

Geometric and Bolt Position Effects on the Performance of Bolted T-Joints

Bonded and bolted joints are frequently expected to sustain static or cyclic fatigue loads for considerable periods of time without any adverse effect on the load-bearing capacity of the structure (e.g. 120 years or greater for railroad bridges). A major concern is that under dynamic fluctuating loads, joints will often fail at stress levels much lower than the static strength of the joint. The design of safe and cost effective, structurally efficient joints is a major challenge that requires a good understanding of the effects of geometric and material parameters on joint stiffness and strength, and long-term performance under cyclic fatigue and creep loading conditions.

This Measurement Note considers the influence of specimen geometry and bolt location on the stiffness and yield strength of a bolted aluminium T-joint. Finite element analysis (FEA) was used to establish the effects of changes in bolt position, web and base plate thickness, flange radius and thickness on the stiffness and load-capacity of the joint. The effects of these parameters were assessed under direct tension (pull-off), lateral tension and 45° (to horizontal) tension loads. Simple mathematical relationships demonstrating the effect of changing the dimensions of key geometric features on joint stiffness and strength are included. In future work, predicted performance will be compared with experimental data. This exercise has also been carried out for T-joint adhesively bonded with a rubber-toughened epoxy adhesive with a similar geometry - see Measurement Note MATC(MN)29.

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INTRODUCTION

The design of safe and cost effective, structurally efficient joints requires a good understanding of geometric and material parameters on joint stiffness and strength, and long-term performance under cyclic fatigue and creep loading conditions. At present, there is insufficient information available as to the reliability of methodologies for predicting the strength and life expectancy of bolted and bonded joints, particularly under fatigue and creep loads [1-5].

This Measurement Note considers the influence of geometric parameters and bolt location on the stiffness and yield strength of a bolted aluminium T-joint. Finite element analysis (FEA) was used to establish the effects of changes in bolt position, web and base plate thickness, flange radius and thickness on the stiffness and load-capacity of the joint (see Figure 1). The effects of these parameters were assessed under direct tension, lateral tension and 45° (to horizontal) tension loads. Simple mathematical relationships relating the effect of changing the dimensions of key geometric features on joint stiffness and strength are included. This exercise has also been carried out for T-joint adhesively bonded with a rubber-toughened epoxy adhesive with a similar geometry [6-7].

FEA PARAMETRIC STUDY

A series of simulated experiments using FEA were conducted on T-joint configurations to determine the influence of geometric parameters on predicted joint strength and stiffness. All the analyses formulated were solved and post-processed using the LUSAS Composite (Version 13.4) FEA package.

The basic joint geometry/dimensions used in the parametric study is shown in Figure 1. The depth of the joint was held constant at 50 mm and the bolts were centred at an edge distance of 25 mm. The diameter of the bolt shanks was 12 mm and the bolt holes were 12.2 mm in diameter (see Figure 2).

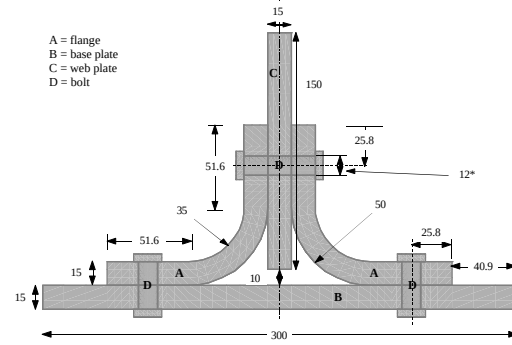


Figure 1: Basic joint configuration used in FEA study (width or depth = 50 mm).

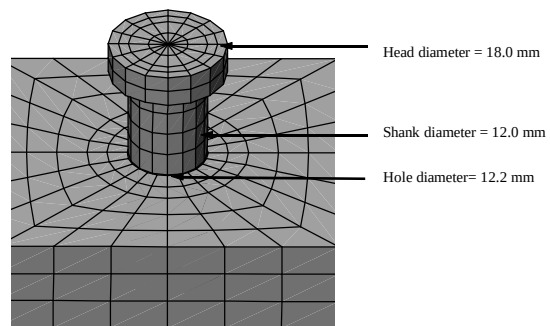


Figure 2: Bolt and hole dimensions.

