

**Project MMS11
Report 3**

**Finite Element Assessment of
Geometric and Material Property
Effects on the Strength and Stiffness
of Bonded and Bolted T-Joints**

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ABSTRACT

Finite element analysis (FEA) studies have been carried out on both bonded and bolted T-joints of similar geometry in order to determine the effects of key geometric parameters and material properties on the predicted mechanical performance of the joint. A series of simulated experiments have been conducted on aluminium and glass fibre-reinforced plastic (GRP) T-joint configurations for this purpose. 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 bonded joints. The effects of these parameters were assessed under direct tension, lateral tension and 45° (to horizontal) tension loads. The exponent Drucker-Prager materials model was used to characterise deformation behaviour of the rubber-toughened epoxy adhesives used for bonding the T-joints. A similar parametric exercise was carried out for bolted T-joints in which the previously mentioned geometric features were studied along with the effect of bolt position on joint performance.

The FEA results produce some simple empirical relationships that estimate the effects of the geometric parameters on joint stiffness and strength for this complex geometry. The effects of these parameters depend on the loading conditions. A fully bonded joint was shown to be far superior to a joint where the adhesive is restricted to only metal-metal interfaces. The presence of thermal residual stresses only had a small effect on joint strength. The performance of both bonded and bolted T-joints is 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 generally increase as the dimensions of key geometric features are increased or when the bolt position is moved towards the central vertical axis. Base plate thickness had the largest influence on the component performance but increasing this adds to the component mass. Failure location is also dependent on loading mode, failure criteria selected and the joint geometry. In future work, predicted performance will be compared with experimental data.

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1 INTRODUCTION

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 or constant loads, joints will often fail at stress levels much lower than the strength of the joint determined under quasi-static, monotonic loading. Altering the geometry of a bonded or bolted joint will invariably alter the stress and strain distributions within a joint. These differences can have a profound affect on the stiffness, load-capacity and life expectancy of the joint. It is therefore important to appreciate the consequences of changing the geometric and material parameters.

A series of simulated experiments using finite element analysis (FEA) have been conducted on aluminium and glass fibre-reinforced plastic (GRP) T-joint configurations for this purpose. 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 bonded joints bonded using adhesives. The exponent Drucker-Prager materials model was used to characterise deformation behaviour of the rubber-toughened epoxy adhesives used for bonding the T-joints. The T-joints were subjected to direct tension, transverse tension or 45° (to horizontal) tension. A similar parametric exercise was carried out for bolted T-joints in which the previously mentioned geometric features were studied along with the effect of bolt position on joint performance. The clamping pressure and other bolt parameters were kept constant for the different joint configurations.

The research presented in this report forms part of the DTI funded project “Measurement for Materials Systems (MMS) Project – Design for Fatigue and Creep in Joined Systems (MMS11)”. The project aims to provide a systematic approach to the design (including data requirements and methods of data generation), fabrication, testing and analysis of bolted and bonded metallic and composite structures for use under monotonic, fatigue and creep loading conditions. The project includes the development of a new model for characterising the behaviour of rubber-toughened adhesives. This model accounts for the influence of rubber particle cavitation on the yield behaviour of adhesives. Work is currently underway to compare predicted analysis with experimental data.

The report is divided into six (6) sections (including Section 1, Introduction). Section 2 and 3 covers the numerical modelling of bonded T-joints using FEA and the parallel work carried out on bolted T-joints. The effects of geometric and material parameters on bonded and bolted T-joint performance are considered in Sections 4 and 5, respectively. Conclusions and discussion are given in Section 6. Material property data used in the FEA is presented in Appendix 1. Appendix 2 presents force-extension results from the parametric study conducted on adhesively bonded aluminium T-joints.

2 T-JOINT GEOMETRY

2.1 STANDARD GEOMETRY AND PARAMETER VARIATION

2.1.1 Aluminium T-Joints

A series of simulated experiments using FEA were conducted on both bonded and bolted T-joint configurations to determine the effects of geometric parameters on predicted joint strength and stiffness.

The standard aluminium T-joint configurations for the bonded and bolted joints used in the parametric study are shown in Figures 1 and 2 respectively. In both cases the width of the joint was held constant at 50 mm. In the bolted joint, bolts were centred at an edge distance of 25.8 mm (83.3 mm from the centre line)

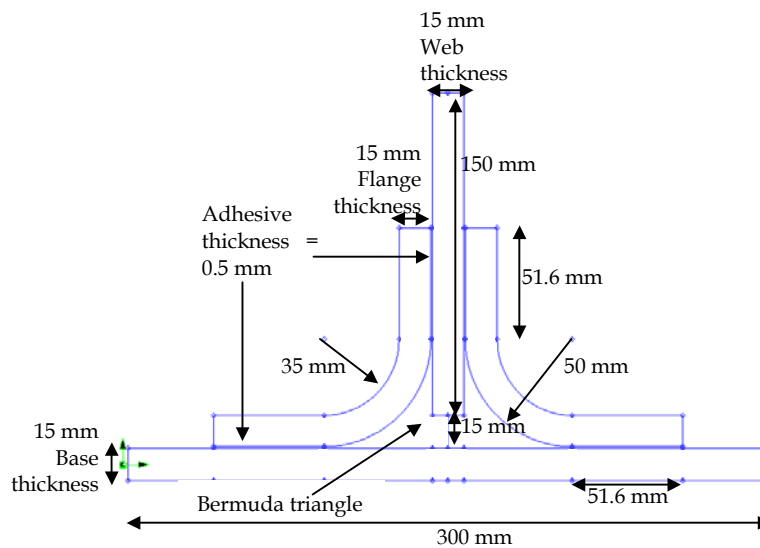
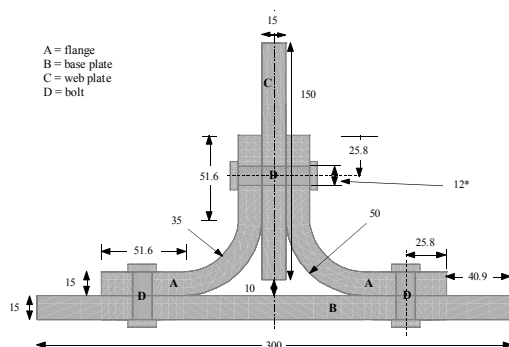
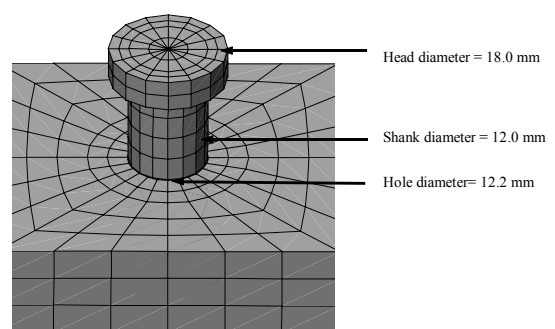


Figure 1: Standard bonded aluminium T-joint configuration used in FEA (width = 50 mm)



Basic joint configuration



Bolt and hole dimensions

Figure 2: Standard bolted aluminium T-joint configuration used in FEA (width = 50 mm)

The parametric study consisted of systematically changing various dimensions of the standard T-joints (Figures 1 and 2). The dimensions considered were:

- Web and base plate thickness,
- Flange radius and thickness,
- Position of bolts (bolted joint only),
- Adhesive layer thickness (bonded joint only),
- Web – base plate separation distance (bonded joint only),
- Shape of the flange ends - either square or tapered (bonded joint only),
- Volume of adhesive used -Bermuda Triangle filled or unfilled (bonded joint only).

The dimensions used for the parametric studies are shown in Tables 1 and 2 for the bonded and bolted joints respectively.

Table 1: Geometric Factors and Levels (mm) for the Bonded Aluminium T-joint

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 2: Geometric Factors and Levels (mm) for the Bolted Aluminium T-Joints

Base Plate Thickness	Web Thickness	Flange Thickness	Outer Radius
15.0	15.0	5.0	25.0
30.0	30.0	10.0	35.0
		15.0	40.0
			50.0

2.1.2 Composite T-Joints

A series of parametric FEA trials were also performed on a generic T-joint configuration, manufactured from the glass fibre-reinforced epoxy system. The dimensions and geometry of the initial bolted T-joint configuration are shown in Figure 3. The width of the joint was held constant at 50 mm and the bolts were centred at an edge distance of 25 mm (81.88 mm from centre line). The diameter of the bolt shanks was 12 mm and the holes were 12.2 mm in diameter (see Figure 2).

Two standard geometries were used for the parametric studies on bonded GRP T-joints. The dimensions of the first geometry (case 1) are shown in Figure 4. The base plate consists of 75 plies of $\pm 45^\circ$ giving a thickness of 30mm. The second standard geometry (case 2) was identical to case 1 except that the base plate was modelled using the standard composite lay-up (detailed in Section 2.2.2) giving a base thickness of 12.16 mm.

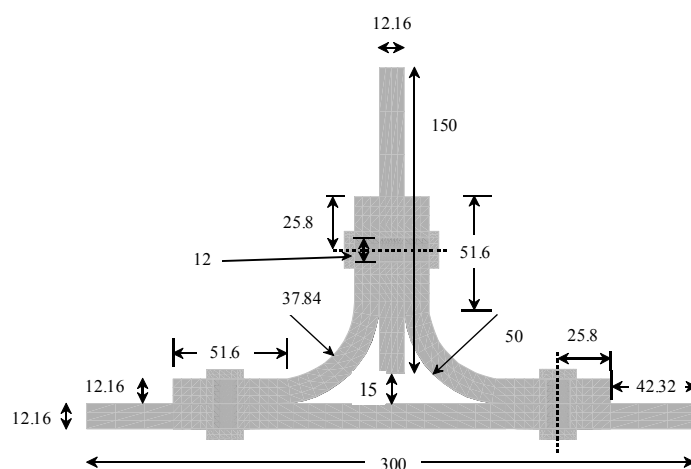


Figure 3: Standard bolted GRP T-joint configuration used in FEA (width = 50 mm)

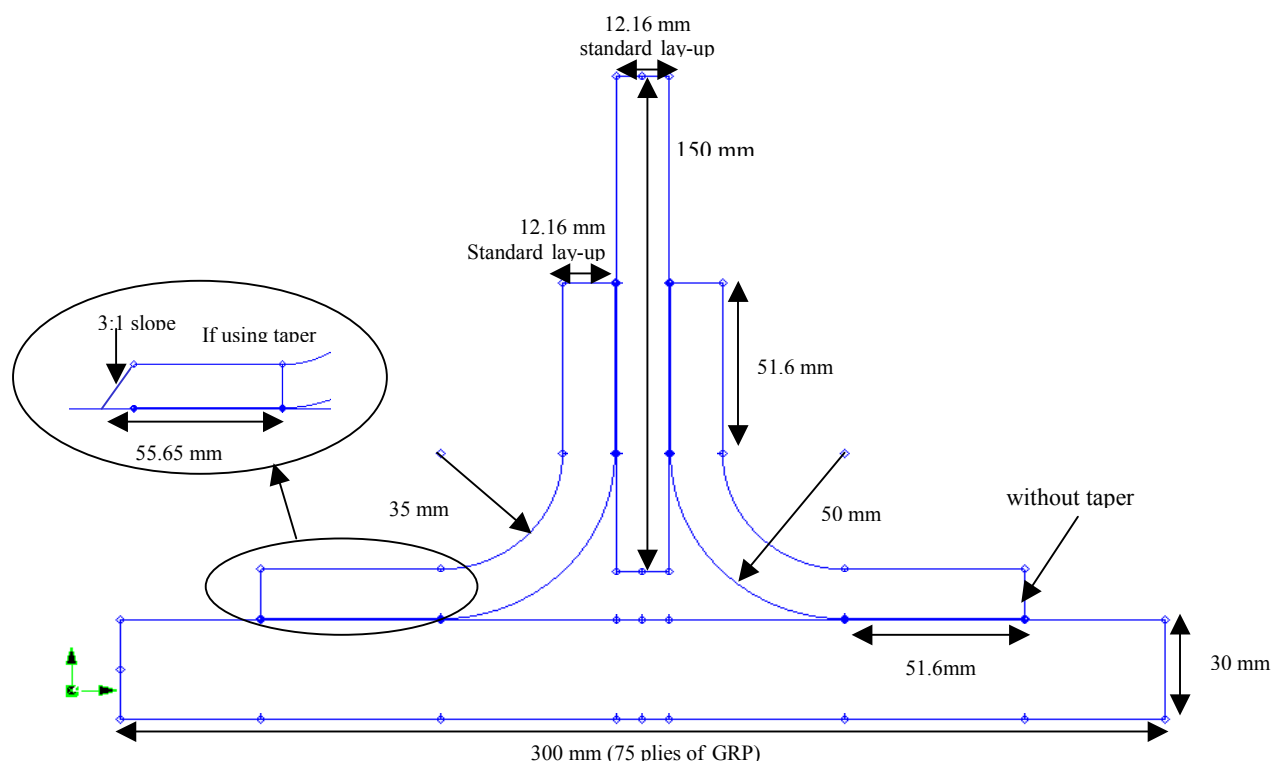


**Figure 4: Standard (Case 1) bonded GRP joint configuration used in FEA
(width = 50 mm)**

Various dimensions were systematically changed during the parametric studies of the GRP T-joints. The parameters considered were:

- Web thickness,
- Flange radius,
- Position of bolts (bolted joint only),
- Shape of the flange ends - either square or 3 in 1 taper (case 1 bonded joint only),
- Volume of adhesive - Bermuda Triangle filled or unfilled (case 2 bonded joint only).

The dimensions used for the parametric studies are shown in Tables 1 and 2 for the bonded and bolted joints respectively.

Table 3: Geometric Factors and Levels (mm) for the Bonded and Bolted GRP T-joint

Geometric factor	Levels		Bonded or bolted joint
	25.0	50.0	
Flange radius	25.0	50.0	Both
Web thickness	12.16	24.32	Both
Bolt position (from centre line)	78.3	83.3	Bolted
End geometry	Square	3 in 1 taper	Bonded (case 1)
Bermuda Triangle	Unfilled	Filled	Bonded (case 2)

2.1.3 Loading Configurations

Three loading configurations were used during this study to assess the effect of parameter variation on stiffness and load-capacity of the joint. The three load cases were: (i) vertical (direct) tension; transverse tension; and 45° (to horizontal) tension loads (see Figure 5). These loading directions were used for aluminium and composite, bonded and bolted joints.

