

Fig. 20. Compressive strain distribution.

The upper bound is defined by

$$e_2 = (1.25d + d)/2 = 1.125d, \varepsilon_{AC} = 0.39$$

Interpolation for $e_2 = 1d$

$$\varepsilon_{AC} = 0 + \frac{0.39}{1.125d - 0.75d} (1d - 0.75d) = 0.26$$

Fig. 20 shows the compressive strain distribution along the plate length in front of the bolt.

The plate pile up due to compressive strain is

$$D_C = \varepsilon_{AC} \frac{1}{2} (1.25d - 0.5d) = 0.26 \times \frac{1}{2} \times 0.75 \times 14 = 1.37 \text{ mm}$$

The total bolt hole elongation is

$$D = D_T + D_C = 3.80 + 1.37 = 5.17 \text{ mm}$$

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