Quasi-Static Failure Criteria for Adhesive Joints Based Upon Advanced Analyses

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MTS Adhesives Project 2: Report 6 Annex 4 Quasi-Static Failure Criteria for Adhesive Joints Based Upon Advanced Analyses

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Customer: Department of Trade and Industry

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The work performed to investigate and develop failure criteria based upon advanced stress analyses as part of the Task 3 ‘Development of Failure Criteria’ of the MTS Adhesives Project 2 is described.

The failure criterion adopted is based upon observations of joint failure made in Task 1 of the project and features cohesive failure of the adhesive when a critical value of principal strain is reached and failure of the interface when a critical value of normal or shear stress is reached. These criteria are combined to operate together within finite element analyses based upon an explicit technique, thus allowing progressive failure of joints to occur. The material model for the adhesive which is used incorporates pressure sensitive yield and failure strain for the cohesive part of the failure criterion.

A series of analyses are performed on thin and thick adherend lap shear and T Peel joints. The calculated and experimental load versus displacement characteristics are found to generally agree well up to failure. Failure loads are also predicted with reasonable accuracy in most cases. Where poor agreement between experimental and calculated failure load is achieved, investigation of the sensitivity of the analysis to various parameters has revealed a high sensitivity to details of the fillet which are prone to experimental variation. The calculated failure modes agree well with those observed.
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1 Introduction

The work described in this report forms part of the work programme for the MTS Adhesives Project 2 Task 3 ‘Development of Failure Criteria’. The Task 3 work programme involved the investigation and development of criteria to predict the strength and lifetime of adhesive joints under various loading conditions. This report describes the work undertaken to develop failure criteria based upon advanced stress analyses.
2 Background

2.1 Observations from Task 1

The work undertaken in Task 1 of Project 2 produced detailed information on the way adhesive joints failure under load. Specifically the following observations were made.

Failure of adhesive joints can occur in three locations.

- Failure at the interface (an adhesive failure). This may arise through failure of an interlayer between the parent adherend material and adhesive consisting of
  - an oxide coating or;
  - a primer layer or;
  - a region of adhesive having different properties to the bulk through a different cure mechanism) or;
  - a region where the surface topography acts to create a layer where there is both adhesive and adherend present.

In addition the adhesive to surface bond may fail.

- Failure in the bulk of the adhesive layer (a cohesive failure). This will arise through excessive stress or strain within the adhesive material and may occur anywhere within the adhesive layer. Stresses and strains peak at the ends of the overlap however and generally close to an adherend so this is where we expect failure to occur.

- Failure in the adherend. This will arise through excessive stress or strain within the adherend material and is more common for brittle materials. Joints made with adherends of fibre reinforced composite material and toughened adhesive in particular usually fail by adherend failure, usually delamination of the ply closest to the adhesive.

In all joints investigated there was evidence of sustainable damage occurring prior to final failure i.e. the joint did not fail at the first signs of damage.

In all joints investigated the final locus of failure was close to an adherend.

- For the TAST joints cracks initiated at the edges of the overlap - usually the corners where the adherend is continuous but exceptions to this were observed in the thinner (widthways) joints used for in-situ SEM testing. Generally the cracks ran in from both ends of the overlap along opposite adherends and joined close to the centre of the overlap, although in some cases the cracks crossed the adhesive at the ends of the overlap. Fillets at the end of the joints did not modify this significantly - cracks generally initiated at the ends of the fillet close to the continuous adherend.

- For the T Peel joints the point of crack initiation was variable: some joints initiated cracks at the centre of the joint which then propagated to an adherend within a short distance; others initiated cracks close to an adherend which remained close to that adherend during...
propagation. Stress analysis suggested that this behaviour may be due to the shape of the fillet. A flat fillet generated a strain peak at the adherend whereas a sufficiently rounded fillet both altered the value of this peak and shifted it to the centreline of the adhesive. If it is postulated that crack initiation would start at the some critical value of adhesive strain, then the shape of fillet can be seen to influence both the point of initial cracking and the applied load at which it will appear.

From visual observation of the failed joints, it was not clear whether the joint had failed adhesively or cohesively ie whether the adhesive had been pulled away from the surface of the adherend or whether a crack had run within the adhesive layer. Surface analysis of the failed surfaces usually detected a little adhesive on the surface of the adherend but negligible adherend on the surface of the adhesive. The failed surface of the adhesive also showed the topography of the adherend. A tentative conclusion may be drawn therefore that the failure is truly adhesive ie that the crack had run through an interlayer comprising adhesive and adherend (where the adherend itself may be a combination of parent and oxide).

