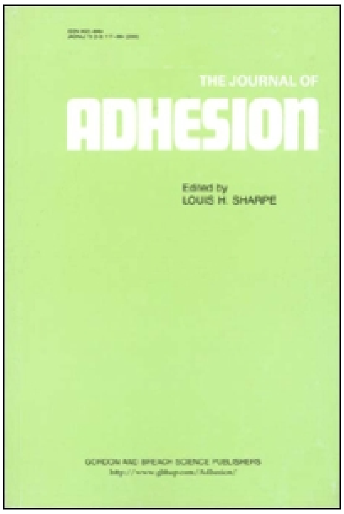

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Strength of Joints Involving Composites*

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A description is given of the stress and strain systems in adhesively-bonded joints; special attention is given to the new problems which arise when bonding advanced fibrous composites. The anisotropic properties of composites can give great strength in the fibre direction, but it must be remembered that the tensile strength transverse to the fibres is *less* than of the matrix. Finite element analysis is used to predict the stresses and strains. In the ultimate, 3-dimensional non-linear mechanics with anisotropic non-linear stress-strain properties must be used. Finally, when using the mechanics principles described here, improvements in actual joint strength of 3 to 5 times were obtained.

KEY WORDS: Stress and strain systems; adhesively-bonded joints; bonding of advanced fibrous composites; CFRP; anisotropic properties; transverse tensile strength; finite element analysis; failure criteria; three-dimensional analysis.

INTRODUCTION

In any engineering structure, the strength of adhesively-bonded joints depends on the strength of the weakest component. This critical lowest strength may occur in many different parts of the joint and depends on the strength of the adherend, the adhesive, or any intermediate zone between them. In a properly made joint between metal adherends, failure usually occurs in the adhesive (called cohesive failure). Only rarely does failure occur in the intermediate layers which are at or very near to the interface (called adhesive failure).

When using advanced fibre reinforced composites, such as carbon fibre reinforced plastics (CFRP), which are often used in modern technology, one of the problems is how to integrate these with the rest of the structure. Because composites often have a low shear strength, riveted and bolted joints can be structurally inefficient. A preferred method of joining is, therefore, adhesive bonding with epoxy resin or similar adhesives. In the work reported here, the finite element method is used to determine the position and magnitude of stress concentrations in joints under tensile load in order to establish the likely failure loci and to estimate the joint strength.

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The low transverse tensile strength of fibre reinforced plastics is also well known. Because of this, attention must be paid to the design of bonded joints using FRP adherends so that premature failure in the adherend caused by transverse tensile stress is avoided. Most of the prediction techniques for joint strength assume failure of the adhesive, and do not address the problem of interlaminar composite adherend failure.

In a lap joint, differential shear in the adherends leads to a shear stress concentration in the adhesive at the edges of the overlap as shown in Figure 1. This situation was first analysed by Volkersen[1]. In addition, internal bending moments are set up in the joint so that a distribution of transverse normal stresses exists as shown by Goland and Reissner[2] and illustrated in Figure 2. The transverse stress shows a maximum value in tension in the adhesive layer at the edges where the outer adherends terminate. The transverse (peel) stresses in this region are very important in assessing joint strength since both the adhesive and the CFRP are weak under this mode of loading.

It is well known that when materials are stretched in tension, they contract laterally (Poisson's ratio). In an adhesively-bonded joint, this leads to lateral strains and stresses which are a maximum at the joint ends[3]. These transverse tensile (across the width) stresses can lead to longitudinal cracking in a unidirectional composite, and to more complex effects in layered composites, as shown in Figure 3.

There are several analytical solutions for the state of stress in adhesive joints and these are summarised in reference[4]. Although these give a qualitative assessment of

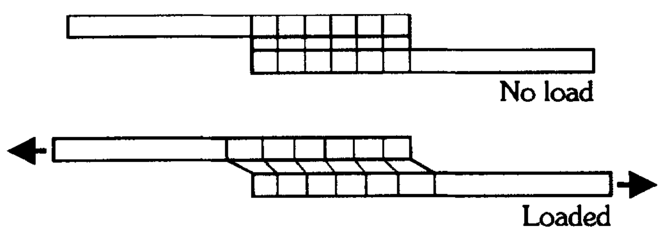

FIGURE 1 Differential shear of the adherends.

