MATC (MN) 10

Geometric and Material Property Effects on the Strength of Rubber-Toughened Adhesive Joints

Altering the geometry of a bonded joint will invariably cause changes to occur in the stress and strain distribution within the adhesive layer. These differences can have a profound affect on the stress concentrations and consequently the load-capacity and long-term performance of the joint. Currently, there are no well-established design procedures for predicting failure behaviour or relating changes in material and geometric parameters to joint strength of bonded structures. Adhesively bonded structures, particularly those employed in primary load-bearing applications often include mechanical fasteners (e.g. bolts) as an additional safety precaution. Such conservative design and engineering practices result in heavier and more costly components.

This Measurement Note considers the influence of specimen geometry and elastic properties of the adherend on the strength of single-lap and scarf joints bonded with rubber-toughened adhesives. The Measurement Note presents the results of study designed to establish the effects of changes in adhesive layer thickness, adherend properties (i.e. thickness and elastic properties), bond length and taper angle (scarf joint only) on joint strength. Finite element analysis (FEA) is used in conjunction with statistical analysis (Design of Experiments) to assess the reliability of different failure criteria and elastic-plastic materials models for determining strength of bonded joints. Predicted joint strengths are compared with experimental data. Simple mathematical relationships relating geometric parameters to joint strength have been derived for the two joint configurations.

This Measurement Note was prepared as a result of investigations undertaken within the DTI funded project "Performance of Adhesive Joints (PAJex1) - Deformation and Failure of Toughened Adhesives".

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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. Currently, there are no well-established design procedures for predicting failure behaviour or relating changes in material and geometric parameters to joint strength of bonded structures [1-5]. The lack of suitable material models and failure criteria has resulted in heavier and more costly structures.

This Measurement Note examines the reliability of commonly used failure criteria (e.g. maximum shear and maximum principal strain) for predicting the static strength of rubber-toughened adhesive joints. The Measurement Note presents the results of a parametric study using finite element analysis (FEA) to evaluate the influence of material and geometric parameters on the strength of single-lap and scarf joint configurations. The assessment includes the effects of varying adhesive layer thickness, adherend thickness, bond length and taper angle (scarf joint only) on joint strength. Simple mathematical formulations relating geometric parameters to joint strength were derived using statistical analysis (Design of Experiments). The FEA results are compared with experimental data.

FEA PARAMETRIC STUDY

A series of simulated experiments using FEA were carried out on single-lap and scarf joint configurations to determine the effects of geometric parameters on joint strength (see [5]). The single-lap joints consisted of CR1 mild steel sections bonded with AV119 (Araldite® 2007), a single-part epoxy adhesive (supplied by Vantico). Scarf joints were constructed from EN3B mild steel, which were bonded with XD4601, a single-part, toughened epoxy adhesive (supplied by Essex Betamate). Both epoxy adhesives are high-temperature curing systems.

Two elastic-plastic materials models (von Mises and Linear Drucker-Prager) were used with the FEA to predict the deformation behaviour of the two configurations. The assessment considered stress and strain based failure criteria, which are described in NPL Report MATC(A)27 [5].

SINGLE-LAP JOINT

A parametric study was carried out to assess the effects of varying: adhesive layer thickness (**t_a** = 0.25, 0.5, 1.00 and 2.00 mm); adherend thickness (**t** = 1.6, 2.4 and 3.2 mm); and bond length (**L** = 12.5, 25.0 and 50.0 mm) on the failure load of single-lap joints (see Figure 1). The ends of the joints were modelled having a fillet with a concave surface with a radius equal in magnitude to the adhesive adhesive layer thickness. In practice, the fillets at the ends of joints were not precisely shaped (Figure 2).

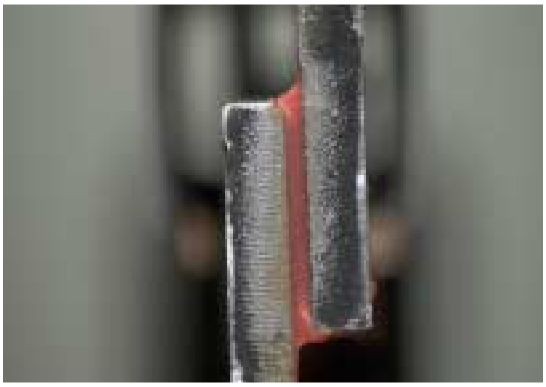

Figure 2: Failed single-lap joint.