For joints manufactured from adherends up to 2mm thick, the load versus joint displacement curves often exhibited a definite knee at the point that the plastic hinge formed in the adherend Figure 1. Beyond this point the joint was much less stiff and irreversible deformation occurred. The rate of rise in peak adhesive strain with applied load also increased beyond this point, because rotation of the overlap caused by the plastic hinge acted to localise stress/strain at the ends of the adhesive. The ultimate failure load usually exceeded the load required to reach this point by less than 20%.

Extensive adherend yield occurred in the T Peel and TLS joints (yield measured in the range 180 to 300 MPa). This yielding manifested itself as a plastic hinge and caused large rotations of the joint area during loading (2→12 degrees for the TLS joints). Some adherend deformation ie adherend bending was also evident in the early TAST joints tested.

The yield properties of the adherend are important for accurate prediction because the formation of the plastic hinge in the adherend has such a large effect upon joint failure. Figure 2 shows an example of this for a TLS joint. These properties may vary significantly for nominally similar materials (a variation of ±50% in yield stress was measured for mild steel) and this variation will affect the failure load of the joint.

Toughened adhesives are inherently non-linear. The toughening mechanism causes irreversible damage (principally shear yielding) to occur in the material.

Adhesives are polymeric materials that exhibit pressure sensitive yield and failure. Hence at a point that the hydrostatic pressure is tensile, the adhesive will yield before it would if the hydrostatic pressure were compressive. Considering failure strain, AV119, a rubber toughened epoxide adhesive will strain to over 50% nominal strain in pure shear but will fail at modest strains of less than 10% in tension.
2.2 IMPLICATIONS FOR MODELLING AND FAILURE CRITERIA

The points made in Section 2.1 lead logically to a number of areas that any modelling activity must address to generate an accurate map of the stress/strain/displacement field in an adhesive joint.

2.2.1 Material non-linearity

When considering toughened adhesive systems which exhibit non-linear material behaviour of some form under test, an analysis must incorporate non-linear material properties. In addition if the adherends can potentially exhibit non-linear deformation and the strength of the joint is such that this behaviour is likely to occur, the analysis should also incorporate non-linear material properties for the adherends. Linear analysis will only generate accurate stress/strain information if the joint exhibits brittle ie non-ductile behaviour throughout (such as might occur with a non-toughened adhesive system in combination with ceramic adherends).

The material properties used for both adherends and adhesive should accurately reflect the those of the joint under investigation. The yield properties of materials may vary significantly from batch to batch and efforts might be necessary to measure these if an accurate calculation of stress/strain (and hence strength) is required.

2.2.2 Geometric non-linearity

Where material non-linearity is a factor in a joint, there is likely to be significant deformation of the joint also. This will to some extent be dependent upon the geometry of the joint but is likely to be particularly severe where a plastic hinge has occurred for instance as occurs in thin lap shear joints. It is therefore important that analyses incorporate geometric non-linearity ie large displacement so that load paths are correctly maintained with respect to the deformed joint.

2.2.3 Pressure sensitive yield

For toughened adhesive systems where material non-linearity will be important, it will also be important to incorporate a yield surface that varies according to hydrostatic pressure. Possible models are Mohr Coulomb and Drucker Prager.

2.2.4 Progressive failure

Failure of joints is often a progressive process. Cracking at a point of high stress/strain may result in the load carried at that point falling and consequent load redistribution. Other areas of the joint will then see increased load resulting in higher stresses and strains but this may not be sufficient to immediately fail them. Hence the applied load can be further increased before these points ultimately crack and fail. In addition a cracked region may be able to still maintain significant load due to a system of complex cracks forming that do not completely separate or fibril bridging across the crack.

To accurately predict ultimate load of a joint therefore an analysis needs to account for this progressive failure and load redistribution mechanism. Hence the analysis needs to incorporate failure criteria as follows.

- Increment load whilst checking for failure
• When failure detected account for material effects ie reduce stiffness of failed areas to redistribute stress and strain whilst maintaining applied load.
  Note that further failure may occur as a result of this process.
• Continue to increment load accounting for increased damage until final failure

2.2.5 Location of failure
From the experimental observations, failure may occur within the bulk of the adhesive layer (and are thus clearly 'cohesive') but many failures occur at or very close to the adhesive/adherend interface (and hence may loosely be termed 'adhesive').

Cohesive failure
The majority of failure criteria addressed in the review paper[1] which formed the first activity for Task 3 are aimed at failure of this type, the underlying arguments being that the adhesive fractures at some level of some component of stress or strain. Provided the stress/strain analysis is sufficiently detailed and the points made above are incorporated, a good estimate of stress or strain in the bulk of the adhesive should be attainable to use in a failure criteria.

