

Geometric and Material Property Effects on the Performance of Adhesive 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 on the stiffness and strength of an aluminium T-joint bonded with a rubber-toughened epoxy adhesive. Finite element analysis (FEA) was used to establish the effects of changes in adhesive layer thickness, web and base plate thickness and separation distance, flange radius and thickness, and taper angle on the stiffness and load-capacity of the joint. The effects of these parameters were assessed under direct tension, lateral tension and 45° (to horizontal) tension loads. The study compares the strength and stiffness for a fully bonded joint and a joint where the adhesive is restricted to regions of metal-metal contact. Simple mathematical relationships relating geometric parameters 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 a bolted T-joint with a similar geometry - see Measurement Note MATC(MN)30.

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INTRODUCTION

Safe and reliable design of bonded structures is dependent on the availability of reliable materials models and failure criteria that can be used to predict the failure behaviour of adhesively bonded structures. It also requires the designer/engineer to have 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. Currently, there are no well-established design procedures for predicting failure behaviour of bonded structures [1-6].

This Measurement Note considers the influence of geometric parameters on the stiffness and strength of an aluminium T-joint bonded with a rubber-toughened epoxy adhesive. Finite element analysis (FEA) was used to establish the effects of changes in adhesive layer thickness, web and base plate thickness and separation distance, flange radius and thickness, and taper angle 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. The study compares the strength and stiffness for a fully bonded joint (basic configuration) and a joint where the adhesive is restricted to regions of metal-metal contact. Simple mathematical relationships relating geometric parameters on joint stiffness and strength are included. Differences between joint strength predictions for the various failure criteria (with and without thermal residual effects) are also examined. This exercise has also been carried out for a bolted T-joint with a similar geometry - see Measurement Note MATC(MN)30 [7].

FEA PARAMETRIC STUDY

A series of simulated experiments using FEA were conducted on T-joint configurations to determine the effects of geometric parameters on predicted joint strength and stiffness. The basic joint configuration used in the parametric study is shown in Figure 1.

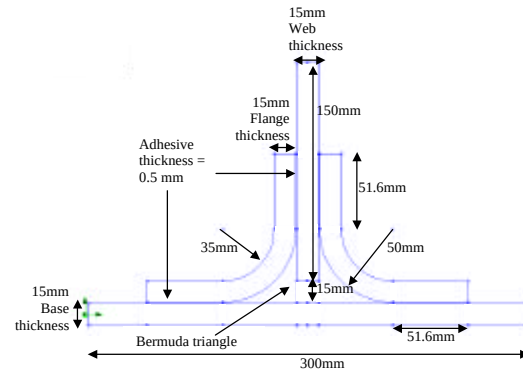


Figure 1: Basic joint configuration used in FEA study (thickness = 50 mm).

All the FE models were constructed and solved using ABAQUS V6.2 standard (implicit) solver while mesh generation was carried out using the FEMGV pre-processor.

The parametric study consisted of systematically changing various dimensions (i.e. adhesive layer thickness, web and base plate thickness and separation distance, flange radius and thickness) of the basic T-joint and determining stiffness and failure load. This re-meshing was achieved relatively easily in FEMGV.

The T-joints consisted of 2014 aluminium (alloy with a high yield stress) adhesively bonded with XD4601 a single-part rubber-toughened epoxy adhesive (supplied by Dow Chemicals). The adhesive was modelled with an elastic-plastic materials model (exponent Drucker-Prager), while the aluminium was modelled as an elastic material. The elastic and strength properties (including stress-strain curves) of the adherend and adhesive used in the FEA study were generated in-house.

Three loading configurations were considered: vertical, transverse and 45° loading. For vertical loading a half model was used due to symmetry conditions. For the other loading configurations a full mesh was required. Initial analyses were carried out using a three-dimensional (3-D) mesh, but the computer processing time was excessive so a two-dimensional (2-D) mesh was constructed using CPE4 continuum elements.