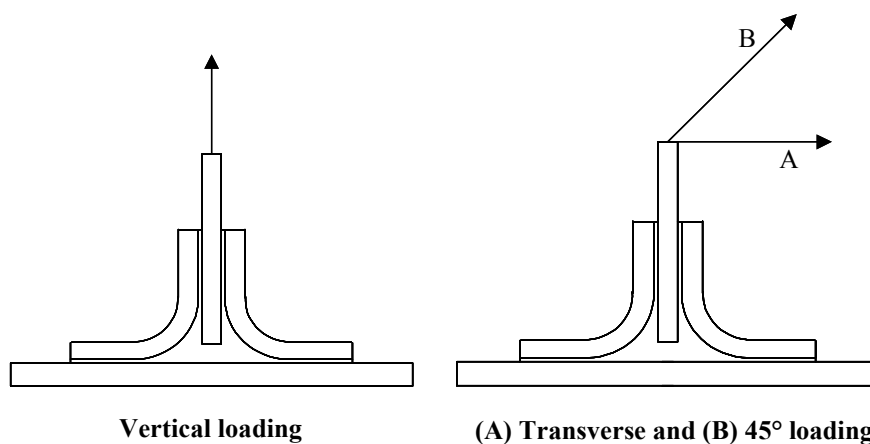


Figure 5: Loading configurations for bonded and bolted T-joints

2.2 MATERIALS

2.2.1 Aluminium T-Joints

The material used for the base, web and flange plates of all the aluminium T-joints was 2014 aluminium alloy, which has a high yield stress. For the bolted joints the material used for the bolts was ultra high strength steel. For the bonded T-joints the adhesive used was XD4601 a single-part rubber-toughened epoxy adhesive (supplied by Dow Chemicals). This is a high temperature cure adhesive requiring curing at 180°C. The elastic and strength properties (including stress-strain curves) of the adherend and adhesive used in the FEA study were generated in-house and are provided in the materials database in Appendix 1.

2.2.2 Composite (GRP) T-Joints

Glass fibre-reinforced epoxy adherends were used for the composite T-joints. The laminate was based on a combination of 0.64mm thick unidirectional plies and 0.4 mm thick biaxial woven plies (double bias biaxial woven fabric where the glass fibres are oriented at +45° and -45° to the panel edges). The standard lay-up is given in Table 4. SP Systems supplied the GRP prepreg for manufacturing laminated panels. For the bolted joints the material used for the bolts was ultra high strength steel. A different adhesive system to that used to bond the aluminium joints was selected for the composite joints. As previously mentioned, XD4601 is a high temperature curing system which is suitable for bonding aluminium, but not the composite. Hence, the adhesive used for the bonded T-joints was DP460, a two-part room-temperature curing epoxy adhesive supplied by 3M, UK. The adhesive and composite properties, generated in-house, are listed in the materials database in Appendix 1. Data are provided for both the unidirectional and biaxial (woven) composite and also the standard laminate.

Table 4: Basic Laminate Configuration

Layer Number	Ply Orientation	Total Thickness (mm)
1-6	0	3.84
7-10	Biaxial Fabric	1.6
11-12	90	1.28
13-16	Biaxial Fabric	1.6
17-22	0	3.84

Note: 0° and 90° layers consist of PG51-531 SE90/L/EG1/1200/1000/32% - unidirectional. Fabric layers consist of PG21-532 SE90/M/XE603D/1250/35% - double bias biaxial woven fabric where the glass fibres are oriented at +45° and -45° to the panel edges.

3 NUMERICAL MODELLING OF T-JOINTS

3.1 FE MESHING AND ANALYSIS

Two different FEA packages were used for the T-joint parametric studies. All bonded T-joint analyses were solved using ABAQUS V6.2 [1] standard (implicit) solver whilst mesh generation was carried out using the Femsys FEMGV pre-processor [2]. All the bolted T-joint analyses were formulated, solved and post-processed using the LUSAS Composite (Version 13.4) FEA package [3]. The use of two FEA packages was due to user expertise. The re-meshing required for the parameter variation was carried out relatively easily in the FEMGV and LUSAS pre-processors.

For all T-joints three loading configurations were considered: (i) vertical; (ii) transverse; and (iii) 45° tensile loading. For vertical loading, a half model was used due to symmetry conditions. For the other loading configurations a full mesh was required. 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 to the displaced node so they all moved 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 and loading conditions applied to the bonded and bolted meshes are shown in Figure 6.

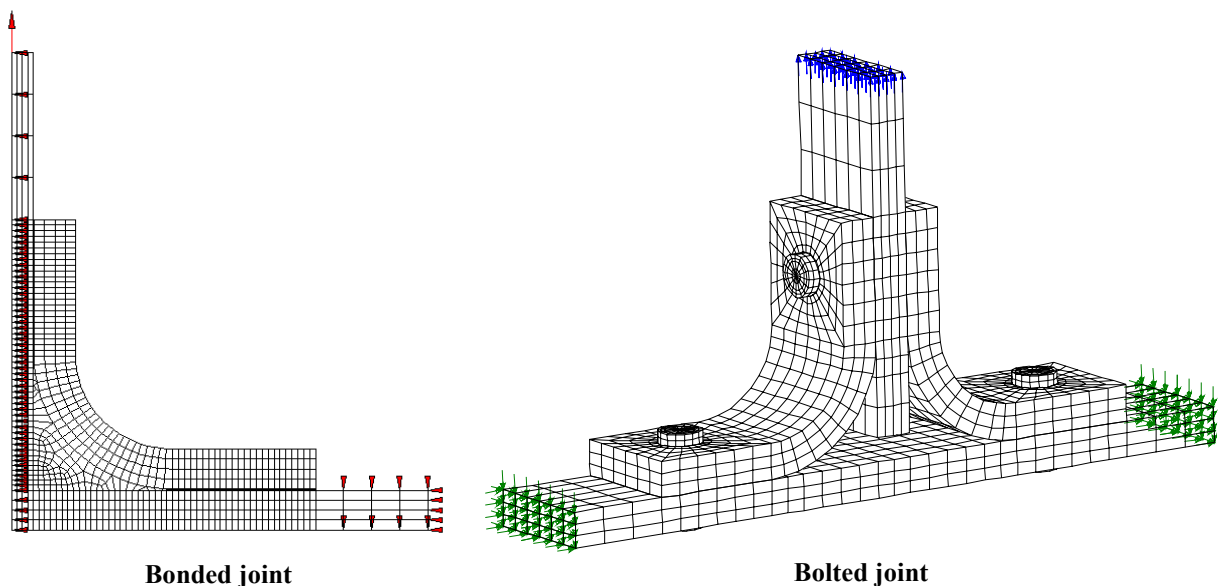


Figure 6: Half and full meshes showing boundary and loading conditions for vertical loading of the standard joints bonded and bolted T-joints

For the bonded joint 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. Analyses showed there was little difference between stress and strain predictions for the two cases.

For the bolted joint all analyses were performed using 3D models. The geometry was meshed using a combination of PN6 and HX8M, linear order three dimensional (3D) solid continuum elements. 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). 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.

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 holes.

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.

3.2 REPRESENTING MATERIALS

3.2.1 Aluminium T-Joints

In the bonded aluminium joint the adhesive was modelled with an elastic-plastic materials model (exponent Drucker-Prager), while the aluminium was modelled as an elastic material. The parameters used for the materials models are provided in Appendix 1. All material properties used in the modelling work were generated from material tests performed at NPL.

To simplify the analyses of the bolted aluminium joint, non-linear material properties were only used for the base, web and flange plates - the steel bolts were considered as perfectly elastic. The aluminium was modelled as a von Mises material.

3.2.2 Composite T-Joints

Metals such as aluminium are quite straightforward to represent in FE analyses, using simple elastic or elastic-plastic materials model for the whole metallic part. Accurately modelling a composite material is more complicated due to the layered nature of a composite. It was decided that for the composite T-joint analyses the individual laminate plies would not be modelled as initial analyses using LUSAS and ABAQUS indicated that computer run times would be excessive. Instead global layers were modelled for example the inner two 90° plies were modelled as one single layer. When defining the geometry, the adherends were divided into separate element sets of the correct thickness (see Table 4). Bulk composite data was used for each layer of the composite material (see Appendix 1). The way in which the composite was represented was slightly different for the bonded and bolted joints due to the different FE packages and meshes used (2D for bonded and 3D for bolted joints).

In the bonded joints the use of a 2-D geometry required transforming the composite ply data to account for a new x, y orientation. The data was transformed such that the through-thickness direction became the x-direction; the longitudinal direction became the y-direction and the transverse direction was the z-direction (see Figure 7). The composite sections in the T-joint are not all oriented the same way. For example, in the base the 0° fibres are horizontal, whereas in the web the 0° fibres are vertical. To account for differences in orientation, local 1, 2 coordinate systems were applied to each different composite section. Care was needed when generating the local coordinate system for the angle section of the flange. The local coordinate systems were set-up so that in all sections the 0° fibres were parallel to the 2-direction. The 1-direction was in the through thickness direction of each section (see Figure 7). The adhesive was modelled with an elastic-plastic materials model (exponent Drucker-Prager) with the model parameters given in Appendix 1. A 3-D version of the T-joint was also modelled. This analysis had a long run time, but the predictions validated the use of a 2-D model for the parametric study.

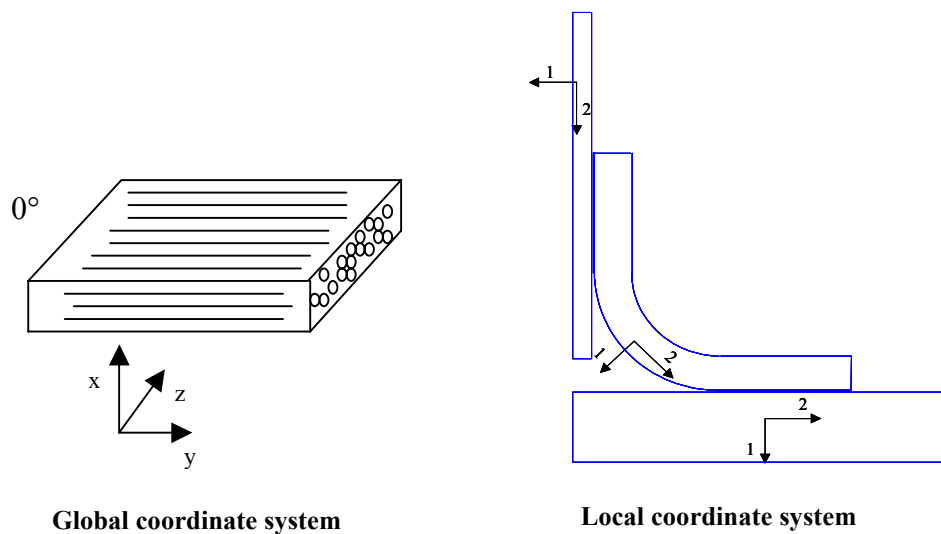


Figure 7: Global and local material property coordinate systems used for FEA of composite T-joints

In the 3D bolted joints local coordinate datasets were defined and assigned to the relevant sections in the model in order to ensure that the ply orientations of the laminate coincided with the correct orientations of the model. For the curved sections of the angle flanges (where it was not possible to define an appropriate local coordinate dataset), the volume orientation axes were positioned such that they coincided with the respective orientations of the laminate. The arrows shown in Figure 8 indicate the direction of the 0° fibres in the top ply. The steel bolts were considered elastic as before.

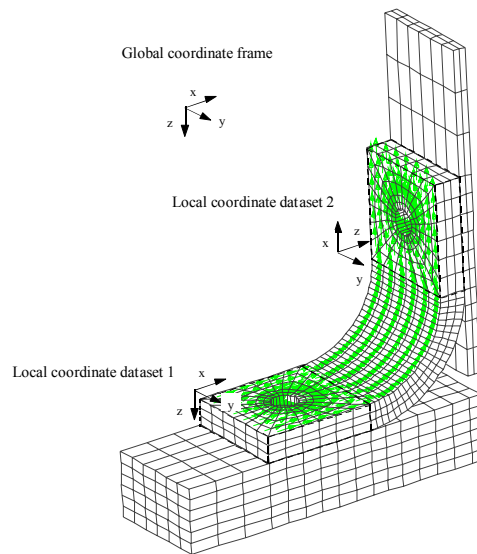


Figure 8: Local coordinate datasets to ensure correct orientation of laminate properties.

3.3 FAILURE CRITERIA

In all analyses the required output was a force-extension curve and a predicted failure load corresponding to a particular failure criterion.

For the adhesive in the bonded aluminium joints the failure criteria considered were (see [4-7]):

- 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 variables [5] were obtained by using a user subroutine (UVARM).

In the bonded GRP joints a predicted failure load could be found for the adhesive and for each layer of the composite. The failure criterion used for the adhesive was maximum principal stress. For the composite material, the failure strengths of the different plies were used. The ABAQUS outputs required were S_{11} , S_{22} and S_{12} (local orientations). The failure strengths in these directions were known for the individual plies. Although composite failure criteria do exist in ABAQUS, it was not possible to use them in these analyses. For the failure criteria to work correctly, the 1- and 2-directions of the material constants defined

for the composite sections must align with the fibre and the transverse to the fibre directions respectively. The choice of local orientations for the angle section of the flange was restricted, and hence limited the set up of all material directions.

It was necessary to obtain the increments when each of these criteria reached their critical value. A 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 post processor and the results are output to a report file. The result files were opened in a text file editor such as Microsoft 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. The location at which failure was predicted to occur was noted for each failure criterion. It was found that there were three common locations: top flange-web interface; bottom flange-web interface and flange-base plate interface. These locations are referred to as locations A, B and C respectively and are shown on a deformed mesh in Figure 9. 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 [6].