For a toughened adhesive system a stress based criterion is unlikely to be successful because adhesive stress is a poor indicator of the state of the material. Under high elongation, stress may fall as elongation increases resulting in two possible strain states for one stress. Strain is therefore a better indicator of the state of the adhesive and is intuitively closer to the parameter driving adhesive failure - some critical separation of the adhesive molecules. This failure will be related to the maximum principal strain in the adhesive and this parameter is therefore adopted as our indicator of failure within the adhesive.

Adhesive failure
The prediction of failure at or close to the interface poses a problem for conventional stress analyses. The change of stiffness that occurs in this region means that a very fine mesh would be required to make an accurate prediction and the problem is exacerbated by the fact that element integration points where the stresses are calculated are made inside the elements. Hence no calculation of stress or strain will be made actually at the interface.

Instead it is proposed that the load transfer across the interface be considered. In a finite element model load transfer between elements is performed at the nodes which also mark the true interface ie the transition between adhesive and adherend.

In addition the complexity of the layer (local surface roughness, material properties of an adhesive interlayer cured under different conditions from the bulk of the adhesive) mitigates against modelling at this level in any detail.

However the purpose of the interface (including interlayer) is to transfer normal and shear loads between the adherend and the adhesive and its effect on joint stiffness and stresses and strains in the bulk of the joint (other than failure) is negligible. Viewed in this way it is suggested that the interface can be modelled with sufficient accuracy by considering failure alone and that the failure should occur at some prescribed value of load or stress acting either in shear or normal to the adherend/adhesive interface.
2.2.6 **Pressure sensitive cohesive failure**

The value of strain at which a toughened adhesive fails in bulk tests depends upon the mode of loading\(^{12 \& 23}\) ie whether it is in shear or tension. As with yield this may be viewed as a dependence upon the hydrostatic pressure within the adhesive. Results from shear tests\(^3\) indicate that in pure shear the strain to failure for an adhesive may vary at least an order of magnitude greater than in pure tension: for AV119 the strain to failure in pure shear can exceed 70% but a typical strain to failure in pure tension is closer to 10%\(^4\).

To accurately predict ultimate load of a joint therefore an analysis needs to account for this pressure sensitive failure strain in a similar manner to that for pressure sensitive yield.

2.2.7 **3D Effects**

It is well recognised that stress analyses based upon a two dimensional slice of a joint neglect effects that occur in a real joint. These include:

- stress/strain variations that occur due to free edge effects;
- residual stresses and strains due to differential contraction following cure;
- widthways variation in geometry.

Opinions vary as to the importance of performing a full three dimensional analysis to account for these effects, but moving to a full three dimensional analysis greatly increases model size and solution times and for this reason 3D effects were not included in the modelling undertaken in this Task.
3 Implementation within a Finite Element Model

From the discussion in Section 2.2 it was considered important that the models generated to investigate failure prediction of adhesive joints based upon experimental evidence from the MTS adhesive programme and literature incorporated the following effects:

- material non-linearity;
- geometric non-linearity;
- pressure sensitive yield;
- progressive failure;
- failure at both interface and within the adhesive layer;
- pressure sensitive strain to failure for the adhesive.

The implementation of these effects within a finite element model are now discussed.

3.1 NON-LINEARITY AND FAILURE

The requirement to be able to study progressive failure implies an iterative loop as discussed in Section 2.2.4. This type of loop could be implemented manually with the user running a stress analysis at increasing values of applied load or displacement and checking for failure (exceeding some value of strain in the adhesive or load transfer at the interface). Once failure is detected, element material stiffness is altered to account for failure and the analysis restarted at the same load to determine if further failure occurs. This procedure is repeated until catastrophic failure occurs.

However the above loop is tedious and too time consuming to be workable in practice. Consequently it is necessary to implement the scheme within the analysis (finite element) code. This therefore requires that the analysis code be capable of handling extreme material non-linearity, where the material characteristic may have a rapid change (fall) in stiffness over a small increment of strain (Figure 3).
Work during Task 1 of the Project to utilise an adhesive characteristic which incorporated such a failure had shown that the level of non-linearity introduced by failure is beyond the capability of the implicit finite element technique. An alternative solution technique was utilised to complete that work which uses explicit integration. The nature of the algorithms used for this type of solution means that it can handle extreme non-linearity in both material and geometry provided that one criterion is met: the time increment for the solution must not exceed the time taken for a stress wave to cross the smallest element of the most dense material. If this criterion is met then almost any material non-linearity can be accommodated including the type of failure required of Figure 3.