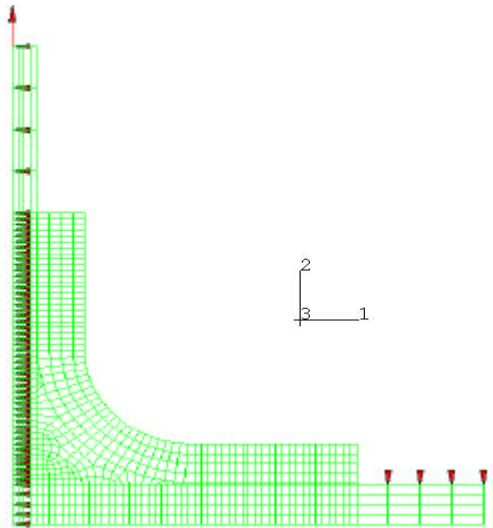


Figure 2: Half mesh showing boundary conditions and loading direction.

Analyses showed there was little difference between stress and strain predictions for the two cases. A displacement was applied to a point on the top face of the web in either the 2-direction (vertical loading); 1-direction (transverse loading) or in both directions (45° loading). All nodes along the top face of the web were coupled so to the displaced node so they all move the same distance. For the half model symmetry conditions were imposed by constraining the nodes at the symmetry plane against movement in the 1-direction. The boundary conditions applied to the half model mesh are shown in Figure 2.

An example of a deformed mesh for the full model is shown in Figure 3, while Figure 4 shows a contour plot of the S_{11} variable for the half mesh. The stress contours are shown for the adhesive only.

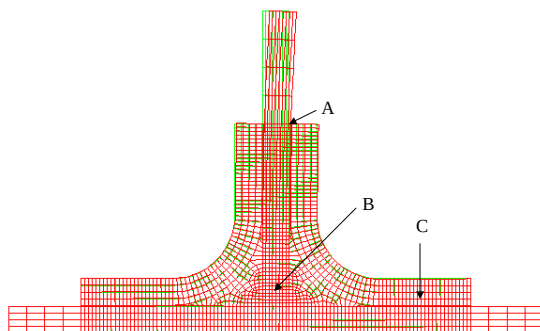


Figure 3: Transverse tension - deformed mesh (red) over original mesh (green).

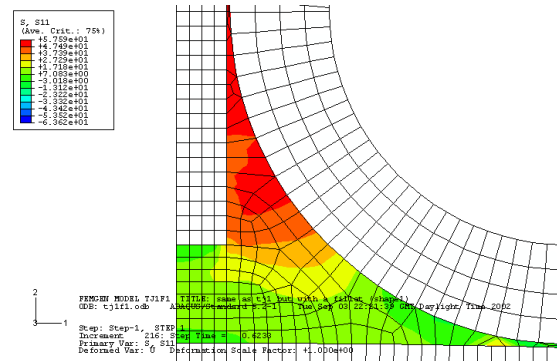


Figure 4: Contour plot of S_{11} stress at the predicted failure load. The contours are shown for only the adhesive region.

The required output from each analysis was a force-extension curve and a predicted failure load corresponding to a particular failure criterion. The failure criteria considered were (see [8-11]):

- Maximum tensile stress
- Maximum shear stress;
- Maximum principal stress
- Hydrostatic stress
- Maximum tensile strain
- Maximum shear strain
- Maximum principal strain
- Guest-Tresca
- von Mises
- Hill's failure criteria

The Guest-Tresca; von Mises and Hill's variable were obtained by using a user subroutine (UVARM). It was necessary to obtain the increments when each of these criteria reached their critical value. One Python script file was written to output the force-extension data. Another Python script file was used to output the maximum and minimum values calculated at integration points for each of these variables at every increment in the analysis. The script file is run through ABAQUS/viewer and the results are output to a report file.

The result files were opened in word and searched for each variable in turn, noting the increments either side of the critical value. The load is known at each increment from the output force-extension curve so the data can be interpolated to obtain the failure load at the critical value of each variable.

Table 1: Predicted Failure Loads (kN) and Position for Basic T-Joint Configuration
(A = flange-web interface (top), B = flange-web interface (bottom), C = flange-base plate interface)

Criteria	Direct Tension		Transverse Tension		45° Tension	
Maximum tensile stress	176.9	B	54.26	A/B	130.0	A/B
Maximum shear stress	96.04	C	15.60	A	77.24	C
Maximum principal stress	86.58	B	18.36	A	55.86	A
Maximum tensile strain (true)	117.8	B	33.40	A	98.40	A
Maximum shear strain (true)	112.2	B	26.62	A	78.66	A
Maximum principal strain (true)	104.9	B	23.36	A	69.68	A
Guest-Tresca	95.36	C	14.62	A	76.90	C
von Mises	71.98	C	11.40	A	58.64	C
Hill's	78.28	B	10.42	A	50.80	A
Hydrostatic stress	87.38	B	20.46	A	61.76	A

In some cases, the analysis failed to converge before a particular critical value was reached, but failure loads were obtained for the majority of geometry and failure criterion combinations. Further information on the use of FEA for design with adhesives can be found in NPL Measurement Good Practice Guide No. 48 [10].