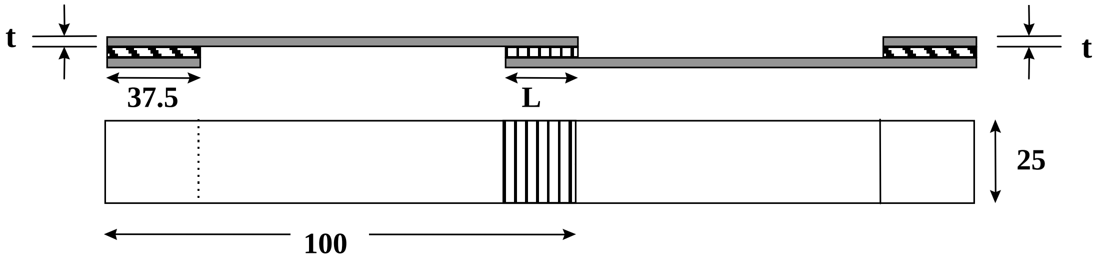

Figure 1: Schematic of single-lap joint specimen (mm).

Table 1: Failure Loads (N) for CR1 Mild Steel/AV119 Single-Lap Joints (w = 25 mm, r = t_a = 0.25 mm, t = 2.5 mm)

Failure Criteria	Bond Length (mm)		
	12.5	**25**	**50**
<u>Maximum Shear Strain</u>			
FEA - Von Mises	8,711	10,168	13,512
FEA - Linear Drucker-Prager	7,985	10,594	13,930
Experimental	**8,850 ± 250**	**10,700 ± 950**	**15,825 ± 1,575**

The Linear Drucker-Prager materials model combined with maximum shear strain failure criteria provided the closest fit to experimental data (further details given in [5]). At short overlap lengths (i.e. 12.5 mm) the von Mises materials model is marginally more accurate than the Linear Drucker-Prager model. Table 1 compares FEA simulation results with experimental data. Experimental data was generated under standard laboratory conditions (23 ºC and 50% relative humidity) using an Instron 8500 servo-hydraulic test machine. Instron Series IX software was used to control the test equipment and for data capture.

It was possible to relate the predicted joint strength to the adherend thickness and bond length using simple empirical relationships. The following formulations were derived for the combination of Linear Drucker-Prager materials model and the maximum shear strain failure criteria.

Adherend Thickness Effect (1.6 ≤ t ≤ 3.2)

$$P_{failure} = 3{,}878 + 3{,}085t$$

Bond length Effect (12.5 ≤ L ≤ 50)

$$P_{failure} = 5{,}999 + 131.5L$$

Adhesive Thickness Effect (0.25 ≤ t_a ≤ 2.00)

$$P_{failure} = 9{,}367 \pm 2{,}680$$

The failure strength of the joint for any combination of the three main factors can be calculated from the three constitutive equations and the grand average performance (GAP) value obtained from the full factorial experiment. The equation for calculating the joint strength is given below:

$$P_{failure} = 3{,}878 + 3{,}085t + 5{,}999 + 131.5L - GAP$$

where GAP was calculated to be 9,367.

Three-dimensional analyses show no through-width distribution of stress, and therefore it is reasonable to assume joint strength is directly proportional to the specimen width.

Experimental and predicted strength data were in reasonable agreement (see Table 2). The predicted values were calculated using the empirical relationship and corrected where necessary to account for changes in specimen width. The empirical relationship was derived from FEA simulations of joints where **L** ≤ 50 mm, and therefore the accuracy of the predictive analysis can be expected to decrease as the bond length is increased beyond 50 mm (see Table 2). The "apparent" shear strength decreases substantially with increasing bond length.

Table 2: Predicted Failure Loads for CR1 Mild Steel/AV119 Single-Lap Joints $P_{failure}$ = {3,878 + 3,085t} + {5,999 + 131.5L} - GAP

Specimen Width (mm)	Adherend Thickness (mm)	Bond Length (mm)	Failure Load (N)	
			Predicted	**Measured**
15	2.5	12.5	5,012	4,610 ± 146
25	1.5	12.5	6,781	8,350 ± 275
25	2.5	12.5	9,867	8,496 ± 250
25	2.5	25	11,510	10,700 ± 950
25	2.5	50	14,768	15,825 ± 1,575
50	2.5	50	29,595	31,940 ± 482
50	2.5	100	42,745	36,737 ± 450