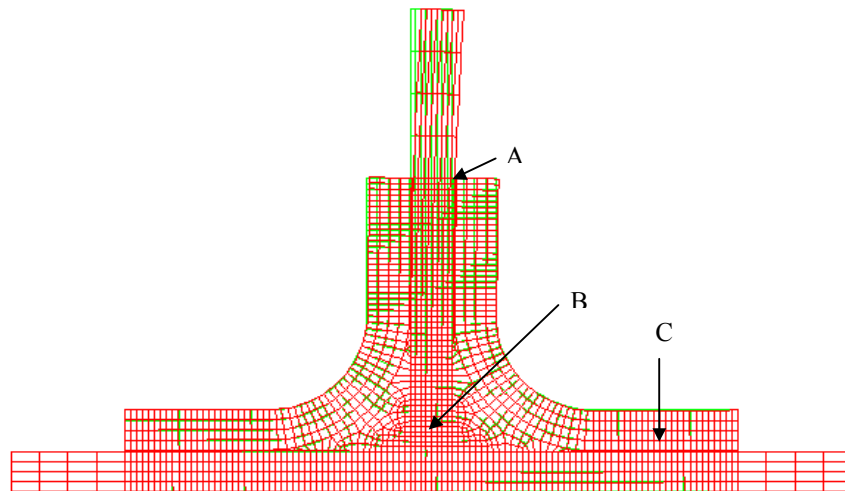


Figure 9: Transverse tension - deformed mesh over original mesh, common failure locations are labelled.

In the bolted joints, the onset of failure was regarded as yielding of aluminium for the aluminium joints or the failure strengths of the different plies for the composite material joints. A predicted failure load was obtained corresponding to the onset of failure (or yielding) at either position A, B or C (see Figure 10). 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.

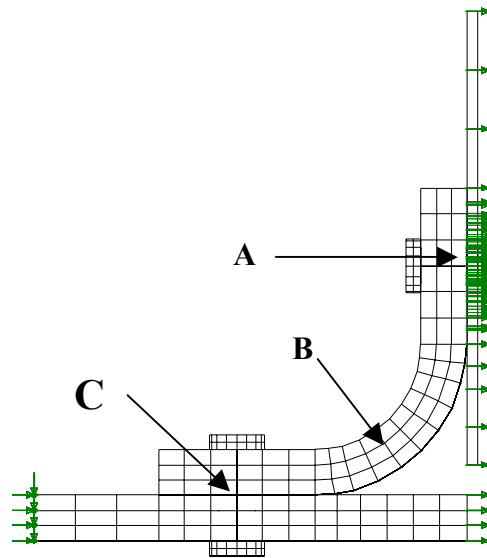


Figure 10: Direct tension – half model showing FEA mesh and symmetry support

4 NUMERICAL RESULTS FOR BONDED JOINTS

4.1 ALUMINIUM JOINT RESULTS

4.1.1 Effect of Failure Criteria

The following sections review the numerical results obtained for the aluminium adhesively bonded T-joints. The FEA results indicate a wide range of strengths for the different failure criteria. Table 5 compares predicted results for the standard aluminium bonded geometry (see Figure 1) for each of the tensile loading modes. Failure locations are also listed in the table, the positions of these three locations are shown in Figure 9. Invariably, maximum tensile stress predicts the highest joint strength and Hill's failure criteria the lowest strength. At no point in any of the analyses did the stress or strain in the aluminium exceed the elastic limit of the alloy. Only failure criteria for the adhesive layer are considered.

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 predicted failure varies for the different failure criteria and with the direction of the applied load, locations are shown in Figure 9. Predicted 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 predict failure at the top of the flange-base-plate 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 be predicted to occur in most cases at either position A or position C.

Table 5: Predicted Failure Loads (kN) and Position for Basic Aluminium T-Joint
(A = top of flange-web interface, B = bottom of flange-web interface, C = flange-base plate interface)

Criteria	Direct Tension		Transverse Tension		45° Tension	
Maximum tensile stress	176.9	B	20.54	A/B	130.0	A/B
Maximum shear stress	96.04	C	5.88	A	77.24	C
Maximum principal stress	86.58	B	6.80	A	55.86	A
Maximum tensile strain (true)	117.8	B	12.84	A	98.40	A
Maximum shear strain (true)	112.2	B	10.16	A	78.66	A
Maximum principal strain (true)	104.9	B	8.88	A	69.68	A
Guest-Tresca	95.36	C	5.5	A	76.90	C
von Mises	71.98	C	4.3	A	58.64	C
Hill's	78.28	B	3.86	A	50.80	A
Hydrostatic stress	87.38	B	7.18	A	61.76	A

There is evidence from research conducted at NPL on single-lap, scarf and butt joints that from the list of failure criteria in Table 5, 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 [4-7]. These criteria give reasonably similar predicted strengths in each loading mode. Future work will include tests on the basic joint geometry in order to check the applicability of the various failure criteria.

4.1.2 Geometric Effects

This section examines the effects of changing key geometric parameters on joint stiffness and strength for the three loading conditions. For the bonded joint the Bermuda Triangle region was filled with adhesive. The maximum principal stress criterion was used as the failure criterion for the adhesive. Table 1 (section 2.1.1) shows the factors and the levels used in this study. 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 all 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 [8].

To assess the effects of varying different parameters three levels of each parameter was modelled whilst the remaining parameters were set to their basic values. The key observations from the parametric study are summarised in Table 6 (see also Appendix 3). In each case, the parameter was increased and the effect on joint stiffness and strength was determined.

Table 6: Summary of Parametric Study on Bonded Aluminium T-Joints
(increase each parameter whilst keeping others at base values)

Parameter (increasing dimension)	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	↑↑	-	↑	-	↑	-

↑↑ = large increase; ↑ = increase; ↓ = decrease; - = no significant change

Direct Tension: Figure 11 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:

$$k = -12.1 + 6.5t_{bp} \text{ (kN/mm)} \quad (1)$$

$$P_f = 37.7 + 3.3t_{bp} \text{ (kN)} \quad (2)$$

The joint properties in most cases can be represented by a simple linear relationship. Extrapolation of these relationships outside the test envelope will not necessarily result in sensible predictions. Appendix 3 presents the predicted force-extension response as a function of key geometric features (i.e. flange radius and thickness, web, base plate and adhesive layer thickness, and web-base plate separation).

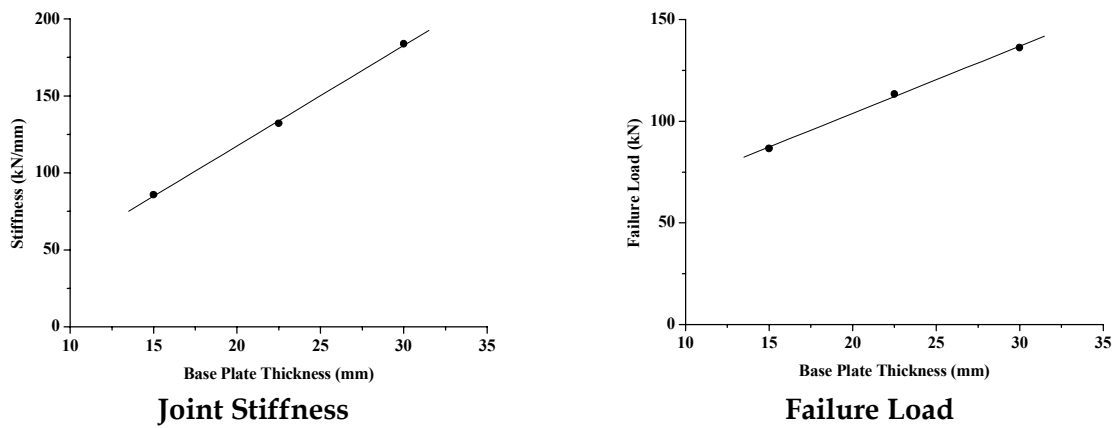


Figure 11: Direct tension - effect of base plate thickness on joint stiffness and failure load

Care needs to be taken when varying specimen dimensions as often stiffness may increase while strength decreases or vice-versa (see Table 6). Both joint stiffness and strength increased as the base plate thickness was increased. 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 6). In fact, it can be counter-productive. 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 5) is far weaker under transverse tension. A reduction in flange or web thickness will severely compromise lateral stiffness and strength (e.g. see Figure 12). Imbedding the web almost to the base plate has a beneficial effect on joint stiffness and strength.

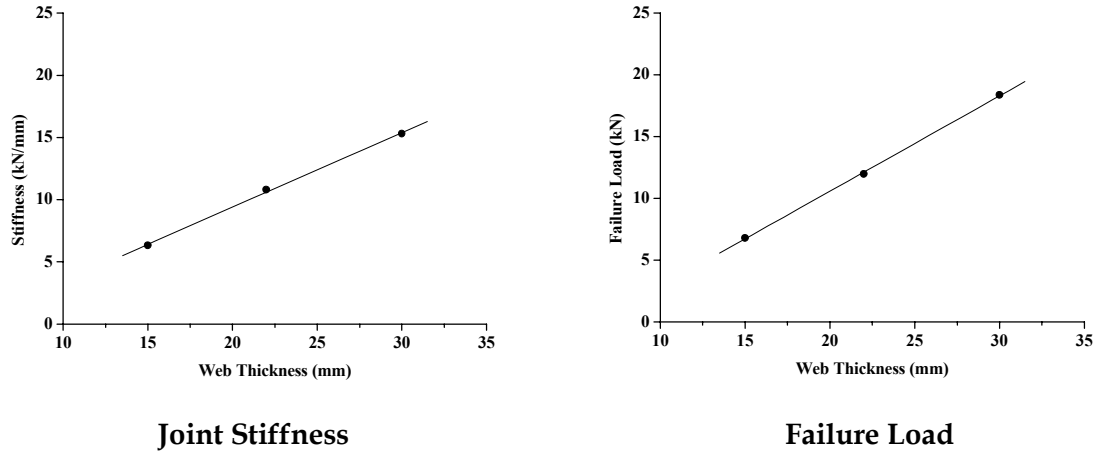


Figure 12: Transverse tension - effect of web thickness on joint stiffness and failure load.

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

$$k = -2.6 + 0.6t_{web} \text{ (kN / mm)} \quad (3)$$

$$P_f = -4.8 + 0.8t_{web} \text{ (kN)} \quad (4)$$

and

$$k = 109.1 + 1.5t_{web} \text{ (kN / mm)} \quad (5)$$

$$P_f = 31.6 + 2.6t_{web} \text{ (kN)} \quad (6)$$

for transverse and 45° tension, respectively.

4.1.3 Fully Bonded Versus Partial Bonding

FEA runs were conducted with the central region between the flanges (known as the **Bermuda Triangle**) either completely filled with XD4601 or with the adhesive present only at the metal-metal interfaces. Force-extension curves in Figure 13 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 86.58 kN for the fully filled system with XD4601, almost four times as strong as the unfilled joint (24.34 kN). The stiffness gain was 50% when the Bermuda Triangle was completely filled.

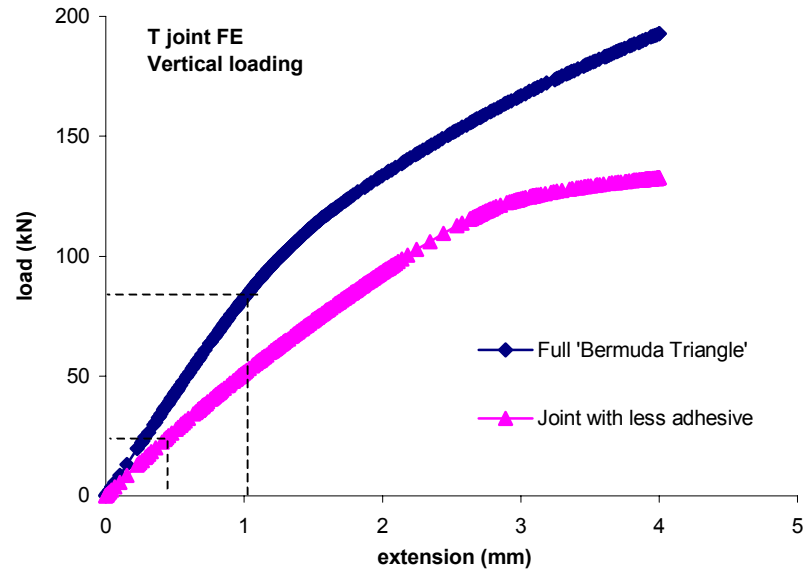


Figure 13: Plot comparing joint deformation for a fully bonded joint with XD4601 and a joint where the adhesive is restricted to regions of metal-metal contact

4.1.4 End and Fillet Geometry

FEA trials were carried out in which the bond length of 51.6mm (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 14). 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 also had little 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.

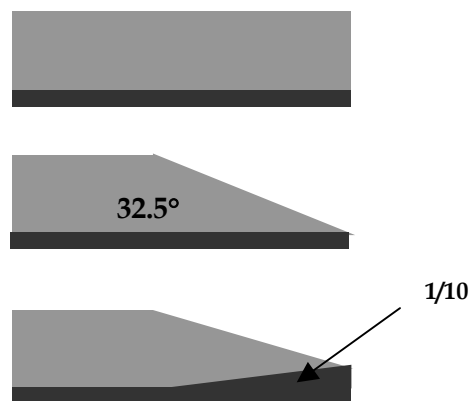


**Figure 14: Flange end shapes
(square (top); external taper (middle); external and internal taper (bottom))**

The introduction of an adhesive fillet ($\sim 55^\circ$) at the ends of the flanges (see Figure 15) had minimal effect on the strength of the basic T-joint configuration under direct tension loading. The failure location is predicted to occur at the bottom of the flange-web interface (B, see Figure 9) inside the **Bermuda Triangle** (which was filled in these analyses), thus it is unsurprising that the fillet had minimal effect on joint strength. Compressive stresses are also predicted to exist at the end of the flanges. Table 7 compares predictive failure loads for T-joints with and without the fillet using either linear elastic behaviour or the exponent Drucker-Prager materials model.

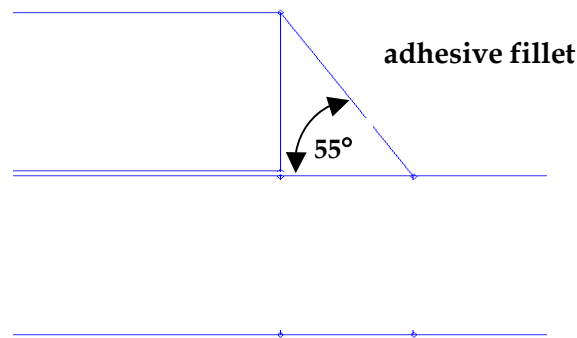


Figure 15: Schematic of adhesive fillet.