Due to time constraints it was only possible to analyse a configuration consisting of single bolts connecting left and right flange plates to the base plate, and a single bolt connecting both flange plates to the web plate. In order to reduce the complexity of the analyses, washers were not modelled. The parametric study encompassed changing the values of the following geometric variables:

- Position of bolts
- Outer/inner radius of flange plates
- Thickness of flange plates
- Thickness of base plate
- Thickness of web plate

The stiffness, failure load, and failure location were determined for each joint configuration.

The material used for the base, web and flange plates was 2014 aluminium alloy, which has a high yield stress, and the material for the bolts was ultra high strength steel.

To simplify the analyses, non-linear material properties were only used for the base, web and flange plates - the bolts were considered as perfectly elastic. The model used for the non-linear material properties for the aluminium alloy was a von Mises stress potential approximation. The geometry was meshed using a combination of PN6 and HX8M, linear order three dimensional (3D) solid continuum elements. The mesh discretisation used for the initial configuration is shown in Figure 3.

Three global loading conditions were studied: vertical or direct tension (pull-off), lateral tension, and 45° (to horizontal) tension. All global loads were applied to nodes on the end face of the web plate as shown in Figure 3. In order to model the clamping force of the torqued bolts, a pre-stress was applied to elements in the shank of each bolt (29.5 MPa in the bolt through the web and 28 MPa in the bolts through the base plate). In the analyses, the bolt pre-stresses (load case 1) were applied first, followed by application of the global load (load case 2).

All analyses were performed using 3D models and were based on the full model shown in Figure 3. For the vertical load case only, a plane of symmetry permitted the use of a half model as shown in Figure 4. An initial check verified that the results obtained for the half model were identical to those obtained for the full model. The support conditions used for the full and half models are shown in Figures 3 and 4.

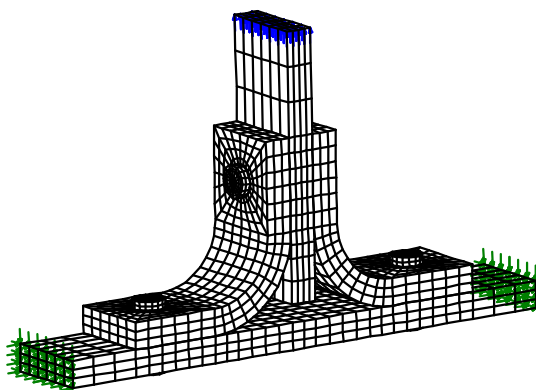


Figure 3: Direct tension - full model showing discretisation mesh, applied load and supports.

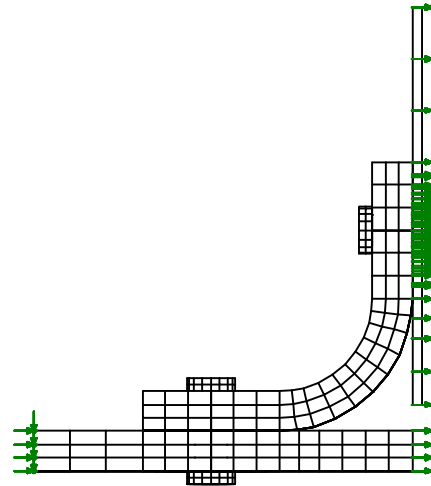


Figure 4: Direct tension - half model showing mesh discretisation and symmetry support condition.

An important feature of the bolted configuration being analysed was that of contact between component parts. Parts of the model that were in contact before a load was applied or would come into contact during loading were identified. These regions were:

- Initial contact between web, base and flange plates,
- Initial contact between the underside of the bolt heads to web, base and flange plates,
- Loss of, or increased contact between flanges and web/base plates,
- Potential contact between the bolt shanks and bolt holes.