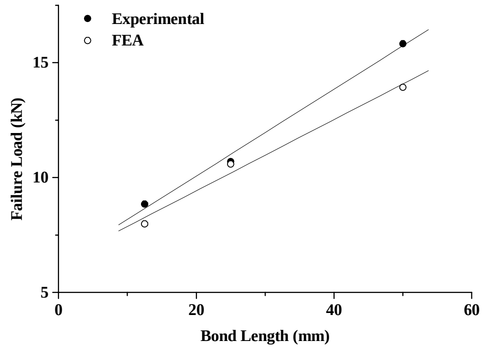

Figure 3: Comparison of measured and FEA predicted failure loads for CR1 mild steel/AV119 single-lap joints (w = 25 mm, r = t_a = 0.25 mm, t = 2.5 mm).

Figure 3 compares the predicted and measured failure loads ($12.5 \leq L \leq 50$) for lap joints with an adhesive layer thickness of 0.25 mm. The adherend thickness was 2.5 mm. The relationship between measured failure load and bond length is given below:

$$P_{failure} = 6{,}288 + 188.7L$$

Tensile tests (see Table 3) were also carried out on 25 mm wide single-lap joints fabricated from 5251 aluminium alloy, 6Al-4V titanium alloy, and unidirectional carbon fibre-reinforced epoxy and plain woven glass fabric composite materials. Bond length varied from 12.5 to 50 mm and bond thickness was 0.25 mm.

The following observations can be made in relation to the FEA and experimental results.

- Increasing either the adherend modulus or adherend thickness results in an increase in load-bearing capacity of the joint.
- Increasing the lap length increases the load-bearing capacity of the joint.
- All the results are well below the average shear strength measured for the bulk adhesive (41 MPa) and thick adherend shear test (47 MPa) measured under similar conditions.
- The average shear strength does not correspond to a unique material property of the adhesive, and therefore cannot be used as a design parameter.
- It is possible to correlate test data for different test geometries to account for differences in adherend thickness and bond length (e.g. ISO and ASTM test geometries).
- Careful consideration should be given to ensuring that the stress and strain distributions (i.e. maximum peel and shear stresses at the ends of the joint) for different systems are at least similar. As a first approximation:

$$E_1 t_1 = E_2 t_2$$

Subscripts 1 and 2 refer to materials 1 and 2.

Table 3: Failure Load Per Unit Width for AV119 Epoxy Single-Lap Joints

Adherend Thickness/Overlap Length	Load/Width (N/mm)
CR1 Mild Rolled Steel	
1.5 mm thick/12.5 mm overlap	334 ± 11
<u>2.5 mm thick</u>	
• 12.5 mm overlap	354 ± 10
• 25.0 mm overlap	428 ± 38
• 50.0 mm overlap	633 ± 63
5251 Aluminium Alloy	
1.6 mm thick/12.5 mm overlap	191 ± 14
3.0 mm thick/12.5 mm overlap	325 ± 28
6Al-4V-Titanium Alloy	
2.0 mm thick/12.5 mm overlap	457 ± 52
Unidirectional T300/924 Carbon/Epoxy	
2.0 mm thick/12.5 mm overlap	369 ± 41
Plain Woven Fabric (Tufnol 10G/40)	
<u>2.5 mm thick</u>	
• 12.5 mm overlap	275 ± 28
• 25.0 mm overlap	454 ± 27
• 50.0 mm overlap	511 ± 32
5.1 mm thick/12.5 mm overlap	327 ± 27

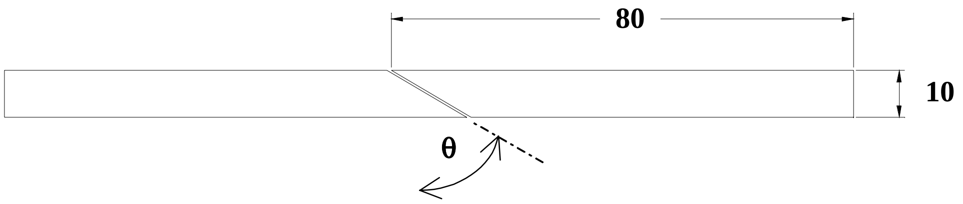

Figure 4: Side view of scarf joint.

SCARF JOINT

FEA simulations were conducted on mild steel scarf joints bonded with AV119 and XD4601 to assess the effect of taper angle ($\theta = 25^o$, 45^o and 60^o) and adhesive layer thickness (t_a = 0.25, 0.5 and 1.00 mm); on the joint strength. The mild steel adherends in the FEA simulations were 25 mm wide (see Figure 4). The FEA results were compared with strength data obtained from tensile tests carried out on 15 mm wide specimens. The test conditions for the joint specimens corresponded to the test conditions used for generating bulk adhesive data used for the FEA simulations.