The criterion leads to very small time increments however - time increments of $10^{-7}$ to $10^{-8}$ seconds are common - and hence analyses can require $10^6$ increments or more to complete. As explicit integration does not require matrix inversion however, each increment is completed relatively quickly, usually in a few seconds on a workstation, several orders quicker than for an implicit solution. Hence overall analysis times can still be reasonable.

Commercial codes which utilise this type of solution include ABAQUS/Explicit, DYNA2D and DYNA3D. The majority of the analyses performed as part of this work used VEC-DYNA3D (a version of DYNA3D by Livermore Software Technology Corporation): a few analyses were performed using ABAQUS/Explicit.

### 3.2 PRESSURE SENSITIVE YIELD AND FAILURE STRAIN

Appendix 1 illustrates the importance of pressure sensitive yield for certain joint types. Material data from uniaxial tensile tests (where hydrostatic pressure in the material is $\frac{\sigma}{3}$ and $\sigma$ is the applied tensile stress) under-estimates the yield point in pure shear (where the hydrostatic pressure in the material is zero). For joints where a significant volume of the adhesive is in pure shear, reliance upon tensile data together with a pure von Mises yield criterion in an analysis will result in the calculation of adhesive stresses which are too low and a peak load which is below the measured experimental value.

The introduction of a pressure sensitive yield criterion corrects this behaviour providing:

- good correlation between peak experimental and calculated loads;
- calculated peak shear stresses in the joint which agree with peak shear stresses from bulk shear measurements.

The equivalent Mohr Coulomb factor to provide this match between results for a Thick Adherend Shear Test specimen is 0.3. This value was therefore used for the pressure sensitive modelling in the remainder of this work.

Pressure sensitive yield was implemented in ABAQUS/Explicit using the Drucker Prager material model. In DYNA3D it can be implemented via material models 5 (Soil and Crushable Foam), 10 (Isotropic-Elastic-Plastic-Hydrodynamic) and 16 (Pseudo Tensor Concrete/Geological Model). In practice a material model was developed specifically for the work because of the need to include pressure sensitive failure strain.
The model was based upon DYNA3D material model 24 (Piecewise Linear Isotropic Plasticity). Pressure sensitive yield was included through the use of the Mohr Coulomb relation. This modifies the shear stress for flow, \( \tau_m \), at the point according to the hydrostatic component of the stress tensor \( p \):

\[
\tau_m = \tau_m^0 - p \mu_m
\]

where

\[
p = \frac{\sigma_{\text{prim}}^1 + \sigma_{\text{prim}}^2 + \sigma_{\text{prim}}^3}{3} \quad \text{(the hydrostatic pressure at the point)};
\]

\( \sigma_{\text{prim}}^i \) are the principal stresses at the point;

\( \tau_m^0 \) is the shear flow stress in pure shear;

\( \mu_m \) is the Mohr Coulomb coefficient.

Using this criterion the yield surface effectively grows as the 'pressure' in the material increases.

Pressure sensitive failure strain was included by assuming that failure strain for the adhesive varies according to:

\[
\varepsilon_f = \varepsilon_f^u \times \frac{p_{\varepsilon_f}}{p} \quad \text{for } p_{\varepsilon_f} < p < 0
\]

where

\( \varepsilon_f \) is the adhesive failure strain at the current point;

\( \varepsilon_f^u \) is the adhesive failure strain in a uniaxial tensile test;

\( p_{\varepsilon_f} \) is the hydrostatic pressure at the failure strain in a uniaxial tensile test;

\( p \) is the hydrostatic pressure at the current point.

If \( p \geq 0 \) ie pure shear or the adhesive is in hydrostatic compression, no failure is allowed and if \( p \leq p_{\varepsilon_f} \), the failure strain is set to \( \varepsilon_f^u \).

### 3.3 INTERFACIAL FAILURE

Interfacial failure was modelled by using interface elements between the adhesive and adherend. The interface elements tie nodes together within the finite element mesh, transferring nodal forces up to some predetermined value at which the nodes are allowed to separate. Consideration of the nodal spacing and consequent area of the interface element allows the failure load to be specified in terms of a stress. Further consideration of the force component at which the nodes separate allows the introduction of separate normal and shear failure stresses.

For the DYNA3D models the interface elements were implemented via Type 9 (tie break) 'Sliding Interfaces'. 
4 Analyses and Results

4.1 GENERAL DESCRIPTION OF MODELS

A series of models were created to examine the predicted failure modes and loads to some of the thin adherend lap shear, thick adherend lap shear and T Peel joints tested experimentally within the project. Details of the joints are given in Table 1.