FAILURE CRITERIA

The FEA results indicate a wide range of strengths for the different failure criteria. Table 1 compares predicted results for the basic test geometry (Figure 1) for each of the tensile loading modes. Invariably maximum tensile stress predicts the highest joint strength and Hill's failure criteria the lowest strength.

All the failure criteria indicate that the load-bearing capacity of the basic T-joint configuration is a maximum for direct tension and a minimum for transverse tension. Strength reduction under 45° tension is far less compared with transverse tension. The position of failure varies for the different failure criteria (see Table 1 and Figure 3) and with the direction of the applied load. Failure occurs either at the top (A) and/or bottom (B) of the flange-web interface, or at the flange-web interface (C). Transverse loading tends to initiate failure at the top of the flange-web interface; independent of failure criteria, whereas failure will occur at either position B or C for direct tension. For the intermediate loading condition (45° tension), failure tends to occur in most cases at either position A or position C.

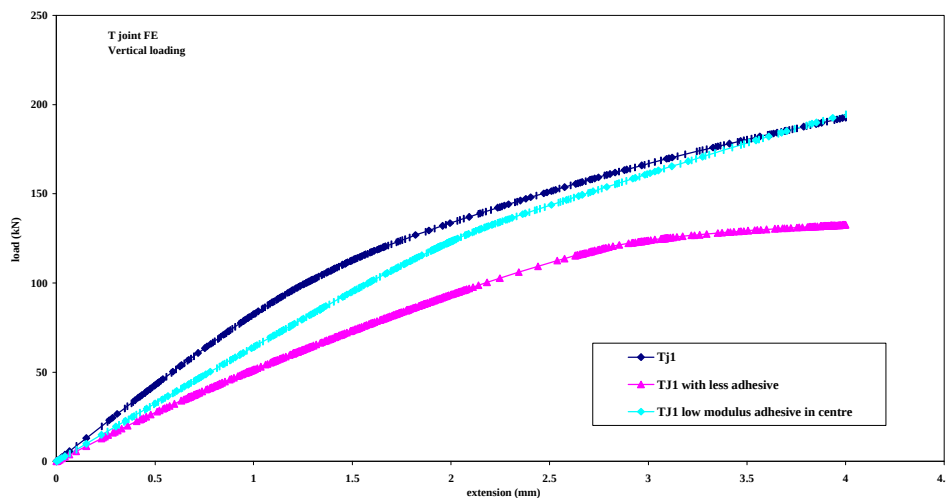


Figure 5: Plot comparing joint deformation for a fully bonded joint with either XD4601 or a low stiffness adhesive and a joint where the adhesive is restricted to regions of metal-metal contact.

There is evidence from research conducted at NPL on single-lap, scarf and butt joints that from the list of criteria in Table 1, the maximum principal stress and hydrostatic stress criteria produce the best agreement between experiment and theory when used with either the exponent Drucker-Prager materials model or a new cavitation materials model developed at NPL [8-11].

Future work will include tensile tests on the basic joint geometry shown in Figure 1 in order to check the applicability of the various failure criteria. The maximum principal stress criteria was used in the parametric study to assess the effects of changes in specimen dimensions on joint stiffness and strength.

FULLY VERSUS PARTIAL BONDING

FEA runs were conducted with the central region between the flanges (known as the “Bermuda Triangle”) completely filled with either XD4601 or a low stiffness adhesive, or where the adhesive is only present at the metal-metal interfaces. Force-extension curves in Figure 5 clearly show joint efficiency is enhanced when the “Bermuda Triangle” is completely filled. Joint stiffness and strength increases as the stiffness of the adhesive is increased.

The joint strength according to the maximum principal stress criteria was almost four times as strong for the fully filled system with XD4601 compared with the unfilled joint.