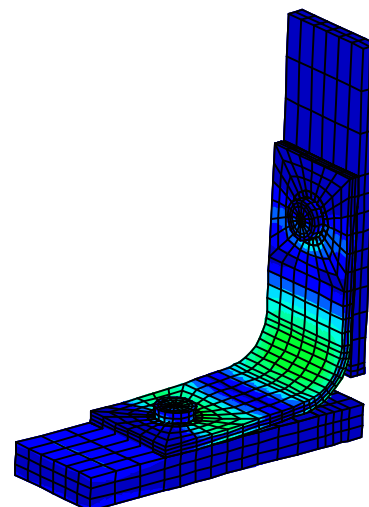


Figure 5: Half model showing deformed mesh and contours of equivalent stress.

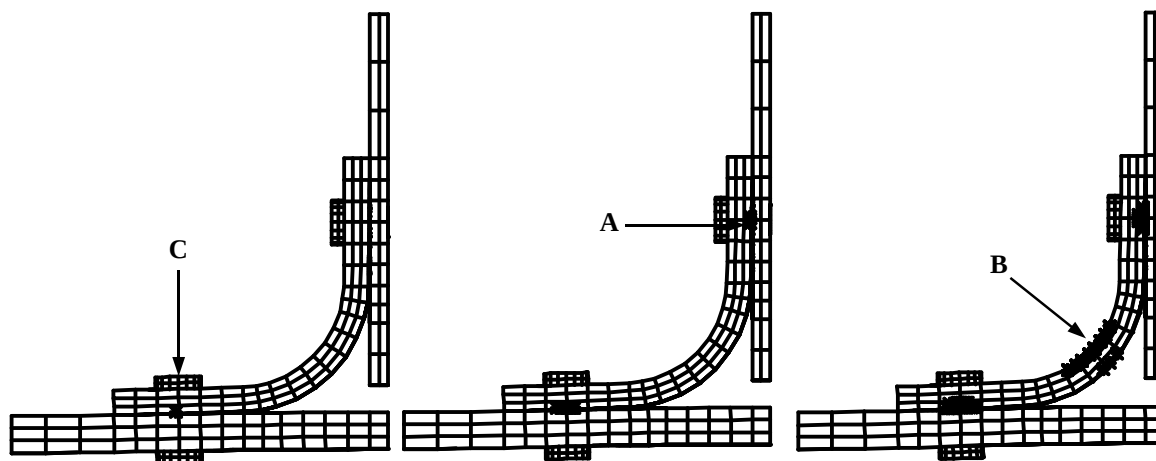


Figure 6: Direct tension—damage accumulation with increasing load (left to right).

LUSAS slidelines were used to model the existing or potential areas of contact, as these are ideal for modelling situations where there is no exact prior knowledge of the contact process. Figure 5 shows a half model deformed mesh and contours of equivalent stress.

The required output from each analysis was a force-extension (F-d) curve and a predicted failure load corresponding to the onset of failure (or yielding) at either positions A, B or C (see Figure 6). The load is known at each increment from the output force-extension curve so that data can be interpolated to obtain the failure load at the critical value. Failure load and stiffness values were determined for each joint configuration. In some cases, yielding occurred at more than one position and in most cases the joint was capable of withstanding substantial additional load following initial yielding (see Figure 6). The force-extension was expressed in terms of **Fz** and **dz** for vertical or z-direction loading, **Fx** and **dx** for lateral or x-direction loading, and **Fres** and **dres** for 45° loading where **res** denotes resultant.