<table>
<thead>
<tr>
<th>Code</th>
<th>Type</th>
<th>Adhesive Thickness (mm)</th>
<th>Adherend Thickness (mm)</th>
<th>Overlap Length (mm)</th>
<th>Fillet (Degrees/%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLS/12.5/0.5/nf</td>
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<td>0.51</td>
<td>1.47</td>
<td>12.5</td>
<td>-</td>
</tr>
<tr>
<td>TLS/25/0.5/45f</td>
<td>TLS</td>
<td>0.55</td>
<td>1.5</td>
<td>25</td>
<td>45°</td>
</tr>
<tr>
<td>TLS/12.5/1/45f</td>
<td>TLS</td>
<td>1.1</td>
<td>1.47</td>
<td>12.5</td>
<td>–</td>
</tr>
<tr>
<td>TAST/6.25/0.5/nf</td>
<td>TAST</td>
<td>0.5</td>
<td>6.25</td>
<td>6.25</td>
<td>–</td>
</tr>
<tr>
<td>TAST/12.5/0.5/nf</td>
<td>TAST</td>
<td>0.5</td>
<td>6.25</td>
<td>12.5</td>
<td>–</td>
</tr>
<tr>
<td>TP/0.5/0%f</td>
<td>T Peel</td>
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<td>2</td>
<td>30</td>
<td>0%</td>
</tr>
<tr>
<td>TP/0.5/25%f</td>
<td>T Peel</td>
<td>0.5</td>
<td>2</td>
<td>30</td>
<td>25%</td>
</tr>
<tr>
<td>TP/0.5/100%f</td>
<td>T Peel</td>
<td>0.5</td>
<td>2</td>
<td>30</td>
<td>100%</td>
</tr>
</tbody>
</table>

Notes
1. T Peel joints had a 6mm internal radius at the 90° bend

Table 1: Joints investigated

All models were analysed using DYNA3D using the techniques described in Section 3. The models used solid brick elements throughout and were one brick thick i.e. joint widthways with the widthways degree of freedom restrained on all nodes to simulate plane strain conditions.

Models were loaded by invoking a constant velocity at the nodes of the loaded adherend thus simulating a constant velocity test under displacement control. The calculation was run for specified event times so as to generate failure within the joint by the application of a prescribed displacement. Model data was stored at times through the analysis and thus providing a record of displacements, stresses and strains against applied displacement.

The results of the analysis were examined using TAURUS the dedicated DYNA3D post processor. This was used to generate plots of displacement, stress and strain and to calculate the applied force at any applied displacement by integrating over a section of adherend close to the displaced end.

A simple bilinear model (DYNA3D material 12) was used for the adherend material (Figure 4). Data used reflected measured values on specific samples:

- for TAST analyses the yield point was set at 500MPa and post yield modulus at zero (perfectly plastic);
- for TLS joints the yield point was set at 190MPa and post yield modulus at;
For T Peel joints the yield point was set at 321MPa and post yield modulus at.

A linear piece-wise model was developed for the adhesive material. This was based upon DYNA3D material 24 and modified to include pressure sensitive yield and failure. This type of model assumes non-associative flow which does not completely fit the observed behaviour of polymeric adhesives. A further development would therefore be to include associative flow which may improve the match between experimental and calculated failure loads. The data used in the adhesive material model is shown in Figure 3, although the failure strain was varied in early analyses to determine its effect on progressive joint failure. For the later work and in particular the results presented in Figure 5 the curve as presented in Figure 3 was used together with an interfacial shear and normal strength of 70MPa. This latter value was used because it represented the asymptotic value of the adhesive curve and also was the strength of good butt tension tests achieved in MTS Adhesives Project 3.

TAST and TLS joints were modelled in full and completely constrained at the left-hand side. T Peel joints were half symmetric along the adhesive centreline with the bottom of the adhesive on the centreline completely constrained. For all joints a prescribed displacement parallel to the adherend was applied at the right-hand side, with no constraint applied to movement perpendicular to the adherend.

The work proceeded in a developmental fashion with aspects of the models being incorporated one at a time. Early work focused on matching calculated and experimental load versus displacement, Figure 5, displacement being measured at the loaded end for T Peel joints, across a 50mm gauge length situated centrally across the overlap for the TLS joints or as measured by a thick adherend shear transducer at the overlap mid-length for TAST. This required development of quasi-static parameters within DYNA3D. Pressure sensitive yield was then added followed by pressure sensitive cohesive failure. Finally interfacial failure was added to the models.