END SHAPE

FEA trials were carried out in which the bond length between the base plate and the right flanges (Figure 1) was kept constant, but the end geometry of the flange was altered from a right angle (square) to a taper with a gradient of 32.5° (see Figure 6).



Figure 6: Flange end shapes: square (top); external taper (middle); external and internal taper (bottom).

The FEA results showed minimal difference in stiffness and strength between the two geometries. An internal taper with a gradient of 1:10 was introduced to the specimen with the external taper. This additional feature had minimal effect on joint stiffness and strength. Design guides suggest that the external taper should have a gradient of 1:10 in order to reduce peel stresses. A local thickening of the adhesive through the use of an internal taper is also considered beneficial. The benefits of either feature may become apparent with increased bond length between base plate and flange, and between the web and flange.

GEOMETRIC EFFECTS

This section examines the effects of changing key geometric parameters on joint stiffness and strength for the three loading conditions. Table 2 shows the factors and the levels. The width of the joint in all cases was 50 mm. Due to the large number of variables (6) and levels (3), and the limited time available it was not possible to use Design of Experiments (DoE) approach to assess changes in dimensions. A full factorial would have required 729 trials, which could only be reduced to a minimum of 64 trials using a D-Optimal analysis [12].

Table 2: Geometric Factors and Levels (mm)

Base Plate Thickness	Web Thickness	Flange Thickness	Inner Radius	Web-Base Separation	Adhesive Thickness
15.0	15.0	7.5	35.0	5.0	0.25
22.5	22.0	11.5	38.5	10.0	0.37
30.0	30.0	15.0	42.5	15.0	0.50

Table 3: Summary of Parametric Study

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

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

Direct Tension

The key observations from the parametric study are summarised in Table 3. In each case, the parameter (see Table 2) was increased and the effect on joint stiffness and strength was determined. Figure 7 shows that the joint stiffness k and failure load P_f increase linearly with base plate thickness t_{bp} . Within the envelope of the geometric variables studied, the two properties are related to t_{bp} by:

$$k = -12.1 + 6.5 t_{bp} \text{ (kN/mm)}$$

$$P_f = 37.7 + 3.3 t_{bp} \text{ (kN)}$$

The joint properties in most cases can be represented by a simple linear relationship. For example:

$$k = 84.1 + 6.6 t_{fl} \text{ (kN/mm)}$$

$$P_f = 193.1 + 3.9 t_{fl} \text{ (kN)}$$

and

$$k = 190.5 + 14.0 t_{adh} \text{ (kN/mm)}$$

$$P_f = 72.6 + 128.3 t_{adh} \text{ (kN)}$$

where t_{fl} and t_{adh} are flange and adhesive layer thickness, respectively. The basic geometry was used in both cases, but with a plate thickness equal to 30 mm. Extrapolation of these relationships outside the test envelope will not necessarily result in sensible predictions.

Care needs to be taken when varying specimen dimensions as often stiffness may increase while strength decreases or vice-versa (see Table 3). Both joint stiffness and strength increased as the base plate and adhesive layer thickness were increased.

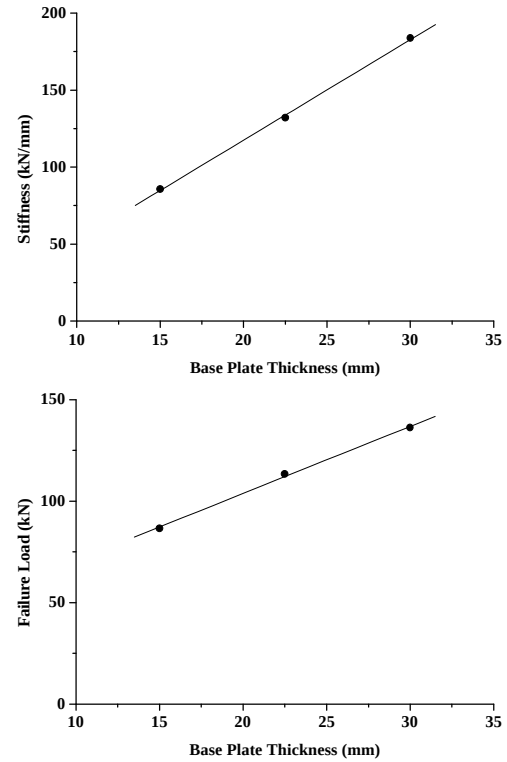


Figure 7: Direct tension - effect of base plate thickness on joint stiffness (top) and failure load (bottom).