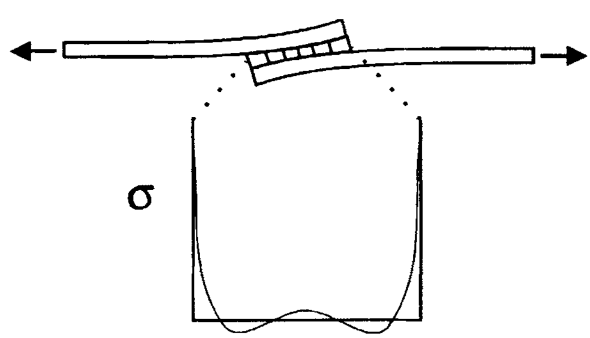

FIGURE 2 Influence of bending moments.

the effects of various parameters, analytical solutions do not enable joint strengths to be quantified. A principal reason is that a complete analysis of the various components of stress is required, including variations through the thickness of both the adherends and the adhesive. Also, the non-linear properties of the adhesive must be included if realistic materials are to be modelled. Finally, joint strength is significantly influenced by the local geometry in the critical regions of the joint, so it is necessary to account for the existence of a fillet of adhesive at the edges of the overlap, the sharpness of the adherend corner, and so on. *Closed-form algebraic (analytical) solutions cannot allow for these factors on the scale necessary for accurate joint strength prediction.*

Thus, it is necessary to use a numerical solution such as the finite element method (FEM) for predicting joint strength.

FINITE ELEMENT METHOD

The finite element method is now a well-established means for mathematically modelling stress (and many other) complex field problems. Its advantage lies in the fact that the stresses in a body of almost any geometrical shape under load can be determined. The method is, therefore, capable of being used for analysing an adhesive joint with the fillet as shown in Figure 4. The adhesive fillet at the edge of the

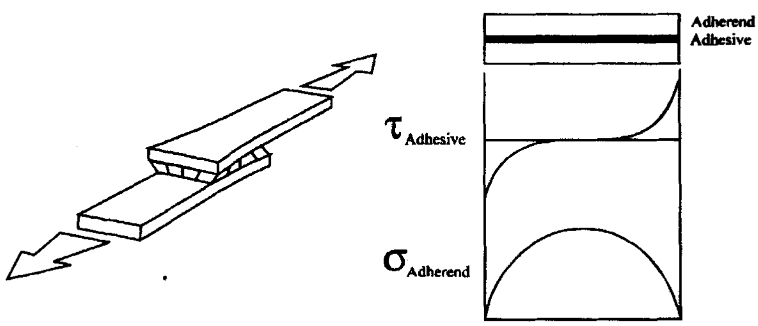

FIGURE 3 Lateral straining of the single lap joint.

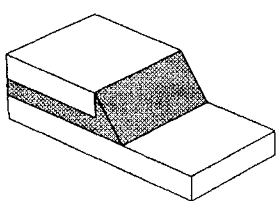

FIGURE 4 Adhesive fillet.

adhesive layer has been shown, using finite element techniques, to reduce the maximum stresses in the adhesive[5]. This has been utilised in various attempts to improve joint strength, but it has particular advantages with composites. The presence of the fillet causes a significant change in the stress pattern, which is a most important consideration in the highly-stressed region at the ends of the joint. The stress in the fillet are predominantly tensile, with a maximum stress concentration at this end being at the included corner.

Figure 5a shows the stress pattern at the end of a square-edged adhesive layer in a typical aluminium/aluminium lap joint bonded with a structural epoxy adhesive. The highest tensile stress exists at the corner of the adhesive adjacent to the loaded adherend and represents a stress concentration of at least 10 times the average applied shear stress.

The influence of a fillet on the stress pattern is shown in Figure 5b, which is at the tension end of a double lap joint. Even though only a very small triangular fillet, 0.5 mm high, was used, the stress system is very different from that of Figure 5a. Also, it can be seen that the adhesive at the ends of the adhesive layer and in the spew fillet is essentially subjected to a tensile load at about 45° to the axis of loading. The highest stresses occur near the corner of the unloaded adherend because the 90° corner introduces a stress-concentrating effect. As the maximum stress occurs within the fillet and not at or near the adhesive surface, it is unlikely that the approximation to the spew shape by the triangular fillet has a significant effect on the stress distribution.