The load versus displacement plots were found to be a good way of gaining confidence in the analyses. Comparisons were also made to analyses performed using ABAQUS/Standard. Although these analyses using identical material properties, meshes and boundary conditions, significant differences were noted in the load versus displacement plots Figure 5 which was not explained, although it is suspected that the difference relates to the large displacements occurring.

Figure 6 summarises the results obtained from the analyses and they are described in more detail below. In all cases identical failure parameters ie 10% principal strain for cohesive failure and 70MPa interfacial strength are used throughout unless stated otherwise.

4.2 THICK ADHEREND SHEAR MODELS

Figure 7 shows the mesh for the TAST/6.25/0.5/nf joint. The density for the TAST/12.5/0.5/nf joint was similar. Figure 8 shows the deformed shape of the 6.25mm overlap TAST joint. Little deformation occurs in the adherends because of their high yield point and deep section. All but the last 0.5mm of the adhesive has been deformed in shear, the ends having undergone a more complex deformation due to local tensile stresses (see Appendix A.1 of Report3 Annex 1).
The measured load versus displacement curve of the TAST/6.25/0.5/nf joint is shown in Figure 9 (curve 'Experiment'). Peak load of 2630N is reached well before failure and the joint exhibits a 'soft' characteristic with shear strains above 10% with the load gradually rising and then falling as strain increases to the final failure strain of approximately 45%. Observations made in Task 1 revealed cracking at the edges of the joint during the latter part of the curve.

Figure 10 shows the calculated stress and strain distributions of the TAST/6.25/0.5/nf joint in the adhesive at peak load. Overall these analyses agree with the results from Task 1: the majority of the adhesive is loaded primarily in shear; at the corners of the adhesive however, tensile and compressive stresses are generated. The addition of pressure sensitive yield has however altered the strain distribution, in particular creating a diagonal region of high strain and it is along this region that most joint deformation occurs at higher strains.

Figure 11 shows von Mises stress and effective total strain in the most highly loaded elements at one end of the bondline (see Figure 7 for location) against pseudo time (which represents applied displacement) for an analysis without the failure criterion. The von Mises stress is highest in the elements closest to the discontinuous adherend (elements 210 curve 'A' and 220 'C'). However these elements are primarily in a state of compression and the hydrostatic yield criterion therefore suppresses yield (and would also suppress failure) in these elements. Conversely the elements closest to the continuous adherend (elements 300 curve 'D' and 299 'F') are in a state of tension. Consequently they yield at a lower stress, but their strain is high. It is in this area that failure occurs in practice. For the end element (300) 10% strain is exceeded and hence cohesive failure expected at pseudo time 63E-6.

Figure 12 mirrors Figure 11 but with the failure criterion included. An interfacial failure now initiates at pseudo time 58E-6 at the edge of the bondline against the continuous adherend. This acts to unload the end element (300 curve 'D': the plot shows it unloading from 40E-6 but this is because data was only collected in increments of 20E-6), pushing more load and hence stress and strain into the adjacent element (299 curve 'F'). The strain in this element then increases rapidly with increasing applied displacement until it fails at pseudo time 123E-6. Its strain then becomes very large and its stress falls to zero. The failure of this element initiates the failure of other elements and the load carried by the joint falls (note however that the joint does not fail completely and continues to carry significant loads as displacement increases). Hence the debonding at the edge of the joint has allowed the joint to deform to a greater displacement and carry higher loads.

Predicted load versus displacement from the analyses for the TAST/6.25/0.5/nf joint agree well over the initial part of the curve up to approximately 30% shear strain (curve 'Cohesive: 50%' Figure 9). The final part of the curve however is controlled by the assumed failure mechanism in the joint.

The curve designated 'Cohesive:10%' assumes that the adhesive fails when a principal strain of 10% is reached i.e there is no interfacial failure. This is approximately the measured tensile failure strain for AV119 (~10%). As can be seen using this criterion, the joint is predicted to fail when the shear strain at the centre of the overlap is 10%, providing a poor fit to the experimental data. However because the load/displacement curve is flat in this region, the calculated failure load is close to the measured value (2420N).
To replicate the measured shear strain at failure of the joint would require the adhesive to fail at a strain of over 50% (curve 'Cohesive: 50%' Figure 9), far in excess of the measured values for bulk samples.

Including interfacial failure within the joint alters this position (curve 'cohesive 10%: IF 70MPa' Figure 9). As the strain increases, the tensile stress in the adhesive at the corners of the bondline pulls the adhesive from the surface of the adherend ie an interfacial failure occurs (Figure 13). This acts to reduce the peak principal strain in the joint (the overlap length at this critical point has been effectively reduced and the strain with it) and hence the adhesive does not fail until a substantially greater shear strain has been applied to the joint. Thus the strain relieving function of limited interfacial failure appears crucial to a more accurate prediction of peak loading in this type of adhesive joint. Calculated peak load of 2730N agrees well with the measured value (2630N) but shear strain at failure in the centre of the overlap is low (16%) compared to experiment.