Table 7: Effect of Adhesive Fillet on Predicted Failure Loads (kN) for Aluminium T-Joints

Failure Criteria/Configuration	Linear Elastic	Exponent Drucker-Prager
<u>Maximum Principal Stress</u>		
No fillet	73.89	86.58
Fillet	73.42	86.14
<u>Hydrostatic Stress</u>		
No fillet	96.66	87.38
Fillet	96.41	86.75

To simplify modelling it is common practice to model adhesive behaviour as a linear-elastic material when in fact the adhesive undergoes elastic-plastic deformation. Linear-elastic material models tend to predict higher peel and shear stresses at the end of joints, and hence lower failure loads compared with elastic-plastic material models that are able to 'shed load' into other parts of the component. The maximum stress criterion, as with most of the other failure criterion, tends to support this supposition. Conversely, the hydrostatic stress criterion predicts the opposite. The experimental programme should be able to determine which of the failure criterion is most appropriate.

4.1.5 Thermal Residual Effects

Thermally induced residual stresses have been 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 the difference in coefficient of thermal expansion (CTE) between aluminium adherend and XD4601 adhesive. Table 8 compares the two cases for the

standard joint configuration (Figure 1), but where the adhesive is restricted to regions of metal-metal contact (i.e. unfilled **Bermuda Triangle**). Joint strength either increases or decreases depending on the failure criteria selected.

Table 8: Effect of Thermal Residual Stresses on Failure Load (kN)
(Standard Geometry with **unfilled Bermuda Triangle**)

Criteria	Excluding Thermal Effects	Including Thermal Effects
Maximum tensile stress	122.42	122.61
Maximum shear stress	88.68	89.05
Maximum principal stress	24.34	25.15
Maximum tensile strain (true)	30.66	31.63
Maximum shear strain (true)	38.94	39.77
Maximum principal strain (true)	30.64	31.57
Guest-Tresca	78.8	79.39
von Mises	62.76	63.06
Hill's	16.58	17.31
Hydrostatic stress	18.92	20.82

4.1.5 Structural Efficiency

Structural efficiency (i.e. stiffness and/or strength-to-weight ratio, also referred to as specific stiffness and specific strength) is dependent on the size (dimensions) of the individual components within the joint assembly. Increasing the size (e.g. thickness) of individual components may result in a stiffer and stronger joint, but as a result the structural efficiency (i.e. specific properties) of the joint may decrease. Increasing the size of the joint will also add to the manufacturing costs through increased material and machining requirements.

This section compares the structural efficiency of five T-joint configurations (see Table 9) under direct tension, 45° tension and transverse tension loading conditions. Adhesive layer thickness and web base-plate separation distance in each case are 0.5 mm and 15 mm, respectively. The failure criterion used is the Maximum Principal Stress. The weight of the adhesive in the joint is not included in the calculations. Specific stiffness and specific strength values presented in Tables 10 to 12 are expressed in terms of kN/mm/kg and kN/kg, respectively.

Table 9: Direct Tension - Dimensions (mm) of Bonded Aluminium T-Joints
Joint A is standard joint (Figure 1)

Joint	Base Plate Thickness	Web Thickness	Flange Thickness	Inner Radius	Web-Base Separation	Adhesive Thickness
A	15.0	15.0	15.0	35.0	15.0	0.50
B	15.0	15.0	7.5	42.5	15.0	0.50
C	15.0	15.0	15.0	10.0	15.0	0.50
D	30.0	15.0	7.5	42.5	15.0	0.50
E	30.0	30.0	15.0	35.0	15.0	0.50

Table 10: Direct Tension - Stiffness and Strength for Bonded Aluminium T-Joints

Joint	Weight (kg)	Stiffness (kN/mm)	Specific Stiffness (kN/mm/kg)	Strength (kN)	Specific Strength (kN/kg)
A	1.651	85.8	52.0	86.6	52.4
B	1.310	46.9	35.8	102.8	78.5
C	1.620	67.6	41.7	58.6	36.2
D	1.941	133.3	68.7	165.5	85.3
E	2.598	201.4	77.5	137.6	53.0

Table 11: 45° Tension - Stiffness and Strength for Bonded Aluminium T-Joints

Joint	Weight (kg)	Stiffness (kN/mm)	Specific Stiffness (kN/mm/kg)	Strength (kN)	Specific Strength (kN/kg)
A	1.651	61.9	37.5	55.9	33.9
B	1.310	38.8	29.6	75.0	57.3
C	1.620	49.0	30.2	53.0	32.7
D	1.941	95.4	49.1	101.7	52.4
E	2.598	154.0	59.3	109.1	42.0

Table 12: Transverse Tension - Stiffness and Strength for Bonded Aluminium T-Joints

Joint	Weight (kg)	Stiffness (kN/mm)	Specific Stiffness (kN/mm/kg)	Strength (kN)	Specific Strength (kN/kg)
A	1.651	6.31	3.82	6.80	4.12
B	1.310	3.75	2.86	7.56	5.77
C	1.620	5.49	3.39	7.52	4.64
D	1.941	4.53	2.33	7.55	3.89
E	2.598	7.53	2.99	6.72	2.59

Key observations from the FEA results presented in Tables 10 to 12 are summarised below.

General

- A joint may be stiff, but not necessarily strong and vice-versa.
- A joint may be stiffer and/or stronger than other joints for one loading condition, but less resistant to other loading conditions.
- A joint may be stiffer and/or stronger than other joints, but have a lower stiffness and/or strength-to-weight ratio (i.e. structurally less efficient) than the other joints.
- All the joints are structurally weak under transverse loading conditions.

Direct Tension

- The order of increasing stiffness remains the same when the weight of each joint is taken into account. However, the difference in stiffness between the lowest and highest cases is significantly reduced when allowing for the weight of each joint. "E" is 4.3 times as stiff as "B" in absolute terms, but in terms of specific stiffness it is only twice as stiff.

- The order of increasing strength changes when the weight of each joint is considered.
- Stiffest joint “E” also happens to be structurally much weaker than “B”, the joint with the lowest stiffness when weight is considered.
- “D” offers a good balance of both stiffness and strength when joint weight is taken into account.

45° Tension

- The order of increasing stiffness remains the same when the weight of each joint is taken into account. Difference in stiffness between lowest and highest is significantly reduced when allowing for the weight of each joint.
- The order of increasing strength changes when joint weight is considered. “E” (highest strength) is twice as strong as “C” (lowest strength), but in terms of specific strength it is only slightly stronger (1.3 times as strong).
- Again, “D” offers a good balance of both stiffness and strength when weight is taken into account.

Transverse Tension

- The order of increasing stiffness changes when the weight of each joint is taken into account. In absolute terms, differences in stiffness and strength between the various joint configurations are small in comparison to the other loading modes.
- “A” and “C” offer the best balance in terms of both specific stiffness and specific strength. The specific stiffness and specific strength are almost on a par.
- A more effective method of enhancing structural efficiency (i.e. increase resistance to lateral loads) is to reduce the separation distance between the web and the base plate. This is achieved without having to increase the weight of the joint.

4.2 COMPOSITE JOINT RESULTS

4.2.1 Comparison of Aluminium and Composite T-Joints

This section presents the FEA results obtained for T-joints manufactured from glass fibre-reinforced epoxy and bonded with DP460 adhesive. Details of the laminate lay-up and T-joint geometry are presented in Section 2.

FEA trials were carried out on the standard Case 2 joint geometry used for the composite T-joints (see section 2.1.2) to assess the differences in stiffness and strength, and specific stiffness and strength between aluminium and GRP joints bonded with DP460. The aluminium T-joint analyses presented here were run using the same Case 2 geometry to allow direct comparison of predictions. The results presented in Tables 13 and 14, and Figure 16 show that for all loading conditions the stiffness is higher for aluminium joints. Stiffness is greatly enhanced with the **Bermuda Triangle** completely filled with adhesive. When calculating the specific stiffness and strength a mass of 1.338kg is used for the aluminium adherends and a mass of 0.973kg is used for the composite adherends. The mass of the adhesive is not considered.

Table 13: Stiffness (kN/mm) of Bonded Aluminium and GRP T-Joints
(composite Case 2 geometry for both adherend types)

Loading Mode	Filled		Unfilled	
	Aluminium	GRP	Aluminium	GRP
Direct Tension	52.2	20.5	31.6	11.9
45° Tension	37.6	14.8	22.8	8.60
Transverse Tension	3.55	1.60	1.93	0.84

Table 14: Specific Stiffness (kN/mm/kg) of Bonded Aluminium and GRP T-Joints
(composite Case 2 geometry for both adherend types)

Loading Mode	Filled		Unfilled	
	Aluminium	GRP	Aluminium	GRP
Direct Tension	39.0	21.1	23.6	12.2
45° Tension	28.1	15.2	17.0	8.84
Transverse Tension	2.65	1.64	1.44	0.86

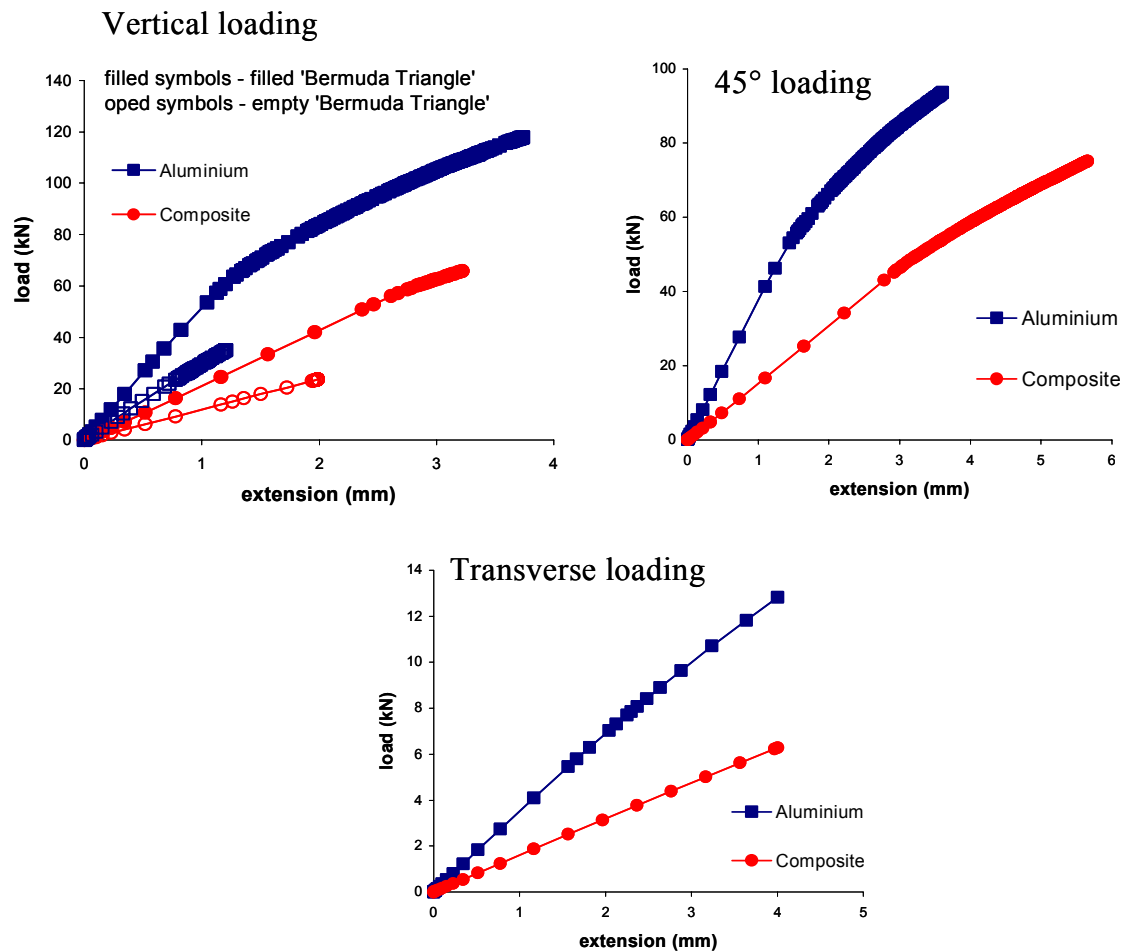


Figure 16: Force-extension responses for bonded aluminium and GRP T-joints

Table 15: Strength (kN) and Failure Location for Bonded Aluminium and GRP T-Joints
(A = flange-web interface (top), B = flange-web interface (bottom), C = flange-base plate interface)
(composite Case 2 geometry for both adherend types)

Loading Mode	Filled		Unfilled	
	Aluminium	GRP	Aluminium	GRP
Direct Tension	49.3 (B)	30.7 (C)	7.41 (B)	6.17 (B)
45° Tension	24.3 (A)	16.6 (A)	6.74 (B)	5.73 (B)
Transverse Tension	2.45 (A)	2.09 (A)	2.41 (A)	1.99 (A)

Table 16: Specific Strength (kN/kg) of Bonded Aluminium and GRP T-Joints
(composite Case 2 geometry for both adherend types)

Loading Mode	Filled		Unfilled	
	Aluminium	GRP	Aluminium	GRP
Direct Tension	36.8	31.6	5.54	6.34
45° Tension	18.2	17.1	5.04	5.89
Transverse Tension	1.83	2.15	1.80	2.05

For most joint and loading configurations, joint strength (see Tables 15 and 16) for the two materials are almost equal, with the Aluminium joints tending to be slightly stronger for total strength and the GRP for specific strength. The obvious difference is the total strength for filled T-joints under direct tension loading. In this case, aluminium is far stronger than its GRP counterpart. All the joints (with the exception of the GRP joint in direct tension) were predicted to fail in the adhesive (i.e. cohesive failure of adhesive layer). The location of failure in each joint is identified in Table 15.

4.2.2 Geometric Effects

A small parametric study (see Table 17) was carried out on the standard Case 1 GRP test geometry (see Figure 4) loaded in direct tension to determine the effect of changing flange radius, web thickness and flange taper on the stiffness and strength of the joint. The **Bermuda Triangle** was unfilled. Table 18 compares the stiffness and strength and failure location for each case. Joint E is the standard geometry.