GEOMETRIC EFFECTS

This section examines the effects of changing key geometric parameters on joint stiffness, failure load and failure location for the three loading conditions. Table 1 shows the factors and levels. In all cases, the width or depth of the joint was 50 mm, web to base plate separation distance was 10 mm, and the bolts were centred at an edge distance of 25 mm. Due to time constraints it was not possible to assess changes in dimensions by performing a full factorial analysis using statistical analysis (Design of Experiments (DoE)).

The key observations from the parametric study are summarised in Table 2. In each case, the parameter was increased and the effect on joint stiffness and strength was determined (i.e. increased, decreased or had no significant effect on joint property). Table 3 compares changes in predicted failure location for the three different tensile loading modes as the dimensions of each geometric parameter (i.e. base plate thickness, web thickness, flange thickness and inner radius of the flange).

Table 1: Geometric Factors and Levels (mm)

Base Plate Thickness	Web Thickness	Flange Thickness	Inner Radius
15.0	15.0	5.0	10.0
30.0	30.0	10.0	20.0
		15.0	25.0
			35.0

Table 2: Summary of Parametric Study

Parameter	Direct Tension		Transverse Tension		45° Tension	
	Strength	Stiffness	Strength	Stiffness	Strength	Stiffness
Base Plate Thickness	-	-	-	-	-	-
Web Thickness	-	-	-	-	-	-
Inner Radius	-	-	-	-	-	-
Flange Thickness	-	-	-	-	-	-

Symbols $\uparrow$, $\downarrow$ and $-$, denote increase, decrease and no significant change in the joint properties, respectively.

Direct Tension

Table 2 shows that an increase in either base plate thickness, flange radius or flange thickness will result in an increase in both joint stiffness and strength. The FEA results indicate:

- Flange thickness has significant effect on joint properties,
- Web thickness has virtually no effect on joint properties,
- Flange radius has a small effect on joint properties,
- Base plate thickness has a significant effect on joint stiffness, but only a marginal effect on joint strength.
- In direct tension, failure tends to occur within the flange in the vicinity of the bolt securing the flange to the base plate (position C); independent of changes in the dimensions of key parameters.

For the envelope of geometric variables studied, there seems to be maximum strength limit of approximately 33.65 kN (see Figure 7). The predicted failure load P_f and stiffness k of the joint can be related using the following Boltzmann Equation:

$$P_f = \frac{A_1 - A_2}{1 + e^{(k - k_0)/dk}} + A_2$$

where $A_1 = -20.96$, $A_2 = 33.65$, $k_0 = 1.94$ and $dk = 4.19$.

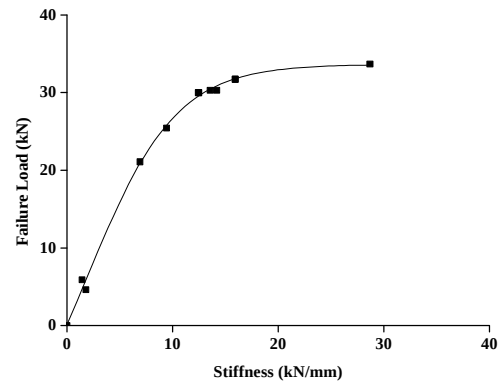
**Figure 7: Direct tension - predicted strength versus stiffness.**

Figure 8 shows that, in direct tension, the joint stiffness k and failure load P_f increase almost linearly with flange thickness t_{fl} . Within the envelope of the geometric variables studied, the two properties are related to t_{fl} by:

$$k = -6.8 + 2.5t_{fl} \text{ (kN/mm)}$$

$$P_f = -2.6 + 0.9t_{fl} \text{ (kN)}$$

Previous FEA trials on adhesively bonded T-joints [6] indicated that the joint stiffness increases linearly with increasing base plate thickness. The joint stiffness of the basic bolted T-joint configuration was observed to almost double from 6.55 to 12.80 kN/mm when the base plate thickness was increased from 15 to 30 mm.