Figure 14 shows the calculated and experimental load versus displacement plots for the TAST/12.5/0.5/nf joint. As with the 6.25mm overlap TAST the two curves agree well up to the point where failure occurs in the calculation, which is at a lower strain than was measured in the experiment. Agreement on peak load however is good (5150N calculated versus 5480N measured) because of the flat nature of the curves in this region. Calculated failure in this joint occurs in the same way as in the 6.25mm overlap: interfacial failure occurs at the edges of the overlap first followed by cohesive failure at higher applied displacement.

4.3 THIN LAP SHEAR MODELS

Figure 15 shows the mesh for the TLS/25/0.5/45f joint. The density for the other TLS joints was similar. Figure 16 shows the deformed shape of the TLS/25/0.5/45f joint. The lower yield point of the adherend material and the adherends’ thinner section and mean that a plastic hinge has formed at the ends of the overlap. Large joint rotations have therefore occurred causing an offset to occur at the ends of the joint. In practice the test machine restricts this overlap introducing additional bending moments into the joint. The effects of these bending moments were investigated in a number of trial analyses and their effect on adhesive stresses and strains found to be negligible.

Figure 17 shows the calculated and experimental load versus displacement plots for the TLS/25/0.5/45f joint. The curves agree well up to the failure point of the joint: the calculated strength exceeding the measured value by 800N. In the calculation the final failure is cohesive ie peak principal strain exceeds the allowable of 10%, occurring at the end of the fillet (Figure 18).

Figure 19 shows the calculated and experimental load versus displacement plots for the TLS/12.5/2/45f joint. Two experimental curves ('Expt 1: GL' and 'Expt 2: GL') are shown, indicating the spread in results sometimes seen in the experimental curves. The calculated curve falls some way between the two experimental results and has two distinct knees. The first is caused by the onset of plasticity in the adherend and the second by onset of almost perfect plastic behaviour in the adhesive at the end of the fillet (Figure 20). In the calculation the final failure is cohesive ie peak principal strain exceeds the allowable of 10%, occurring at the end of the fillet, as occurs in joint TLS/25/0.5/45f.
Figure 21 shows the calculated and experimental load versus displacement plots for the TLS/12.5/0.5/nf joint. Again the experimental and calculated curves agree well. The calculated curve shows the effect of adherend yield more distinctly than the experimental curve (the knee which occurs at approximately 1300N applied load) and peak load is reached at a slightly lower value. In the calculation the interfacial region at the end of the overlap fails first at an applied load of approximately 1600N (Figure 22) but the joint continues to accept higher loads until the adhesive fails cohesively at 2110N (Figure 22).

4.4 T PEEL MODELS

Figure 23 shows the mesh for the TP/0.5/25%f joint. The density for the other joints was similar. Figure 24 shows the deformed shape of the TP/0.5/25%f joint. The adherend has extensively yielded both in the vicinity of the top of the adhesive and at the end of the bend.

Figure 25 shows the calculated and experimental load versus displacement plots for the TP/0.5/25%f joint. Two calculated plots are shown, one has no failure criteria and the other the normal failure criteria adopted throughout this report (cohesive failure at 10% principal strain: interfacial failure at 70MPa). Other analysis parameters between the two calculated plots are nominally identical. The fit between the experimental and no failure plots is excellent but including failure has degraded the fit. The reason for this degradation remains unresolved.

Figure 26 shows the failure that occurs in the TP/0.5/25%f joint. Initial failure occurs in the interface at the top of the adhesive but this is immediately followed by failure in the adhesive i.e. cohesive failure, in the top element closest to the adherend. The failure immediately propagates down approximately one tenth of the overlap, the load transfer occurring upon failure of the first element causing these lower elements to become over-strained and fail. The failure propagation then halts until an increase of 5 microns displacement has been applied at which point it restarts.

This behaviour can be clearly seen in Figure 25. Peak load of 743N is reached at 68microns displacement, after which it falls to 250N at 74microns. The load then increases again to 486N at 84microns displacement at which point further failure propagation occurs. This 'stick/slip' type behaviour was noted in the Task 1 experimental work and is well replicated by the analysis.

The low calculated failure load may in part be explained by the poor representation of the fillet. The model incorporates a flat top fillet which forms a sharp angle with the adherend. In practice a rounded fillet forms as surface tension effects draw the adhesive up the adherend. The shape of the fillet was shown in Task 1 to have a major effect on local stresses and it might therefore be expected to strongly influence failure also. This does not explain the overall discrepancy between the calculated plots with and without failure however.