The Linear Drucker-Prager materials model combined with maximum principal strain failure criteria provided the closest fit to experimental data (see [5]). Tables 4 and 5 compare FEA results with experimental data for the two adhesive systems. The FEA results have been corrected to allow for the 15 mm width of the test specimens.

It is possible to estimate the failure load of mild steel/XD4601 scarf joints using simple empirical relationship. The following formulation was derived for the Linear Drucker-Prager materials model combined with the maximum shear strain failure criteria:

$$P_{failure} = 13{,}931 + 412.6e^{(\theta - 31.78)/11.04}$$

Joint strength was observed to be independent of adhesive layer thickness. Table 6 compares measured and predicted strength values where the predicted strength values were calculated using the above relationship. The butt-tension strength (i.e. θ = 0°) is predicted to be 55.8 MPa, which is almost the same as the measured butt-tension strength (59.0 MPa) and the tensile strength of the XD4601 adhesive (57.6 MPa).

A simple strength-of-materials analysis approach, resolving stresses and areas, can also be used to determine shear stress τ and normal stress σ_T in a simple scarf joint [6].

Table 4: Predicted and Measured Failure Loads (N) for Mild Steel/AV119 Scarf Joints (w = 15 mm, $r = t_a$ = 0.25 mm, t = 10 mm)

Failure Criteria	Taper Angle (degrees)		
	25	45	60
<u>Maximum Principal Strain</u>			
FEA - Von Mises	11,095	10,162	13,890
FEA - Linear Drucker-Prager	10,399	10,810	14,788
Analytical Solution	10,113	10,663	13,479
Experimental	**8,850 ± 250**	**10,700 ± 950**	**15,825 ± 1,575**

Table 5: Predicted and Measured Failure Loads (N) for Mild Steel/XD4601 Scarf Joints (w = 15 mm, t_a = 0.25 mm and t = 10 mm)

Failure Criteria	Taper Angle (degrees)		
	25	45	60
<u>Maximum Principal Strain</u>			
FEA - Von Mises	11,020	9,919	11,195
FEA - Linear Drucker-Prager	8,416	9,162	11,668
Analytical Solution	8,880	10,228	13,491
Experimental	**7,618 ± 237**	**10,470 ± 254**	**13,240 ± 191**

Table 6: Predicted Failure Loads for Mild Steel/XD4601 Scarf Joints Linear Drucker-Prager Materials Model and Maximum Principal Strain Failure Criteria

Taper Angle (degrees)	Failure Load (N)		
	Predicted	Measured	Difference (%)
25	8,582	7,618 ± 237	12.65
45	9,178	10,470 ± 254	-12.34
60	11,555	13,240 ± 191	-12.73

The above analysis assumes that as the shear stress distribution is uniform and that there is no elastic trough in the stress distribution along the adhesive layer to alleviate continuous strains (deformations) under prolonged loading (e.g. creep or low frequency cyclic fatigue loads). The shear and normal stress components can be expressed in terms of taper angle as follows:

$$\tau = P\sin\theta\cos\theta / t$$

$$\sigma_T = P\cos^2\theta / t$$

where **P** is the applied (end) load per unit width. Stress components are assumed to be independent of bondline thickness.

The failure loads were determined for different taper angles using the above relationship in conjunction with Hill's quadratic failure criterion:

$$\left(\frac{\sigma_T}{S_{11}}\right)^2 + \left(\frac{\tau}{S_{12}}\right)^2 = 1$$

where $\mathbf{S_{11}}$ and $\mathbf{S_{12}}$ are the tensile and shear strengths of the adhesive.

The relationship between predicted failure load and taper angle (θ) can be represented by exponential growth functions:

Mild Steel/AV119 Scarf Joint

$$P_{\text{failure}} = 10{,}051 + 143.9e^{(\theta - 32.41)/8.70}$$

Mild Steel/XD 4601 Scarf Joint

$$P_{\text{failure}} = 8{,}425 + 657.6e^{(\theta - 30.36)/14.52}$$

The above relationships predict butt-tension strength values for AV119 and XD4601 of 10,054 N (67.0 MPa) and 8,505 N (56.7 MPa), respectively. These values are in good agreement with the bulk adhesive tensile strengths for the two adhesive systems (71.3 MPa and 57.6 MPa.).