Table 17: Geometric Factors and Levels for Bonded GRP T-Joints

Joint	Inner Radius (mm)	End Geometry	Web Thickness (mm)
A	25	Square	12.16
B	25	Square	24.32
C	25	Taper (3 in 1)	12.16
D	25	Taper (3 in 1)	24.32
E	50	Square	12.16
F	50	Square	24.32
G	50	Taper (3 in 1)	12.16
H	50	Taper (3 in 1)	24.32

Table 18: Geometric Effects on Stiffness, Strength and Failure Location of Unfilled GRP T-Joints

(A = flange-web interface (top), B = flange-web interface (bottom), C = flange-base plate interface)

Joint	Stiffness (kN/mm)	Strength (kN)	Failure Location
A	30.99	11.09	B (adhesive)
B	34.29	11.32	B (adhesive)
C	32.71	11.43	B (adhesive)
D	34.28	11.32	B (adhesive)
E (Case 1 geometry)	27.41	9.43	B + C (adhesive)
F	29.17	9.43	B + C (adhesive)
G	27.41	9.42	B + C (adhesive)
H	29.16	9.43	B + C (adhesive)
E (Filled)	48.2	44.9	B + C (adhesive)

Failure tended to be cohesive and occur at the intersection between the web and flange or flange and base plate. Stiffness and strength were unaffected by tapering the flange ends. Earlier results on aluminium joints showed that the end shape of the flanges and the introduction of an adhesive fillet had minimal effect on joint properties. The FEA results also predicts that by increasing the web thickness from 12.16 mm to 24.32 mm will have little effect on the stiffness and strength of the joint under direct tensile loading conditions. Reducing the inner flange radius from 50 mm to 25 mm can be expected to have a positive effect on joint stiffness and strength. Completely filling the Bermuda Triangle region results in a significant increase in both stiffness and strength (see Table 16).

5 NUMERICAL RESULTS FOR BOLTED JOINTS

This section reviews the numerical results obtained for both aluminium and composite (i.e. GRP) bolted T-joints. Details of the joint geometry, numerical modelling and materials database are given in Sections 2, 3 and Appendix 1, respectively.

5.1 ALUMINIUM JOINT RESULTS

5.1.1 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. Figure 1 shows the standard aluminium bolted T-joint geometry and Table 2 (section 2.1.1) shows the factors and levels. In all cases, the width 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 (83.3 mm from the centre line). Due to time constraints it was not possible to assess changes in dimensions by performing a full factorial analysis using statistical analysis (DoE). Analyses were run with each parameter varied whilst the others were held at their base values.

The key observations from the parametric study are summarised in Table 19. 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 20 compares changes in predicted failure location (see Figure 10) 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) increases.

Table 19: Summary of Parametric Study on Bolted Aluminium T-Joints

Criteria (Increasing dimension)	Direct Tension		45° Tension		Transverse Tension	
	Strength	Stiffness	Strength	Stiffness	Strength	Stiffness
Base Plate Thickness	↑	↑↑	↑	↑	↑	↑
Web Thickness	-	-	↑	↑	↑	↑
Inner Radius	↑	↑	↑	↑	↑	↑
Flange Thickness	↑↑	↑↑	↑↑	↑↑	↑↑	↑↑

↑↑ = large increase; ↑ = increase; ↓ = decrease; - = no significant change

Table 20: Failure Location (see Figure 10) as Function of Increasing Parameter Dimension Bolted Aluminium T-Joints

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

Direct Tension

Table 19 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 in direct tension.
- Flange radius has a small effect on joint properties.
- Base plate thickness has a significant effect on joint stiffness, but a smaller 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 (location 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 17). The predicted failure load P_f and stiffness k of the joint can be related using the following Boltzmann Equation:

$$P_f = \frac{A_1 - A_2}{1 + e^{(k-k_0)/dk}} + A_2 \quad (7)$$

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

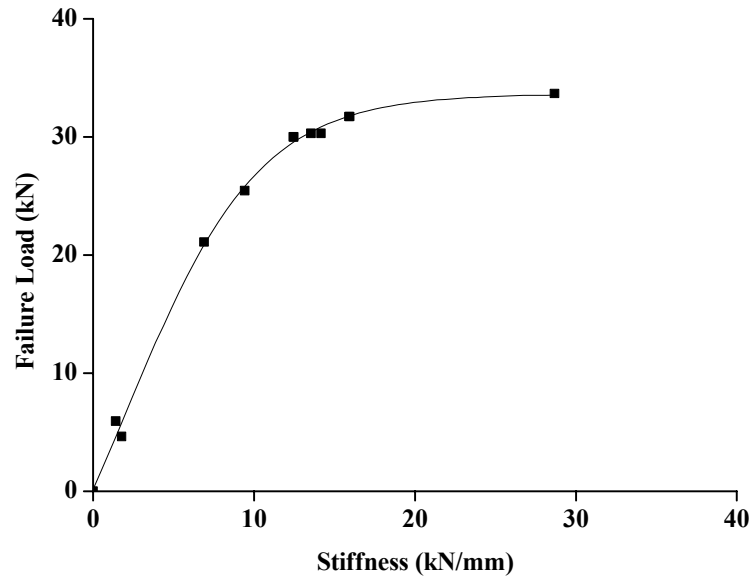


Figure 17: Direct tension - predicted failure load versus stiffness

Figure 18 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:

$$k = -6.8 + 2.5t_{fl} \text{ (kN / mm)} \quad (8)$$

$$P_f = -2.6 + 0.9t_{fl} \text{ (kN)} \quad (9)$$

Previous FEA trials on adhesively bonded T-joints (see Section 4 and also [9]) 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.

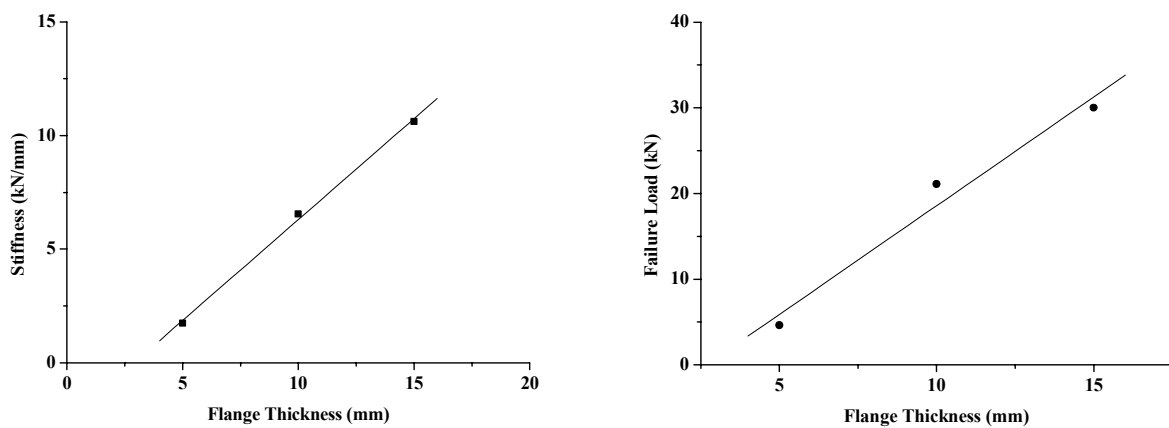


Figure 18: Direct tension - effect of flange thickness on joint stiffness and failure load

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 19 shows a plot of predicted joint strength as a function of predicted stiffness for the transverse and 45° tension.

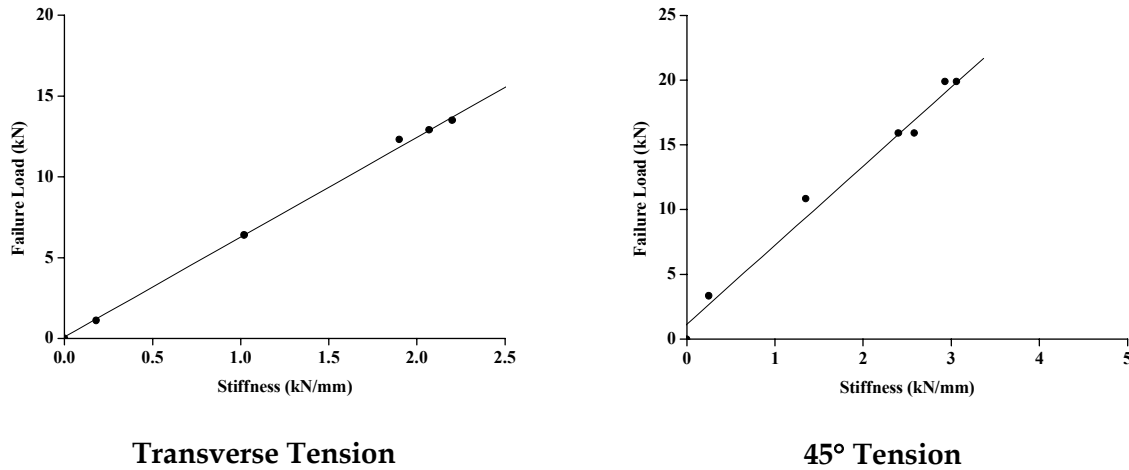


Figure 19: Predicted strength versus stiffness

The predicted failure load P_f and stiffness k of the joint under transverse and 45° tension can be related, within the range of parameters used, by the following linear relationships:

Transverse Tension $P_f = 0.1 + 6.2k(\text{kN})$ (10)

45° Tension $P_f = 1.2 + 6.1k(\text{kN})$ (11)

Table 19 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. Increasing web thickness led to an increase in joint strength and stiffness for 45° and transverse loading only. As each parameter is increased, the initial failure location tends to change position (see Table 20). 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 empirical relationships outside a test envelope without confirmation testing, as there is no guarantee the data will be valid.

5.1.2 Progressive Failure

An important feature of bolted joints is that these structures can withstand loads well beyond the point at which yielding first occurs, without the component parts separating, whereas adhesive joints tend to separate rapidly after the onset of adhesive failure. Figure 20 shows progressive failure within a bolted T-joint under direct tension loading. As load increases, damage appears in a number of locations (crosses in Figure 20), but the structure still remains intact, although significantly deformed.

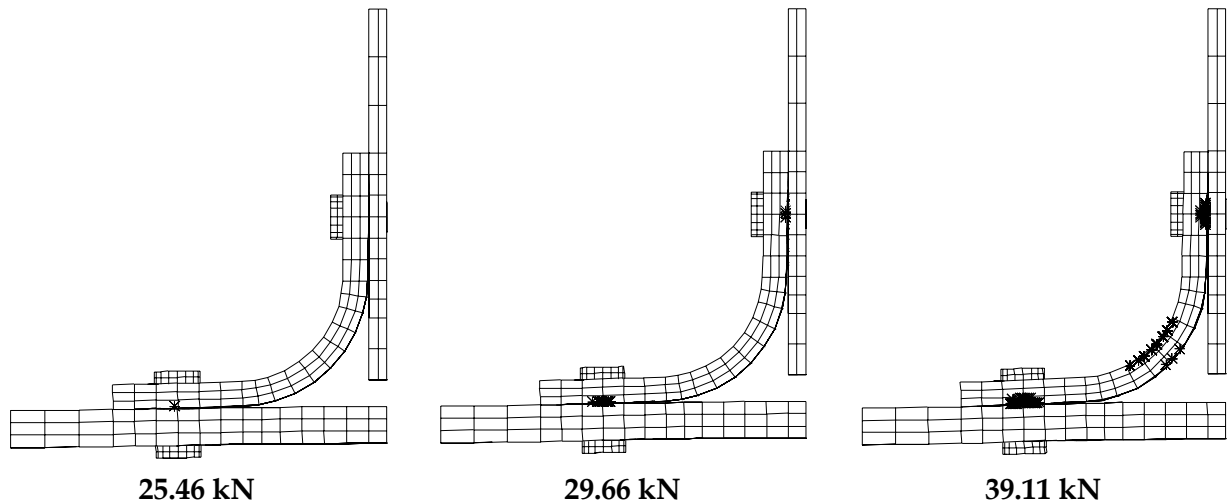


Figure 20: Direct tension – damage accumulation with increasing load (left to right)