Table 3: Failure Location as Function of Increasing Parameter Dimension

Parameter	Direct Tension	Transverse Tension	45° Tension
Base Plate Thickness	C	A	A/C
Web Thickness	C	A	C
Inner Radius	C	A/B→A	B/C→C
Flange Thickness	C	B/C→A	A→B/C

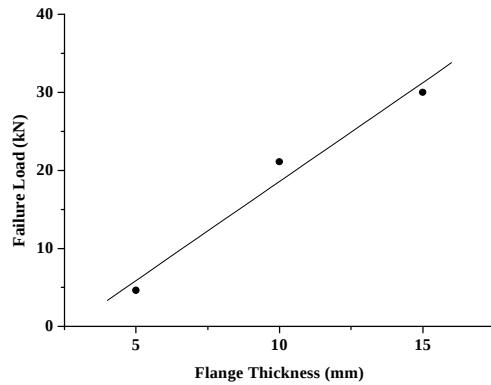
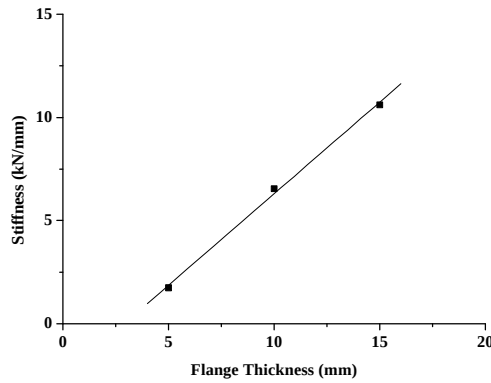


Figure 8: Direct tension - effect of flange thickness on joint stiffness (top) and failure load (bottom).

Transverse and 45° Tension

Optimising properties for direct tension does not necessarily ensure good performance when subjected to lateral loads. In fact, the maximum load that can be supported by the basic configuration under transverse load is 40% of that under direct tension. Within the geometric limitations set, the predicted maximum load capacity was approximately 15.77 kN and 19.89 kN for transverse and 45° tension, respectively. Figure 9 shows a plot of joint strength as a function of strength for the transverse and 45° tension.

The predicted failure load P_f and stiffness k of the joint under transverse and 45° tension can be related using the following linear relationships:

$$P_f = 0.10 + 6.2k \text{ (transverse tension)}$$

$$P_f = 1.2 + 6.1k \text{ (45° tension)}$$

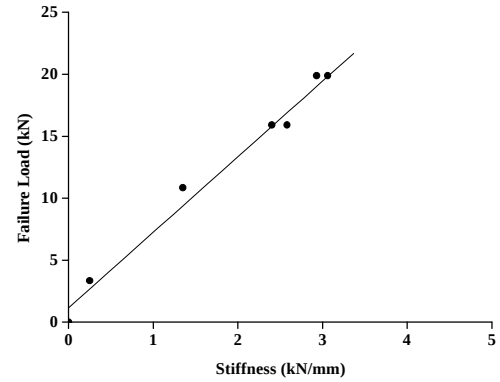
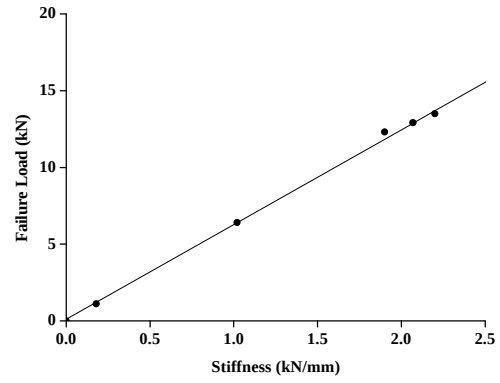


Figure 9: Predicted strength versus stiffness - transverse tension (top) and 45° tension (bottom).

Table 2 shows that an increase in either base plate thickness, flange radius or flange thickness will result in an increase in both joint stiffness and strength. Although the web thickness was unaltered, a similar trend can also be expected. As each parameter is increased, initial failure location tends to change position (see Table 3). There is also a tendency for failure to initiate at more than one location.