Observation of the failure of aluminium to aluminium lap joints bonded with typical structural adhesives shows the cracks are formed approximately at right-angles to the directions of the maximum principal stresses predicted by the elastic finite-element analysis. In general, these cracks run close to the corners of the

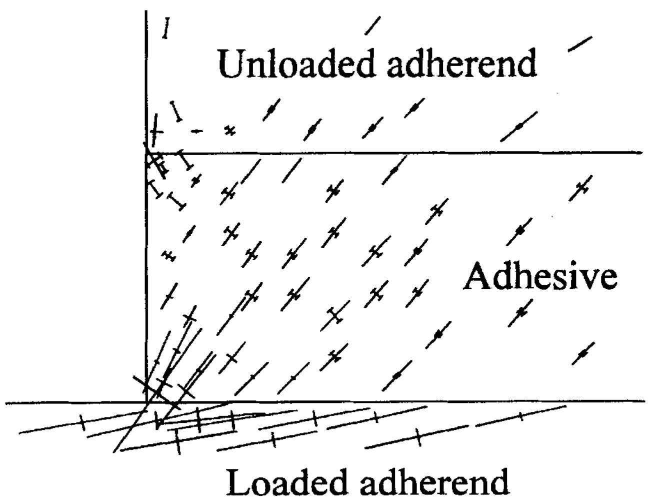

FIGURE 5a Finite element prediction of the principal stress patterns at the end of a square-edged adhesive layer.

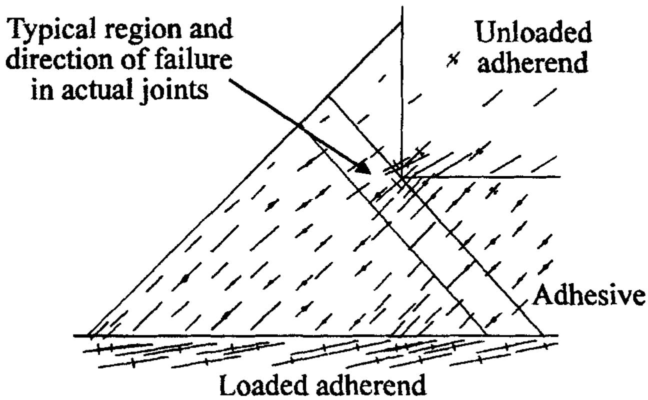

FIGURE 5b Finite element prediction of the principal stress pattern at the end of an adhesive layer with 0.5 mm fillet.

adherends as shown in Figure 5b. Thus, it can be proposed that failure in a lap joint is initiated by the high tensile stresses in the adhesive at the ends of the joint. Cohesive failure of the adhesive occurs in this manner in normal, well-bonded joints. Under further loading, the initial crack in the fillet is turned to run along (or close to) the adhesive-adherend surface.

Modern structural adhesives can develop a large plastic strain to failure. It is, therefore, necessary to consider what happens to the stress distribution when the adhesive can yield. Further, these new adhesives can be so strong that the adherends too may be caused to yield (if these are metallic). Even with the old, brittle adhesives, the adherends in single lap joints often yielded plastically in bending before the joint failed. Two opposite effects occur when the adherends yield[6]. Increased differential straining of the adherends causes the adhesive stresses to be increased, thus leading to premature failure. However, if the adherends are stressed to yield, they will more easily rotate under the effect of the non-collinear applied loads. This causes the Goland and Reissner joint factor "k" to decrease more than if the adherends remained elastic, thus reducing the stresses. It is, therefore, necessary to investigate both adhesive plasticity and adherend plasticity, using either continuum mechanics or numerical (finite element) techniques.