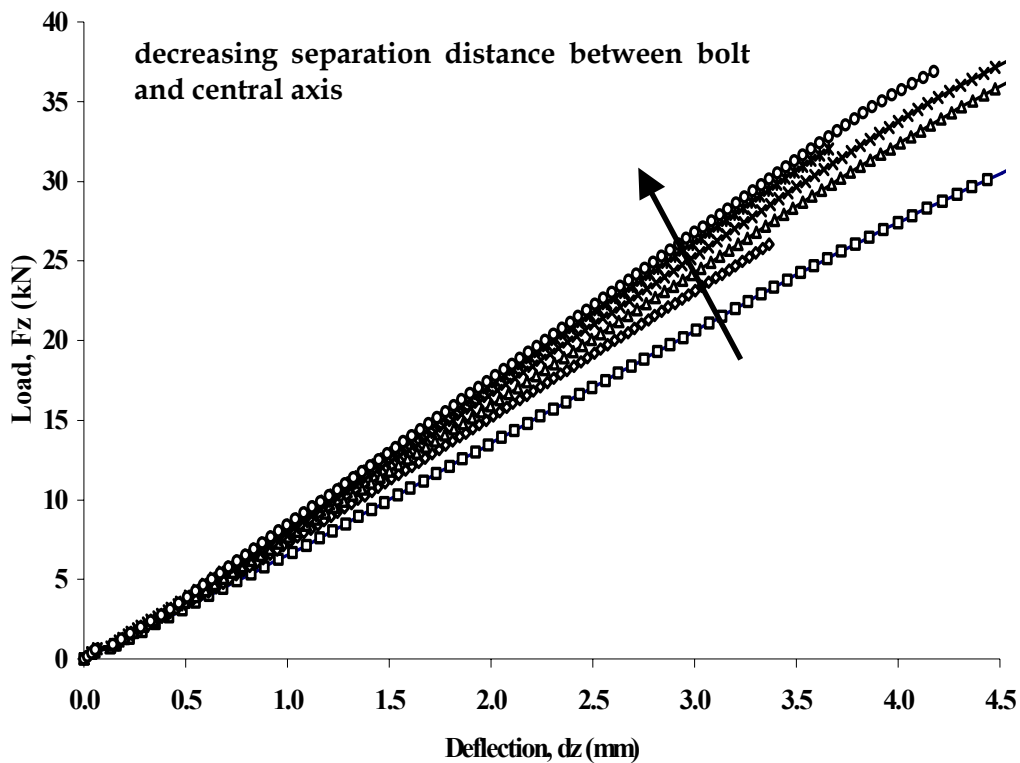


Figure 21: Direct tension - effect of bolt position on joint stiffness

5.1.3 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 21 shows predicted force-extension plots as a function of bolt position. Figure 22 shows that k and P_f increase linearly with bolt position d_{bolt} . The effect of bolt position on joint properties is given by:

$$k = 13.23 + 0.08d_{\text{bolt}} \text{ (kN/mm)} \quad (12)$$

$$P_f = 52.57 + 0.4d_{\text{bolt}} \text{ (kN)} \quad (13)$$

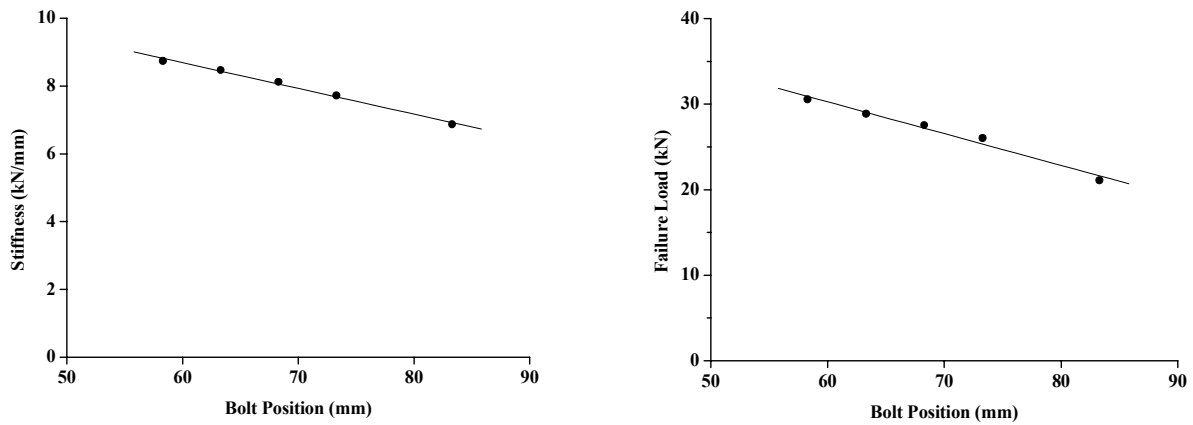


Figure 22: Direct tension - effect of bolt position on joint stiffness and failure load

5.1.4 Structural Efficiency

As previously mentioned, structural efficiency (i.e. stiffness and/or strength-to-weight ratio) is dependent on the dimensions of the individual components within the joint assembly and that increasing the size of individual components may result in a less efficient structure (i.e. lower specific properties) as a result. Increasing the size of the joint will also add to the manufacturing costs through increased material and machining requirements. This section compares the structural efficiency of four T-joint configurations (see Table 21) under direct tension, 45° tension and transverse tension loading conditions. In all cases, the width or depth of the joint was 50 mm, web to base plate separation distance was 10 mm, web thickness was 15 mm, and the bolts were centred at an edge distance of 25 mm (83.3 mm from centre line). The weight of the bolts in the joint is not included in the calculations.

Table 21: Direct Tension - Dimensions (mm) of Bolted Aluminium T-Joints
(Joint C is standard geometry)

Joint	Base Plate Thickness	Web Thickness	Flange Thickness	Outer Radius	Web-Base Separation	Bolt Position
A	15.0	15.0	5.0	50.0	10.0	58.3
B	15.0	15.0	15.0	25.0	10.0	58.3
C	15.0	15.0	15.0	50.0	10.0	58.3
D	30.0	15.0	15.0	50.0	10.0	58.3

Table 22: Direct Tension - Stiffness and Strength for Bolted Aluminium T-Joints
(Joint C is standard geometry)

Joint	Weight (kg)	Stiffness (kN/mm)	Specific Stiffness (kN/mm/kg)	Strength (kN)	Specific Strength (kN/kg)
A	1.181	2.82	2.39	5.91	5.00
B	1.725	11.9	6.90	30.0	17.4
C	1.651	17.0	10.3	31.7	19.2
D	2.280	30.3	13.3	33.9	14.9

Table 23: 45° Tension - Stiffness and Strength for Bolted Aluminium T-Joints
(Joint C is standard geometry)

Joint	Weight (kg)	Stiffness (kN/mm)	Specific Stiffness (kN/mm/kg)	Strength (kN)	Specific Strength (kN/kg)
A	1.181	0.18	0.15	2.10	1.78
B	1.725	2.07	1.20	14.9	8.64
C	1.651	2.20	1.33	16.3	9.87
D	2.280	2.57	1.13	14.4	6.32

Table 24: Transverse Tension - Stiffness and Strength for Bolted Aluminium T-Joints
(Joint C is standard geometry)

Joint	Weight (kg)	Stiffness (kN/mm)	Specific Stiffness (kN/mm/kg)	Strength (kN)	Specific Strength (kN/kg)
A	1.181	0.23	0.19	1.87	1.58
B	1.725	2.81	1.63	12.3	7.13
C	1.651	3.08	1.87	13.5	8.18
D	2.280	3.44	1.51	13.5	5.92

Key observations from the FEA results presented in Tables 22 to 24 are summarised below.

General

- A joint may be stiffer and/or stronger than other joints, but have a lower stiffness and/or strength-to-weight ratio (i.e. structurally less efficient) than the other joints.
- “C” exhibits the best and “A” the worst balance of stiffness to-weight and strength-to-weight ratios for all three loading modes.
- Increasing the base thickness may enhance strength in absolute terms, but cause a reduction in specific strength.
- All the joints are structurally weaker under transverse loading conditions.

Direct Tension

- The order of increasing stiffness (i.e. “A” lowest to “D” highest) remains the same when the weight of each joint is taken into account.
- The order of increasing strength changes when the weight of each joint is considered. “B” has the highest (only slightly higher than “C”) and “A” the lowest strength-to-weight ratio.

45° and Transverse Tension

- The order of increasing stiffness (i.e. “A” lowest to “D” highest) changes when the weight of each joint is taken into account. “C” has the highest specific stiffness.
- The order of increasing strength also changes when the weight of each joint is considered. “C” has the highest strength-to-weight ratio.

5.2 COMPOSITE T-JOINT RESULTS

This section presents the FEA results obtained on bolted T-joints manufactured from glass fibre-reinforced epoxy and compares the predicted stiffness and strength with aluminium joints with similar geometries. A small parametric study was carried out to assess the effect of changing key parameters on the stiffness and strength. Details of the laminate lay-up and T-joint geometry are presented in Sections 2 and 3, respectively. The standard composite geometry shown in Figure 3 was used for the bolted T-joints.

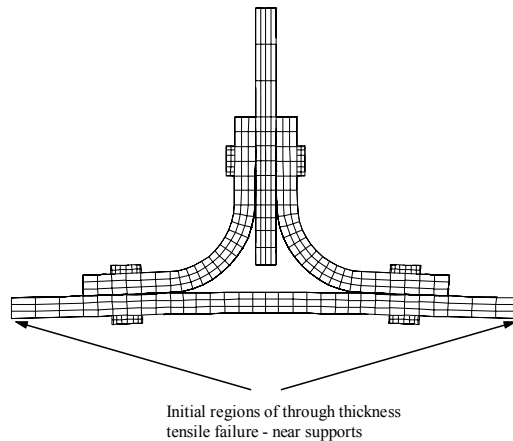
5.2.1 Failure Criteria/Progressive failure

The definition of failure varies widely, which confuses the issue of defining the allowable design strength. An approach frequently used is based on the degree of deformation of the hole under load, however there is a lack of agreement over the allowable level of deformation. Values used vary between 0.5% and 2% of the un-deformed diameter of the hole. A safety factor of 2 is commonly applied to the ultimate strength, which is close to the stress at which damage is initiated. Other definitions of failure criteria are based on:

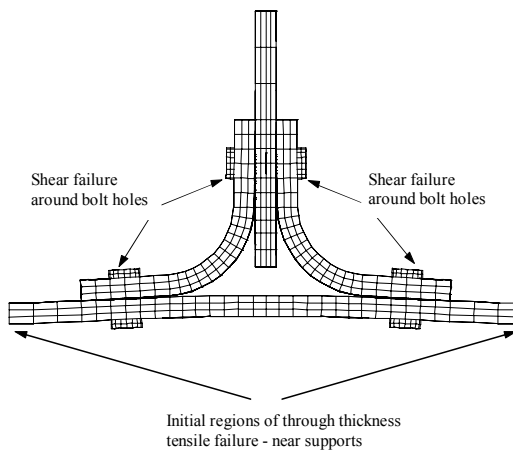
- Onset of damage (used in this study)
- Degree of damage
- Load bearing capacity of the joint

In this study, failure load was taken at the onset of damage anywhere within the structure (i.e. bolts, base, web or flange). Very high tensile strength bolts ($\sigma_{ULT} \sim 1,200$ MPa) were used to ensure composite failure. Figure 23 shows progressive failure in a T-joint under direct tension loading. The joint was predicted to withstand loads well in excess of the onset failure load without separation of components, although severe deformation occurs at high loads.

(a) Load = 10.51 kN



(b) Load = 15.98 kN



(c) Load = 23.27 kN

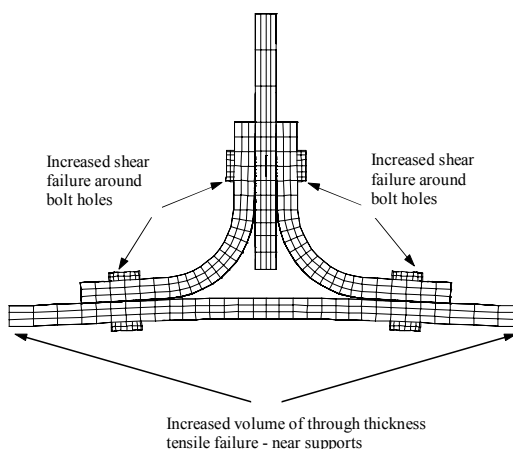


Figure 23: Progressive failure in basic GRP T-joint under direct tension loading

5.2.2 Comparison of Aluminium and Composite T-Joints

FEA trials were carried out on the basic joint geometry used for the composite T-joints (see Figure 3), the same geometry was used for the aluminium t-joints in this comparative study. The predictions were analysed to assess the differences in stiffness and strength, and specific stiffness and strength between aluminium and GRP joints. The specific stiffness and strength values are calculated using adherend masses of 1.338kg and 0.973kg for the aluminium and GRP joints respectively. The results presented in Tables 25 to 28 show that for all loading conditions the stiffness and strength is higher for aluminium joints. A key factor limiting the strength of the GRP T-joints was the low T-T tensile strength (~27 MPa).

Table 25: Stiffness (kN/mm) of Bolted Aluminium and GRP T-Joints
(standard bolted composite geometry for both adherends)

Loading Mode	Material	
	Aluminium	GRP
Direct Tension	8.27	2.50
45° Tension	1.28	0.37
Transverse Tension	0.74	0.28

Table 26: Specific Stiffness (kN/mm/kg) of Bolted Aluminium and GRP T-Joints
(standard bolted composite geometry for both adherends)

Loading Mode	Material	
	Aluminium	GRP
Direct Tension	6.18	2.57
45° Tension	0.96	0.38
Transverse Tension	0.55	0.29

Table 27: Strength (kN) of Bolted Aluminium and GRP T-Joints
(standard bolted composite geometry for both adherends)

Loading Mode	Material	
	Aluminium	GRP
Direct Tension	29.4	10.5
45° Tension	12.4	5.57
Transverse Tension	8.94	4.34

Table 28: Specific Strength (kN/kg) of Bolted Aluminium and GRP T-Joints
(standard bolted composite geometry for both adherends)

Loading Mode	Material	
	Aluminium	GRP
Direct Tension	22.0	10.79
45° Tension	9.27	5.72
Transverse Tension	6.68	4.46

5.2.3 Geometric Effects

A small parametric study (see Table 29) was carried out on the basic GRP test geometry in direct tension to determine the effect of flange radius, web thickness and bolt position (from centre of joint) on the joint stiffness and strength. In all cases, the width or depth of the joint was 50 mm and the web to base plate separation distance was 10 mm. The standard joint geometry (Figure 3) is labelled as Joint A. The results presented in Table 30 indicate stiffness and strength were only slightly affected by altering web thickness, flange radius and bolt location. Thus, reinforcing previous work on the aluminium joints that these parameters are less influential than base-plate thickness and flange thickness. Failure invariably initiates at the ends of the joint in direct tension (Figure 24), whereas failure initiates around the holes when the T-joints are loaded in transverse or 45° tension (Figure 25).