The FEA results indicate:

- Flange thickness has significant effect on joint properties for both transverse and 45° tension,
- Flange radius and base plate thickness have a small effect on joint properties for both transverse and 45° tension.

The relationship between key parameters and joint properties are generally linear in nature (i.e. similar to direct tension).

Warning: It is advised not to extrapolate any data outside a test envelope without confirmation testing as there is no guarantee the data will be valid.

BOLT POSITION

A series of trials were conducted to determine the effect of bolt position on joint stiffness and strength. FEA trials were conducted on a T-joint almost identical to the basic configuration, but with a 10 mm flange thickness. The joint was subjected to direct tension. As the bolt position is moved towards the central vertical axis, the joint becomes steadily stiffer and stronger. The increase in joint properties is associated with a reduction in bending moments about the central axis. Figure 10 shows predicted force-extension plots as a function of bolt position. Figure 11 shows that k and P_f increase linearly with bolt position d_{bolt} . The effect of bolt position on joint properties is given by:

$$k = 6.92 + 0.08d_{\text{bolt}} \text{ (kN/mm)}$$

$$P_f = 21.6 + 0.4d_{\text{bolt}} \text{ (kN)}$$

CONCLUSIONS

The FEA results demonstrated that simple empirical relationships can be used to estimate the effects of the geometric parameters and bolt position on joint stiffness and strength for this complex geometry. The effects of these parameters depends on the loading conditions. Empirical equations can also be used to relate strength to stiffness for each loading condition.

The bolted T-joint was shown to be far superior under direct tension compared with loading conditions containing a lateral tensile component. The FEA predicts that joint stiffness and strength (for all three loading modes) will increase as the dimensions of key geometric features are increased or when the bolt position is moved towards the central vertical axis. Failure location is also dependent on loading mode and the joint geometry (see also [6-7]).

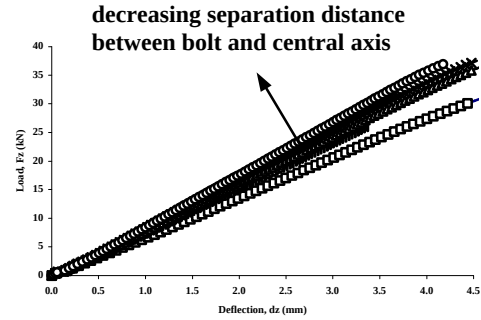


Figure 10: Direct tension - effect of bolt position on joint stiffness.

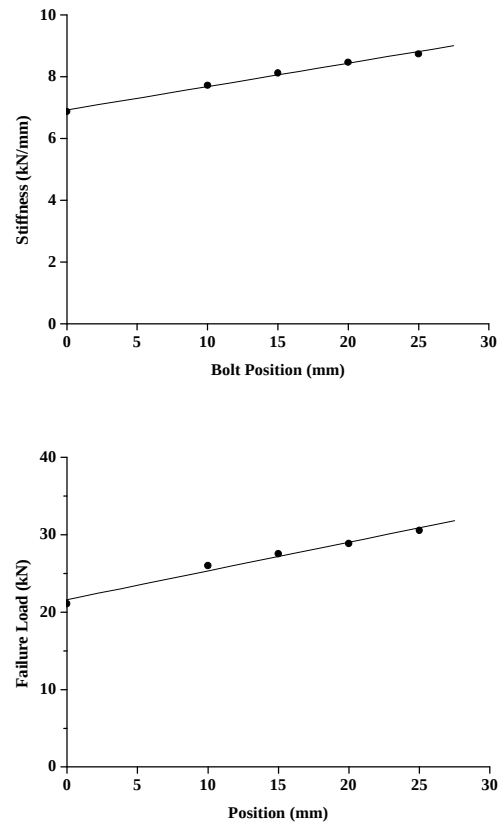


Figure 11: Direct tension - effect of bolt position on joint stiffness (top) and failure load (bottom).

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