Effects of Specimen Geometry on the Strength of Flexible Adhesive Joints

Flexible adhesives (e.g. polyurethane and polybutadiene resin systems) are able to sustain large strains and distribute loads more uniformly than structural adhesives (e.g. epoxies), thereby reducing tensile or peel stresses that adversely affect joint strength and long-term performance. Although flexible adhesives are traditionally associated with non-structural applications (e.g. sealing, packaging and footwear), the properties these materials impart to the joint has resulted in an expansion in their use in structural applications. Safe and effective design of bonded structures using flexible adhesives, as with structural adhesives, depends on the availability of valid materials models and failure criteria for characterising deformation and failure behaviour. In the absence of suitable failure criteria, an alternative approach is to relate joint strength to the strength properties of the adhesive under corresponding test conditions.

This Measurement Note considers the influence of specimen geometry on the strength of single-lap and scarf joints bonded with an elastomeric adhesive. The Measurement Note presents the results of an experimental programme designed to establish the effects of changes in adhesive layer thickness, adherend thickness, bond length and taper angle (scarf joint only) on joint strength. Statistical analysis (Design of Experiments) was used to establish simple relationships between the main factors and the measured failure loads for the two joint configurations. Whilst a failure criterion has not been established for flexible adhesives, it is possible to correlate failure loads of bonded joints with the tensile strength of bulk adhesives.

This Measurement Note was prepared as a result of investigations undertaken within the DTI funded project "Performance of Adhesive Joints (PAJex2) - Flexible Adhesives".

W R Broughton, E Arranz, R D Mera and B C Duncan

JULY 2001

INTRODUCTION

Flexible adhesives (e.g. polyurethane and polybutadiene resin systems) sustain large strains and distribute loads more uniformly than structural adhesives, thereby reducing tensile or peel stresses that may adversely affect joint strength and long-term performance. Hence, these materials are potentially viable alternatives to structural adhesives for load-bearing applications. The lack of information, suitable material models or failure criteria for the constituent materials, however, has inhibited the use of flexible adhesives in structural applications.

This Measurement Note presents the results of an experimental programme designed to establish the effects of changes in adhesive layer thickness, adherend thickness, bond length and taper angle (scarf joint only) on joint strength in an attempt to provide an improved understanding of the factors that control failure of flexible adhesives in bonded structures. Statistical analysis (Design of Experiments) was used to establish simple relationships between the main factors and the measured failure loads for single-lap and scarf joint configurations.

SINGLE-LAP JOINT

An experimental parametric study was carried out to assess the effects of varying: adhesive layer thickness ($\mathbf{t_a}$ = 0.31, 0.52, 0.71 and 1.10 mm); adherend thickness (**t** = 1.5 and 3.0 mm); and bond length (**L** = 12.5, 25.0 and 50.0 mm) on the failure load of single-lap joints (see Figure 1). Tests were carried out using CR1 mild steel adherends (supplied by Corus) and a single-part, heat-curing adhesive, M70 elastomer (supplied by Evode).

The experimental results indicated that the adherend thickness had minimal effect on joint strength. This was expected since **E** (adherend stiffness) >> $\mathbf{E_a}$ (adhesive stiffness). Unsurprisingly, the bond length is the dominant influence on joint strength. Figures 2 and 3 compare the failure load of single-lap joints (1.5 mm thick adherends) for various bond lengths and bondline thicknesses. From Figure 3, the optimum adhesive layer thickness is approximately 0.5 mm.

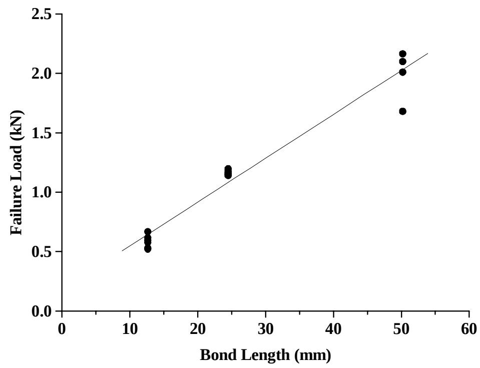

Figure 2: Effect of bond length on lap-joint strength (t = 1.5 mm).