Table 29: Geometric Factors and Levels for Bolted GRP T-Joints

Joint	Outer Radius (mm)	Bolt Position (mm)	Web Thickness (mm)
A	50	81.88	12.16
B	50	81.88	24.32
C	50	76.88	12.16
D	50	76.88	24.32
E	25	81.88	12.16
F	25	81.88	24.32
G	25	76.88	12.16
H	25	76.88	24.32

Table 30: Geometric Effects on Stiffness, Failure Load and Failure Location of GRP T- Joints
(Joint A is the standard geometry)

Joint	Stiffness (kN/mm)	Strength (kN)	Failure Location
A	2.50	10.51	End of joint
B	2.78	10.46	End of joint
C	2.57	10.21	End of joint
D	2.85	10.21	End of joint
E	2.00	9.56	End of joint
F	2.16	9.61	End of joint
G	2.07	9.51	End of joint
H	2.77	9.42	End of joint

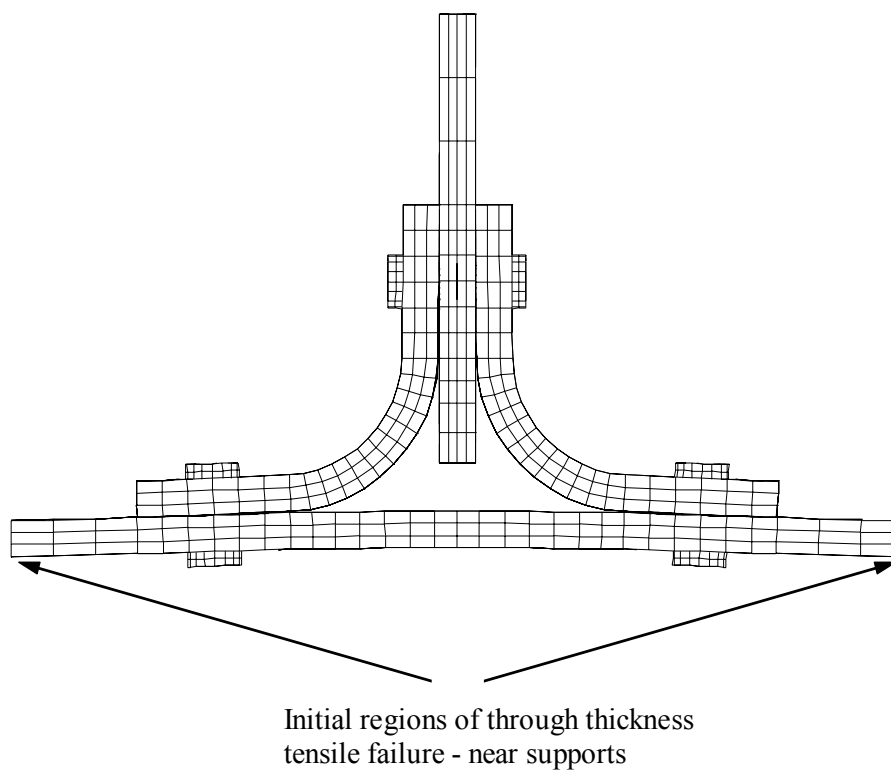


Figure 24: Direct tension of GRP T-joint (showing regions where failure first occurs)

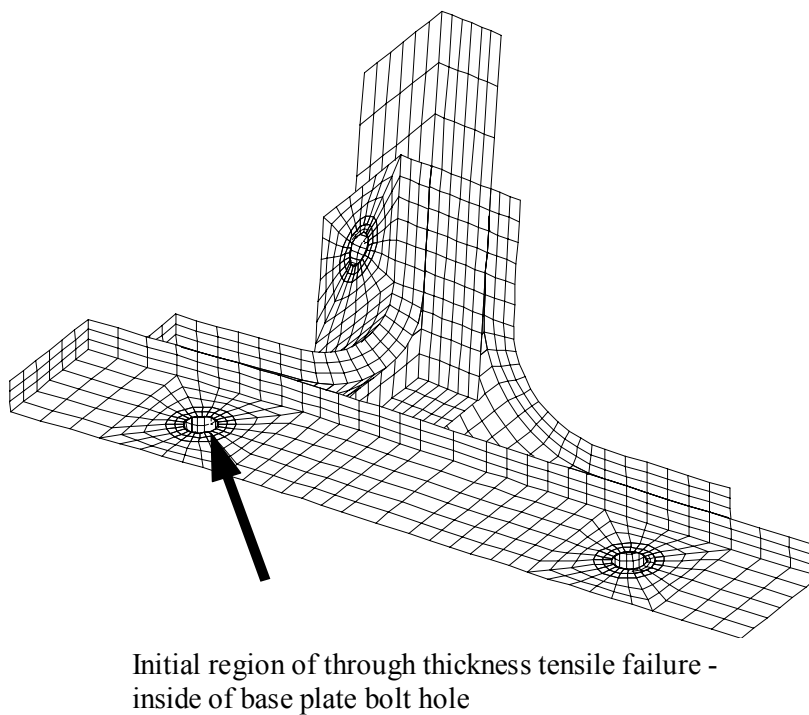


Figure 25: Transverse and 45° loading of bolted GRP T-joints (showing region where failure first occurs)

6 DISCUSSION AND CONCLUDING REMARKS

The FEA results demonstrate that simple empirical relationships can be used to estimate the effects of the geometric and bolt parameters on joint stiffness and strength for complex assemblies, such as T-joints. Empirical equations can also be used to relate strength to stiffness for each loading condition. The effect of geometric parameters on joint stiffness, strength and failure location 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. Increasing the base plate thickness may significantly improve stiffness and strength in absolute terms, but the specific properties (i.e. stiffness-to-weight and strength-to-weight ratios) can be significantly reduced. Both bonded and bolted T-joints are predicted to be far superior under direct tension compared with loading conditions containing a lateral tensile component. Aluminium T-joints were stiffer than their composite equivalents. For bonded aluminium and GRP T-joints the specific strengths of the joints were comparable. For the bolted configurations, aluminium joints were stronger than their GRP counterpart.

Tables 31 and 32 compare the stiffness and strength of bonded and bolted T-joints of a standard T-joint geometry: Case 2 geometry for bonded joints (section 2.1.2) and standard GRP geometry (Figure 3) for the bolted joints. Adhesively bonding the T-joint is predicted to improve stiffness considerably, particularly if the Bermuda Triangle is completely filled. Filling the Bermuda Triangle is also expected to significantly increase the joint strength. Unfilled bonded T-joints tend to be weaker than their bolted equivalent.

Table 31: Comparison of Stiffness for Bonded and Bolted T-Joints (kN/mm)

Loading Mode	Bonded		Bolted	
	Aluminium (Filled/Unfilled)	GRP (Filled/Unfilled)	Aluminium	GRP
Direct Tension	52.2/31.6	20.5/11.9	8.29	2.50
45° Tension	37.6/22.7	14.8/8.60	1.28	0.37
Transverse Tension	3.55/1.93	1.60/0.85	0.74	0.28

Table 32: Comparison of Failure Loads (kN) for Bonded and Bolted T-Joints

Loading Mode	Bonded		Bolted	
	Aluminium (Filled/Unfilled)	GRP (Filled/Unfilled)	Aluminium	GRP
Direct Tension	49.3/7.41	30.7/6.17	29.4	10.5
45° Tension	24.3/6.74	16.6/5.73	12.38	5.57
Transverse Tension	2.45/2.41	2.09/1.99	8.94	4.34

The FEA predicts that for the three loading modes considered joint stiffness and strength will increase as the dimensions of key geometric features are increased or in the case of bolted joints when the bolt position is moved towards the central vertical axis. Failure location is also dependent on loading mode and the joint geometry.

Due to the complexity of the T-joint geometry, it was not possible to apply analytical solutions that have been incorporated into commercial design/analysis software packages (e.g. ESDU Data Sheets - Engineering Sciences Data Services). ESDU Data Sheets 84039 (Strength of Angles and Club-Foot Fittings) and ESDU 85021 (Analysis of Pre-tensioned Bolted Joints Subject to Tensile (Separating) Forces) were examined. Use of analytical methods will be revisited later in the programme.

7 FUTURE WORK

This work demonstrates numerical predictions of the mechanical performance of a bolted or bonded T-joint. These will be verified by experimental tests. Experimental and predicted performance of the basic T-joint configurations (bonded and bolted, aluminium and GRP) will be compared for the three different tensile loading conditions. Particular attention will be given to determining the onset and progression of failure under static, fatigue and to a lesser extent creep loading and ensuring that the FEA correctly represents the loading and boundary conditions experienced by T-joints under test conditions. A new materials (i.e. cavitation) model developed at NPL will be used with the FEA to predict deformation behaviour of T-joints bonded with rubber-toughened adhesives (i.e. XD4601 and DP460).

ACKNOWLEDGEMENTS

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REFERENCES

1. "ABAQUS User's Manual", Version 5.8, HKS Inc., USA, 1998.
2. "FEMGV User's Manual", Version 5.1, Femsys Ltd., 1998.
3. "LUSAS User's Manual", Version 13.4, FEA Ltd.
4. Read, B.E., Dean G.D. and Ferriss D.H., "An Elastic-Plastic Model for the Non-Linear Mechanical Behaviour of Rubber-Toughened Adhesives", NPL Report CMMT(A)289, 2000.
5. Broughton, W.R. Crocker, L.E. and Urquhart, J.M., "Strength of Adhesive Joints: A Parametric Study", W.R. Broughton, NPL Report MATC(A)27, 2001.
6. Dean, G. and Crocker, L., "The Use of Finite Element Methods for Design with Adhesives", NPL Measurement Good Practice Guide No 48, 2002.
7. Dean, G.D. and Broughton, W.R., "Models for Predicting Deformation and Failure in Adhesives and Polymer Matrix Composites", NPL Report MATC(A)68, 2002.
8. "Design-Expert Software Manual", Stat-Ease, Minneapolis, USA.
9. Broughton, W.R. and Crocker, L.E., "Geometric and Material Property Effects on the Performance of Adhesive T-Joints", NPL Measurement Note MATC(MN)29, 2002.

APPENDICES

APPENDIX 1: MATERIALS DATABASE**XD4601 at 23°C****Tensile Data**

Rate (mm/min)	Modulus (MPa)	Poisson's Ratio	Maximum Stress (MPa)	Maximum Strain
10	2955	0.35	57.64	0.084

Shear Data

Rate (mm/min)	Modulus (MPa)	Strength (MPa)	Failure Strain
2.0	1031	42.3	0.146

Drucker-Prager Parameters

E (MPa)	ν_e	$\beta(^{\circ})$	$\psi(^{\circ})$	a
2955	0.35	40	26	0.009

DP460 at 23°C**Tensile Data**

Rate (mm/min)	Modulus (MPa)	Poisson's Ratio	Maximum Stress (MPa)	Maximum Strain
10	2288	0.45	43.96	0.210

Shear Data

Rate (mm/min)	Modulus (MPa)	Strength (MPa)	Failure Strain
2.0	623	30.85	0.37

Drucker-Prager Parameters

E (MPa)	ν_e	$\beta(^{\circ})$	$\psi(^{\circ})$	a
2288	0.45	31	8.35	0.0168

2014 Aluminium Alloy

Property	Measured Values
E_{11} (GPa)	77 ± 2
G_{12} (GPa)	28 ± 1
ν_{12}	0.40 ± 0.01
σ_T^U (MPa)	492 ± 2
σ_T^Y (MPa)	440 ± 3
ϵ_T^U (%)	10.6 ± 0.6
ϵ_T^Y (%)	0.63 ± 0.01

Critical values for failure criteria – bonded joints

Failure Criteria	XD4601 Critical Values	DP460 Critical Values
Maximum tensile stress	57.6 MPa	
Maximum Shear Stress	42.3 MPa	
Maximum Principal stress	57.6 MPa	44 MPa
Hydrostatic Stress	44.4 MPa	
Maximum Tensile Strain	0.071	
Maximum Shear Strain	0.135	
Maximum Principal Strain	0.071	
Guest-Tresca	42.3 MPa	
Von Mises	57.6 MPa	
Hill's	1	

Note: Only Maximum principal stress criteria was used for the DP460 adhesive in the composite T-joint.

SP SYSTEMS GLASS FIBRE-REINFORCED EPOXY
($V_f = 0.56$)

Elastic Properties

Elastic Property	Material		
	Unidirectional PG51-531 SE90/L/EGL/1200/1000/32%	Woven Fabric PG21-532 SE90/M/XE603D/1250/35%	Laminate
E_{xx}^T (GPa)	48.0 ± 1.7	14.6 ± 0.4	38.8 ± 1.1
E_{yy}^T (GPa)	13.4 ± 3.6	14.6 ± 0.4	18.0 ± 0.7
E_{zz}^T (GPa)	11.6 ± 0.1	14.6 ± 0.7	$[14.6 \pm 0.7]$
E_{xx}^C (GPa)	44.4 ± 2.9	13.8 ± 0.4	38.8 ± 1.1
E_{yy}^C (GPa)	12.9 ± 1.0	13.8 ± 0.4	18.0 ± 0.7
E_{zz}^C (GPa)	13.3 ± 0.3	15.8 ± 0.4	$[14.6 \pm 0.7]$
G_{xy} (GPa)	4.81 ± 0.38	13.1 ± 0.4	6.50^*
G_{xz} (GPa)	4.75 ± 0.09	4.81 ± 0.38	$[4.81 \pm 0.38]$
G_{yz} (GPa)	2.84^*	4.81 ± 0.38	$[4.81 \pm 0.38]$
ν_{xy}^T	0.31 ± 0.04	0.58 ± 0.02	0.28 ± 0.01
ν_{yx}^T	0.08 ± 0.01	0.58 ± 0.02	0.12 ± 0.01
ν_{xz}^T	0.25 ± 0.01	0.17 ± 0.01	$[0.17 \pm 0.01]$
ν_{zx}^T	0.07 ± 0.01	0.17 ± 0.01	$[0.17 \pm 0.01]$
ν_{yz}^T	0.42 ± 0.01	0.16 ± 0.02	$[0.16 \pm 0.02]$
ν_{zy}^T	0.48 ± 0.01	0.16 ± 0.02	$[0.16 \pm 0.02]$
ν_{xy}^C	0.33 ± 0.02	0.57 ± 0.02	$[0.57 \pm 0.02]$
ν_{yx}^C	0.09 ± 0.01	0.57 ± 0.02	$[0.57 \pm 0.02]$
ν_{xz}^C	0.23 ± 0.01	0.17 ± 0.01	$[0.17 \pm 0.01]$
ν_{zx}^C	0.07 ± 0.01	0.17 ± 0.01	$[0.17 \pm 0.01]$
ν_{yz}^C	0.46 ± 0.01	0.20 ± 0.02	$[0.20 \pm 0.02]$
ν_{zy}^C	0.45 ± 0.01	0.20 ± 0.02	$[0.20 \pm 0.02]$
$E_{xx}(\text{OHT})$	-	14.2 ± 0.7	37.7 ± 0.1
$E_{yy}(\text{OHT})$	-	14.1 ± 0.4	14.9 ± 0.4
$E_{xx}(\text{filled OHT})$	-	19.6 ± 1.9	36.4 ± 0.9
$E_{yy}(\text{filled OHT})$	-	19.5 ± 0.8	16.2 ± 0.2
$E_{xx}(\text{OHC})$	-	-	40 ± 2
$E_{yy}(\text{OHC})$	-	-	21 ± 0.5
$E_{xx}(\text{filled OHC})$	-	-	40 ± 0.8
$E_{yy}(\text{filled OHC})$	-	-	21 ± 1