Stress concentrations are very important in all structures, especially those joined by adhesive bonding. A sharp corner or crack causes, in theory, an infinite stress (or strain) concentration, often referred to mathematically as a singularity. Since it is impossible in reality to have an infinite stress concentration, the science of fracture mechanics has grown up to explain why such infinite stresses and strains do no exist or, alternatively, if they do exist, then why structures do not collapse under very light loads. *The fracture mechanics approach, especially with ductile adhesives in thin bond lines, must therefore be seen as intellectually suspect.* Indeed, although fracture mechanics has been used by some researchers in adhesive bond studies, there is little or no evidence of a joint having been **designed** on this basis.

In practice, the sharp corners at the ends of a lap joint are always rounded slightly during manufacture, such as by abrasion, or by etching during surface treatment.

Also, the adhesive is not linearly elastic to failure, but can yield. Finally, the authors have observed experimentally that, despite the theoretical stress concentration at the corner of the unloaded adherend, the crack leading to failure rarely, if ever, cuts across the corner, but is usually at about the same distance as the glue line thickness. This implies that whatever condition it is that causes failure, it is not at the actual corner but some distance from it. The influence of the geometry of the corners in adhesive joints has been studied by Adams and Harris[7]. They showed that rounding the corner removed the singularity and produced a uniform stress field in this region, owing to the restraining effect of the relatively rigid adherend. When plastic energy density in the adhesive was analysed, it was shown that the maximum value was generally away from the corner, thus explaining why failure initiated away from the corner and not at it. Using their mathematical model, Adams and Harris were able to predict the strengths of various aluminium/aluminium joints bonded with a rubber-toughened epoxy, and these gave excellent agreement with their experimental results.

APPLICATION OF JOINT STRESS ANALYSIS TO COMPOSITE MATERIALS

A major advantage of adhesive bonding is that it enables dissimilar materials to be joined and so allows fibre reinforced plastics to be bonded to metals or to other composites. Some composites are woven or stitched so that the fibres are not perfectly aligned. High-quality chemical plant may be made from satin-weave glass fibre reinforced polyester or epoxy resin, while lower grade composites usually consist of random glass fibres in a polyester resin. Advanced composites are usually highly anisotropic in respect of both stiffness and strength and, although a unidirectional composite may be very strong and stiff in the fibre direction, its transverse and shear properties may be weak. Adhesive bonding is attractive since it avoids local stresses such as with bolts or rivets.

The techniques of analysis are essentially the same as when isotropic adherends are used, although due attention must be paid to the low longitudinal shear stiffness of unidirectional composites. The use of lamination techniques, in which fibres are placed at different angles to the plate axis, leads to reduced longitudinal and increased shear moduli However, the *transverse* modulus (*i.e.* through the thickness of the adherend) remains low, being only two or three times that of the matrix material (usually epoxy or polyester resin). In addition, the transverse *strength* is low, usually being of the same order or less than that of the matrix. Table I lists some typical properties for carbon fibre reinforced plastics. If the joint experiences transverse

TABLE I
Mechanical properties of CFRP adherends

Longitudinal Young's modulus(E_1)	135	GPa
Transverse Young's modulus(E_2)	7	GPa
Longitudinal tensile strength(σ_1)	1550	MPa
Transverse tensile strength(σ_2)	40	MPa

(peel) loading, there is a strong likelihood that the composite could fail in transverse tension before the adhesive fails. Adhesive peel stresses should, therefore, be minimised where composite adherends are used lest this leads to adherend failure.

Adams *et al.*[8] considered the stress and strain distribution in a series of joints in which CFRP was bonded to steel in the form of a double lap joint, the CFRP being the central adherend. The dimensions and various designs analysed are shown in Figure 6. Most of these designs are modifications of the basic design, keeping the same overlap but aimed at improving joint strength. In designs 2 and 3, the outer adherends were modified by tapering; this reduces the maximum adhesive shear stress in a joint, but only if the taper is continued to fine edge. Design 4 shows the original joint modified to include an adhesive fillet at the end likely to fail. Finally, in design 5 both a taper and fillet have been incorporated.