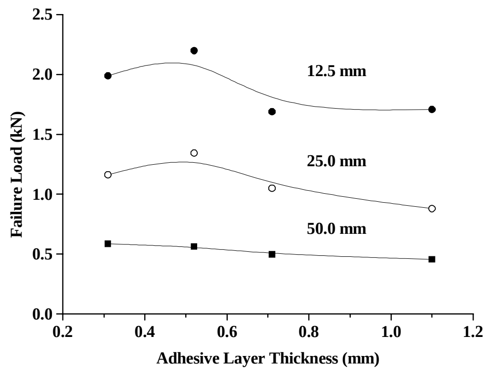

Figure 3: Effect of adhesive layer thickness on lap-joint strength for varying bond lengths (t = 1.5 mm).

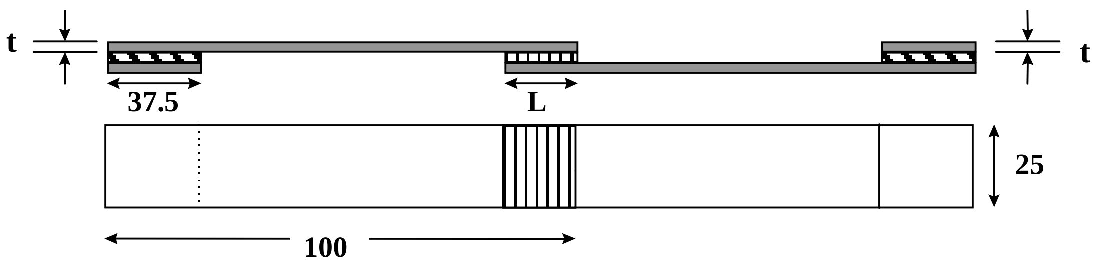

Figure 1: Schematic of single-lap joint specimen (mm).

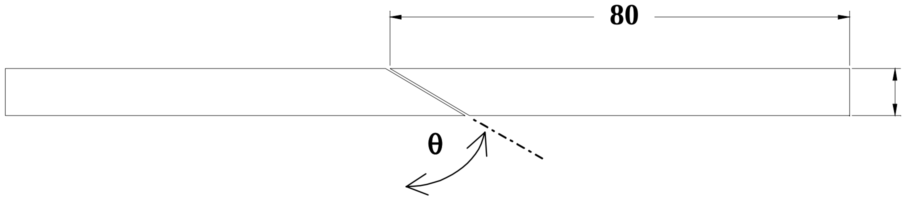

Figure 4: Side view of scarf joint.

It is possible to relate the lap-joint strength to the bond length and adhesive layer thickness using the following relationship:

$$P_{failure} = \{103.2 + 36.7L\}_{bond\ length} + \left\{1{,}014 + 402\,e^{-27.43\,(t_a - 0.45)^2}\right\}_{adhesive\ thickness} - \{1{,}177\}_{GAP}$$

The grand average performance (GAP) was calculated to be 1,177 ± 610. Predicted and measured strengths for various single-lap geometries were in good agreement (see Table 1). For any given adhesive layer thickness, the "apparent" shear strength (i.e. P/A) is almost constant (slight decrease observed at L = 50 mm).

SCARF JOINT

A similar exercise was carried out on 15 mm wide scarf joints (see Figure 4) to determine the effect of taper angle (θ) on the joint strength (Table 1). Adhesive thickness was nominally 0.5 mm thick. The empirical relationship between taper angle and joint strength (Figure 5) is given by :

$$P_{failure} = 182.8 + 66.2e^{(\theta - 34.8)/24.0}$$

Failure stress (i.e. P/A) remains almost constant with increasing taper angle.

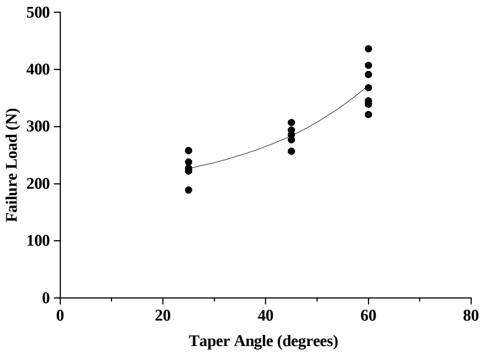

Figure 5: Effect of taper angle on scarf joint strength.