OHT = open hole tension; OHC = open hole compression; * = predicted value
[] Assumed symmetric in the x and y directions or along the x-z and y-z planes

SP SYSTEMS GLASS FIBRE-REINFORCED EPOXY
($V_f = 0.56$)

Strength Properties

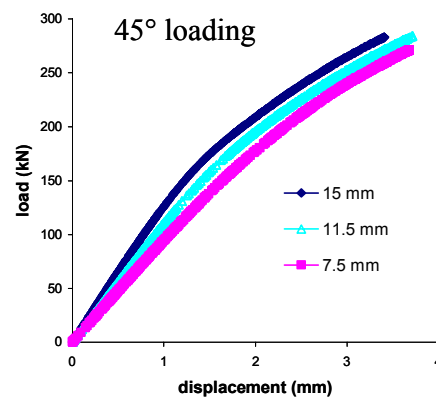
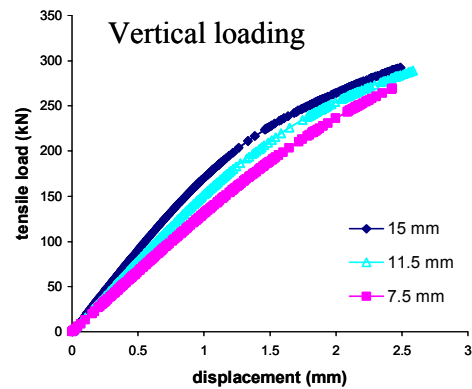
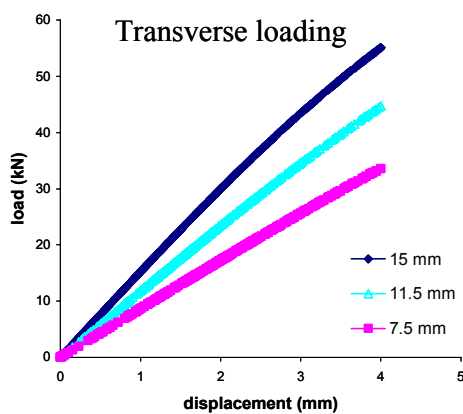
Strength Property (MPa)	Material		
	Unidirectional	Woven Fabric	Laminate
S_{xx}^T (MPa)	1133 ± 82	190 ± 3	889 ± 33
S_{yy}^T (MPa)	43.1 ± 5.0	190 ± 3	211 ± 18
S_{zz}^T (MPa)	27.2 ± 1.0	26.9 ± 1.8	$[26.9 \pm 1.8]$
S_{xx}^C (MPa)	627 ± 25	156 ± 2	551^*
S_{yy}^C (MPa)	141 ± 3	156 ± 2	227^*
S_{zz}^C (MPa)	153 ± 2	611 ± 13	$[611 \pm 13]$
S_{xy} (MPa)	56.5 ± 1.7	56.8 ± 1.5	67.4^*
S_{xz} (MPa)	104 ± 3	57.5 ± 0.5	$[57.5 \pm 0.5]$
S_{yz} (MPa)	51.9^*	57.5 ± 0.5	$[57.5 \pm 0.5]$
$S_{xx}(\text{OHT})$	Not applicable	154 ± 3	510 ± 11
$S_{yy}(\text{OHT})$	Not applicable	143 ± 6	145 ± 5
$S_{xx}(\text{filled OHT})$	Not applicable	$[154 \pm 3]$	500 ± 19
$S_{yy}(\text{filled OHT})$	Not applicable	$[143 \pm 6]$	182 ± 6
$S_{xx}(\text{OHC})$	Not applicable	119 ± 6	433 not failed
$S_{yy}(\text{OHC})$	Not applicable	149 ± 5	217 ± 2
$S_{xx}(\text{filled OHC})$	Not applicable	$[119 \pm 6]$	433 not failed
$S_{yy}(\text{filled OHC})$	Not applicable	$[149 \pm 5]$	222 ± 3
Pin Bearing _{xx}	Not applicable	416 ± 11	446 ± 4
Pin Bearing _{yy}	Not applicable	668 ± 14	422 ± 7
Torque Pin-Bearing _{xx}	Not applicable	$[416 \pm 11]$	711 ± 11
Torque Pin-Bearing _{yy}	Not applicable	$[668 \pm 14]$	665 ± 21

OHT = open hole tension; OHC = open hole compression; * = predicted value
 [] Assumed symmetric in the x and y directions or along the x-z and y-z planes

APPENDIX 2: GEOMETRIC EFFECTS ON BONDED ALUMINIUM T-JOINTS

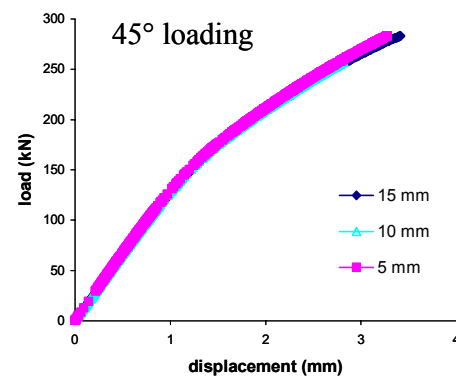
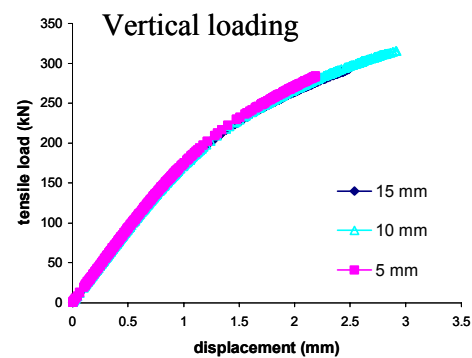
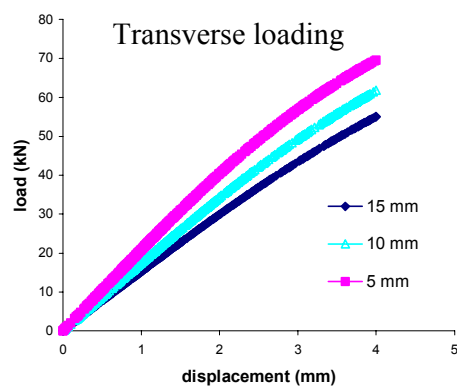
Bonded Aluminium T-Joint 3 Load cases

Effect of Flange Thickness on Stiffness



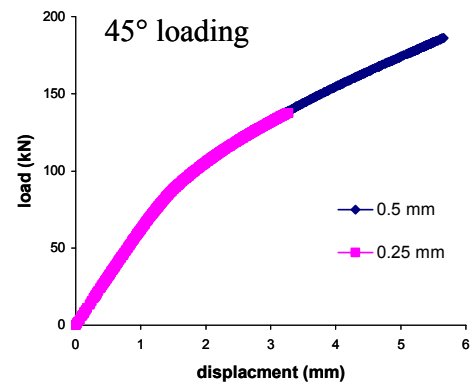
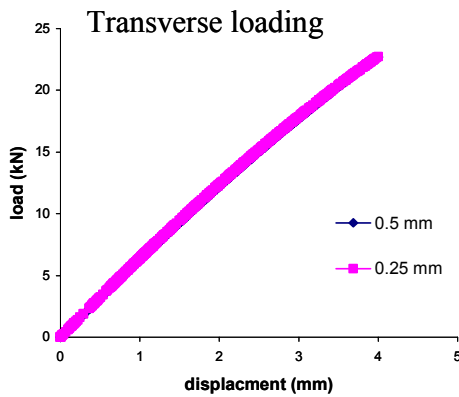
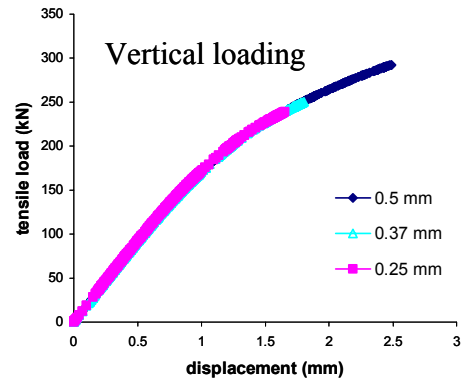
Bonded Aluminium T-Joint 3 Load cases

Effect of Web Height on Stiffness



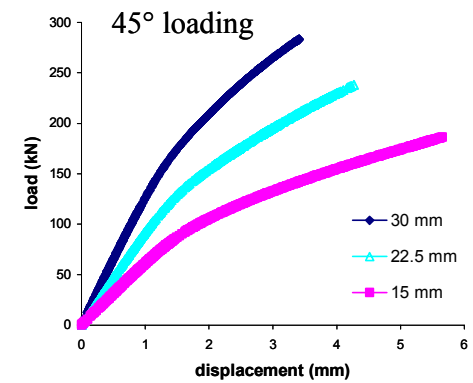
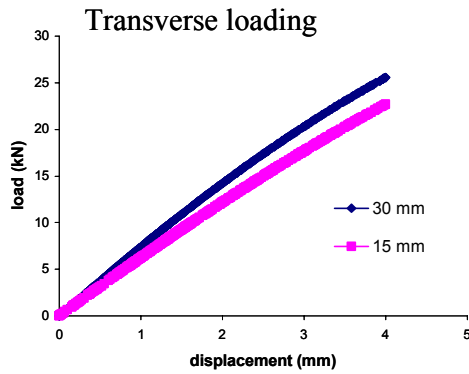
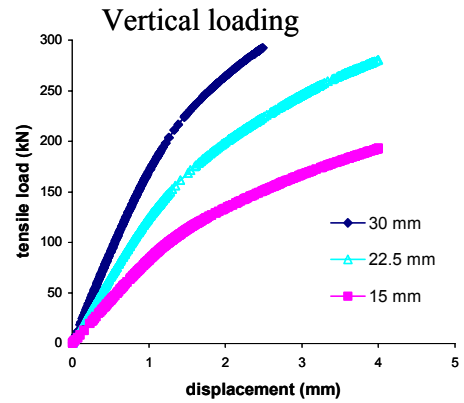
Bonded Aluminium T-Joint 3 Load Cases

Effect of Adhesive Thickness on Stiffness



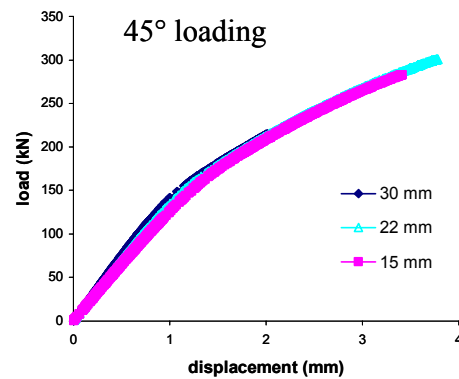
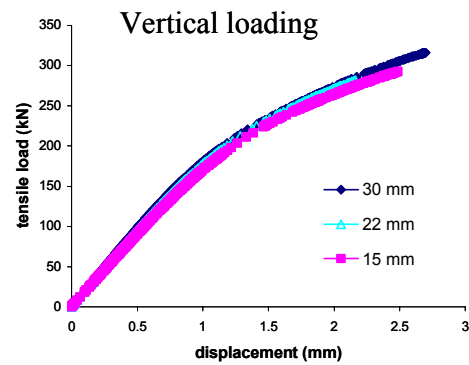
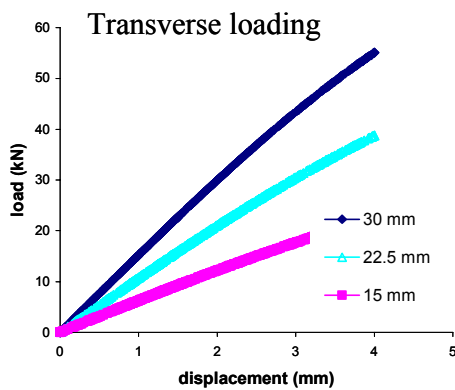
Bonded Aluminium T-Joint 3 Load Cases

Effect of Base Plate Thickness on Stiffness



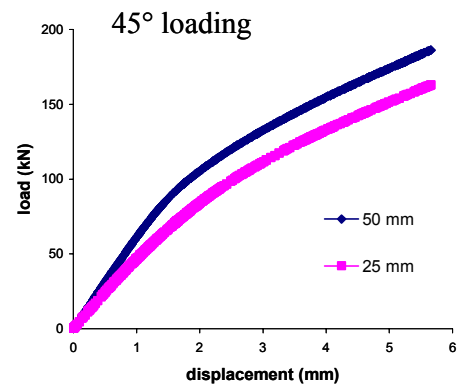
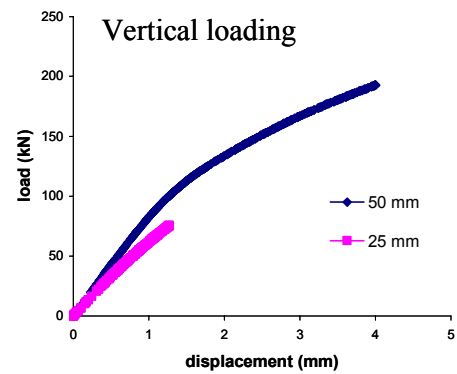
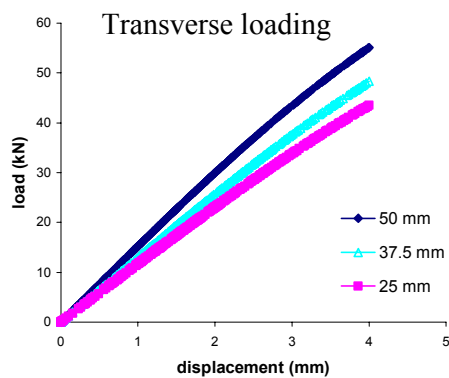
Bonded Aluminium T-Joint 3 Load cases

Effect of Web Thickness on Stiffness



Bonded Aluminium T-Joint 3 Load Cases

Effect of Flange Radius on Stiffness



Bonded Aluminium T-Joint 3 Load cases

Effect of parameters on Joint Strength