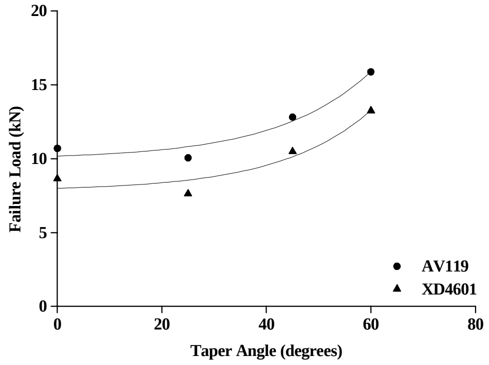

Figure 7: Measured strength for AV119 and XD4601 scarf joints.

The measured joint strength for AV119 and XD4601 scarf joints linearly increases with taper angle over the range 25° ≤ θ ≤ 60° with the two curves being almost parallel.

Mild Steel/AV119 Scarf Joint

$$P_{\text{failure}} = 5{,}775 + 165\theta$$

Mild Steel/XD 4601 Scarf Joint

$$P_{\text{failure}} = 3{,}524 + 160\theta$$

The following equations describe the relationship between failure load and taper angle for 0° ≤ θ ≤ 60°:

Mild Steel/AV119 Scarf Joint

$$P_{\text{failure}} = 9{,}962 + 209.9e^{\theta/17.9}$$

Mild Steel/XD 4601 Scarf Joint

$$P_{\text{failure}} = 7{,}823 + 172^{\theta/17.4}$$

The following observations can be made in relation to the FEA and experimental results.

- Failure is dominated by tensile stresses over the taper angle range 0° ≤ θ ≤ 60° with shear stresses becoming more influential with increasing taper angle.

- Linear Drucker-Prager material model combined with maximum principal strain failure criteria generally provided the best estimate of joint strength.
- An analytical approach can be used to calculate failure loads for different taper angles, provided the adherend thickness and stiffness are sufficient to minimise out-of-plane deformation.

DISCUSSION AND CONCLUSIONS

The results presented in this Measurement Note show that for the two joint configurations bonded with epoxy adhesives AV119 and XD4601 simple algebraic relationships can be used to estimate the effects of the geometric parameters on joint strength. The equations however are empirical, and therefore not related to any physical mechanism. The overall equations relating the main factors are only as good as the constitutive relationships incorporated. Any deficiencies in these relationships will result in poor correlation between predictive model and the measured data.

It is possible to scale the results for the two joint configurations, although the uncertainty can be expected to increase for specimen geometries outside the test matrix. An analytical approach can be adopted for predicting the strength of scarf joints, provided the adherend is sufficiently rigid to prevent out-of-plane deformation. The effects of adhesive thickness, which are not included in the analytical analysis, were observed to have minimal effect on joint strength.

Although a simple criterion applicable to the two joint configurations was not found, it is possible to correlate time-temperature tensile strength data for the adhesive with failure loads of bonded joints tested under similar conditions. Figure 8 compares the tensile strength of the adhesive and the failure loads for single-lap joints under corresponding test conditions. A similar observation was made for flexible adhesives [7-8]. The slope of the curve will be dependent on adhesive and adherend properties, and the interfacial strength of the bonded system.

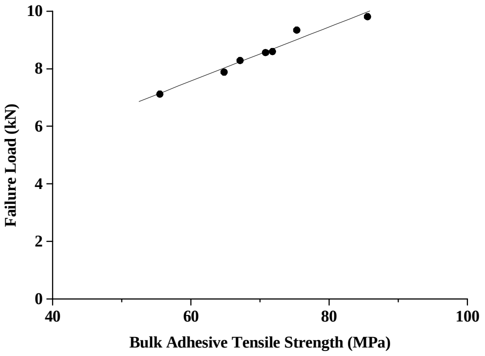

Figure 8: Relationship between single-lap joint strength and bulk adhesive tensile strength for XD4601.

In all cases, the analysis used for predicting joint strength assumes that cohesive failure occurs in the adhesive when in fact failure is a localised event occurring at the interface with the adherend. A suitable failure criteria would need to include the effect of interfacial strength in order to provide accurate predictions. Although it is not possible at present to propose a failure criterion that is universally applicable to all joint configurations, indications are that it should be possible to produce an empirical approach to design of bonded joints that can account for geometric and material parameters.

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