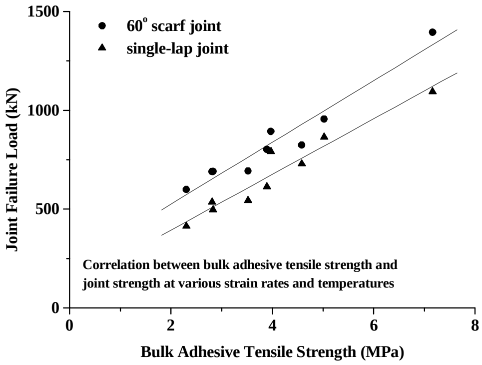

Figure 6: Relationship between joint strength and bulk adhesive tensile strength for single-lap and scarf joint configurations.

Table 1: Single-Lap and Scarf Joint Failure Loads (N)

Bond Thickness (mm)	Single-Lap Joint Bond Length (mm)			Scarf Joint Taper Angle (degrees)		
	12.5	25	50	25	45	60
Predicted						
0.31	634	1,093	2,010	227	284	372
0.52	750	1,209	2,126			
0.71	462	921	1,838			
1.10	399	858	1,775			
Measured						
0.31	585 ± 55	1,162 ± 21	1,988 ± 215	227 ± 25	284 ± 19	372 ± 41
0.52	562 ± 36	1,344 ± 49	2,199 ± 166			
0.71	498 ± 24	1,050 ± 59	1,689 ± 162			
1.10	455 ± 29	880 ± 105	1,707 ± 27			

DISCUSSION AND CONCLUDING REMARKS

Simple empirical relationships can be used to relate the effect of key geometric parameters on joint strength for the single-lap and scarf joint configurations Whilst a failure criterion has not been established for flexible adhesives, it is possible to correlate failure loads of bonded joints with the tensile strength ($\boldsymbol{\sigma}_{\mathbf{UTS}}$) of the adhesive under corresponding test conditions. The master curves shown in Figure 6 represent tests conducted on adhesive joints (single-lap and 60º scarf joints) and bulk adhesive at different strain rates and temperatures [1-3]. Joint strength for the two joint configurations can be represented by the following relationships:

$$P_{failure}\ (\text{lap joint}) = 110 + 141\,\sigma_{UTS}\ ;\quad P_{failure}\ (\text{scarf joint}) = 212 + 156\,\sigma_{UTS}$$

Finite element analysis [1-3] has shown that joint strength is related to the maximum principal stress $\boldsymbol{\sigma}_{\mathbf{3}}$ as follows:

$$P_{failure}\,(\text{lap joint}) = -25.1 + 85.9\,\sigma_3;\quad \sigma_3(\text{lap joint}) = 1.73 + 1.60\,\sigma_{UTS}$$
$$P_{failure}\,(\text{scarf joint}) = -84.1 + 312\,\sigma_3;\quad \sigma_3(\text{scarf joint}) = 0.87 + 0.69\,\sigma_{UTS}$$

Assuming failure stress remains constant, then joint strengths for different taper angles and bond lengths can be determined using these relationships.

REFERENCES

1. *Rate and Temperature Dependent Mechanical Properties of a Flexible Adhesive*, B Duncan, G Hinopoulos, J Ogilvy-Robb and E Arranz, NPL Report CMMT(A)262, 2000.
2. *Evaluation of Hyperelastic Finite Element models for Flexible Adhesive Joints*, B Duncan, L Crocker and J Urquhart, NPL Report CMMT(A)285, 2000.
3. *Failure of Flexible Adhesive Joints*, B Duncan, L Crocker, J Urquhart, E Arranz, R Mera and W Broughton MATC(A)34, 2001.

ACKNOWLEDGEMENTS

The research reported in this Measurement Note was carried out by NPL, as part of the “Performance of Adhesive Joints Programme” funded by the Engineering Industries Directorate, UK Department of Trade and Industry.

For further information contact:

Dr Bill Broughton
NPL Materials Centre
National Physical Laboratory
Queens Road
Teddington
Middlesex
TW11 0LW
Telephone: 020-8977 3222 (*switchboard*)
Direct Line: 020-8943 6834
Facsimile: 020-8943 6177