However, increasing the base plate thickness from 15 to 30 mm gives rise to a significant weight increase. In contrast, a small increase in adhesive layer thickness (0.25 to 0.5 mm) has a strong positive effect on joint strength with only a small increase in joint weight.

Transverse and 45° Tension

Optimising properties for direct tension does not necessarily improve transverse or 45° loading properties (see Table 3). In fact, it can be counter-productive.

Table 4: Effect of Thermal Residual Stresses on Failure Load (kN)

Criteria	Excluding Thermal Effects	Including Thermal Effects
Maximum tensile stress	86.00	125.0
Maximum shear stress	90.97	94.66
Maximum principal stress	35.03	32.76
Maximum tensile strain (true)	50.60	56.69
Maximum shear strain (true)	55.90	45.83
Maximum principal strain (true)	43.16	44.36
Guest-Tresca	89.54	94.75
von Mises	64.35	68.56
Hill's	24.80	21.37
Hydrostatic stress	29.86	27.11

The introduction of transverse loading results in large bending forces, hence lateral restraint needs to be increased to counteract this loading condition. The basic joint configuration (see Table 1) is far weaker under transverse tension. A reduction in flange or web thickness will severely compromise lateral stiffness and strength (see Figure 8). Imbedding the web almost to the base plate has a beneficial effect on joint stiffness and strength.

Simple relationships exist between k and P_f and key parameters. For example, the effect of web thickness t_{web} on joint properties is given by:

$$k = -2.6 + 0.6 t_{web} \text{ (kN/mm)}$$

$$P_f = -4.8 + 0.8 t_{web} \text{ (kN)}$$

and

$$k = 109.1 + 1.5 t_{web} \text{ (kN/mm)}$$

$$P_f = 31.6 + 2.6 t_{web} \text{ (kN)}$$

for transverse and 45° tension, respectively.

THERMAL RESIDUAL EFFECTS

The presence of thermal induced residual stresses are known to have an adverse effect on the strength of bonded joints. FEA was carried out to compare the strength of a joint with and without taking into account thermal induced residual stresses. Table 4 compares the two cases for the basic joint configuration, but where the adhesive is restricted to regions of metal-metal contact. Joint strength either increases or decreases depending on the failure criteria selected.

CONCLUSIONS

The FEA results demonstrate that simple empirical relationships can be used to estimate the effects of the geometric parameters on joint stiffness and strength for this complex geometry. The effects of these parameters depends on the loading conditions. A fully bonded joint was shown to be far superior to that where the adhesive is restricted to only metal-metal interfaces and the presence of thermal residual stresses only had a small effect on joint strength.

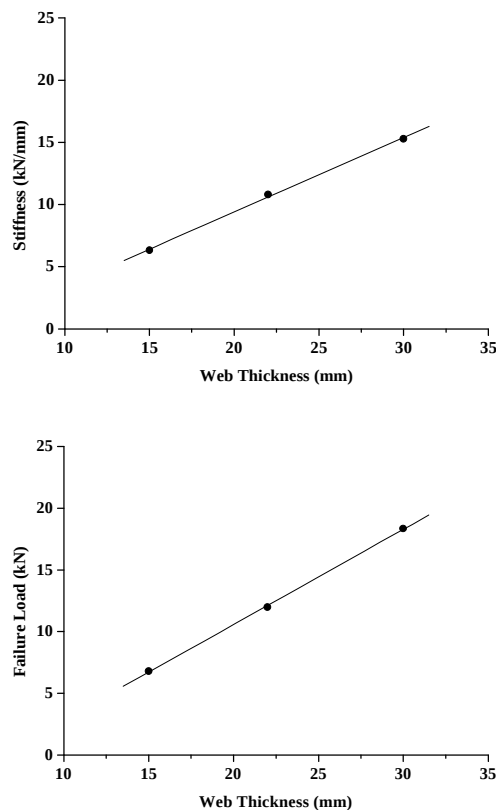


Figure 8: Transverse tension - effect of web thickness on joint stiffness (top) and failure load (bottom).

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