Figure 27 compares the calculated load versus displacement plots for the TP/0.5/25%f and TP/0.5/0%f joints (no experimental load displacement plot was available for the TP/0.5/0%f joint). The failure mode is identical between the two joint with the TP/0.5/0%f joint clearly showing the same 'stick/slip' behaviour. The smaller fillet joint has a lower stiffness because there is more unrestrained adherend to bend and the failure load is lower. Experimental failure loads varied between 345 and 632N with which the calculated value agrees well at 530N.
Figure 28 shows a number of calculated load versus displacement plots for the TP/0.5/100%f. Again no experimental load displacement plot was available, although measured peak load averaged at 1700N. The plot designated ‘Cohesive 10%; IF=70MPa’ shows the results using the nominal data ie analysis parameters and material data as for the other analyses discussed above and a perfect adhesive fillet. Clearly the calculated peak load (3720N) agrees poorly with the experimental value.

A limited parametric study was then undertaken to determine to which parameters the calculated peak load was most sensitive. Figure 28 shows the effect of altering these parameters. Factors which influence joint strength greatly are adherend yield, interfacial normal strength and fillet shape. Factors which influence joint strength little are adherend post yield modulus, mesh density, penalty stiffness (a parameter relating to the stiffness of the interface used to model interfacial failure) and interfacial shear strength.

Following this study the as made joints were re-examined, particularly with respect to the exact shape of the fillet. This was found to not be perfect as in the original model, having reduced depth at the centre of the bond line ie the free surface dipped in this region. As shown, the calculated failure load is very dependent upon exact fillet shape and assuming a slightly reduced fillet (which matched the experimental samples better) reduced the failure load to 2700N. The inclusion of a lower adherend yield (possible given the variation in adherend properties measured) and slightly reduced normal interfacial strength (again possible) would bring the calculated and measured failure loads much closer together. However this has not been done in the summary results of Figure 6 although the value used does relate to the slightly reduced fillet size.

Figure 29 shows how failure that occurs in the TP/0.5/100%f joint. The failure occurs in the adhesive ie cohesive failure, in the elements closest to the adherend at approximately the midpoint of the adherend bend. This agrees with the analyses performed in Task 1 of the project [5] which showed this area to be the most highly strained. As displacement is increased the same ‘stick/slip’ behaviour is seen as in the other T Peel joints with the failure propagating around the adherend in the adhesive closest to the adherend.
5 Conclusions

An accurate calculation of stresses and strains in the joints investigated is dependent upon an accurate representation of both adherend and adhesive properties. TLS and T Peel joints are more sensitive to adherend yield properties than TAST joints.

A combined failure criterion is proposed for adhesive joints. The criterion combines cohesive failure within the bulk of the adhesive based upon maximum principal strain to failure and failure of an interfacial region close to the adherend based upon shear and normal strength.

Using the same failure parameters (10% cohesive strain and 70MPa interfacial strength) reasonable calculation of failure strength has been made for a range of joints of widely differing types ie thick and thin adherend lap shear and T Peel.

TAST joints exhibit flat load/displacement characteristics at high load ie displacement (or shear strain) increases with little or no increase in load. The failure criterion presented here gives good predictions of peak load but under estimates displacement at failure.

The failure criterion presented here gives a reasonable calculation of failure load in TLS joints. The calculation tends to over estimate the strength of joints with fillets and under estimated the strength of joints without fillets.

T Peel joints exhibit a small total displacement to failure. The failure criterion presented here gives good calculation of failure load for a 0% fillet, a reasonable calculation for a 25% fillet and a poor calculation for a 100% fillet. The strength of the T Peel joint has been shown to be very sensitive to fillet shape and this may account for the worsening calculation of failure strength as fillet size increases.

The criterion replicates a number of the observed failure modes for joints. In particular the progressive failure of joints is replicated and this leads to an increase in the calculated strength of joints without fillets as compared to a simpler cohesive criterion.

The exact shape of some fillets is crucial to the joint strength. Representing them accurately is necessary to achieve a good prediction of joint strength.
The combined failure criterion proposed needs to be validated against more joint types (geometries and materials).

A test for interfacial strength needs to be developed to enable measurements of normal and shear strength to be made for the interface.

Many durability issues focus on the degradation of the interface. The combined failure criterion proposed here could be used as part of a predictive tool for calculating the strength of degraded joints by measuring the fall in interfacial strength (via the interfacial strength test proposed above) with exposure.
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