A toughened epoxy adhesive was used in the experimental programme. Mechanical properties measured in a bulk adhesive specimen showed a Young's modulus of 3.05 GPa, a failure stress of 84 MPa, and a failure strain of 4.5 per cent when tested

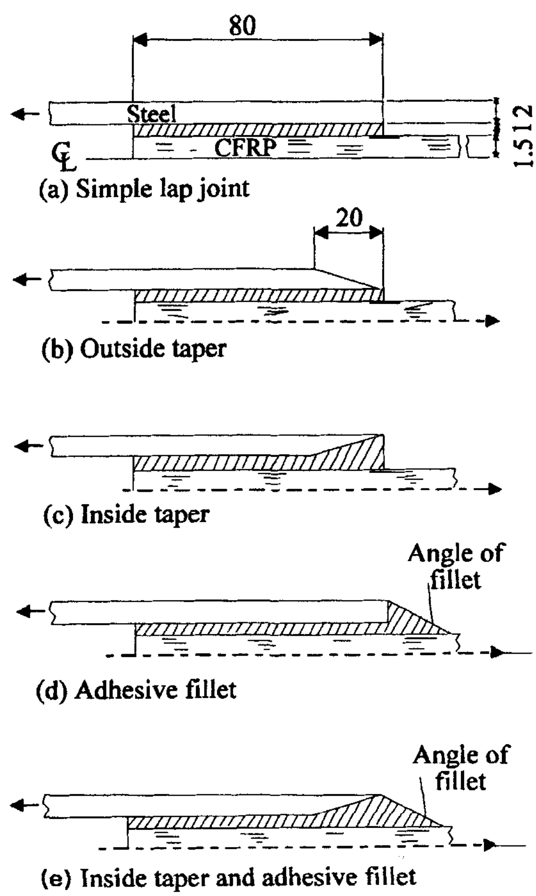

FIGURE 6 Various double lap joint designs for steel-CFRP bonding.

in uniaxial tension. These values were used, together with the CFRP properties given in Table I, for predicting the stresses, strains, and failure loads of the double lap joint specimens.

For all of the joint designs considered, the peak transverse stresses in the composite occurred in the region adjacent to the edges of the outer steel adherends. A contour plot of the transverse stresses was produced for the critical region of design 1 (Fig. 7). Here, as with designs 2 and 3, a large stress concentration exists adjacent to the very edge of the adhesive layer. The abrupt edge of the adhesive layer causes the transfer of the load from the inner CFRP adherend to the outer steel adherends to be focused in this local edge region; the transverse stresses in the CFRP decay rapidly away from this location towards the centre-line of the joint and longitudinally away from the overlap. This pattern of load transfer and stress concentration is affected very little by either the outside or inside taper of designs 2 and 3. It is worth noting that prediction of the magnitude of the concentration of the transverse stress would be very difficult by closed form analytical method, so that the use of finite elements appears justifiable.

By introducing an adhesive fillet in Design 4, an appreciable reduction is obtained in σ_T. Even the relatively small modification of a 45° fillet reduces the stress by a factor of two. The fillet reduces the focus for the transfer of load at the edge of the overlap, giving a more even distribution of the transverse stress in the composite.

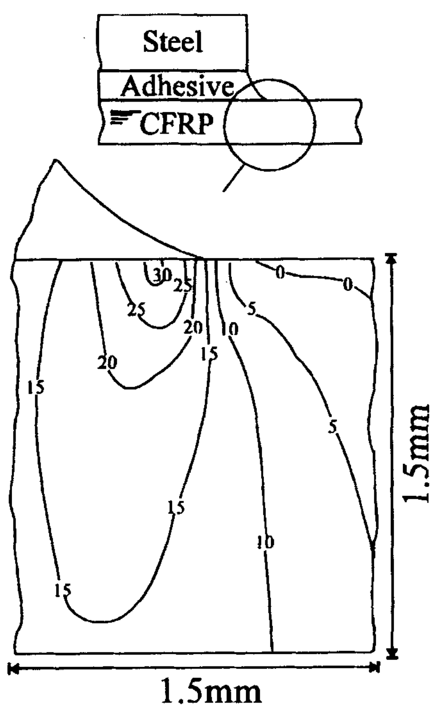

FIGURE 7 Transverse stress (MPa) in the CFRP, for an applied load of 1 MN/m.

A combination of an (internally) tapered steel adherend with an adhesive fillet results in further reductions in the transverse stress concentration (Design 5). In effect, the transverse stiffness is reduced at the edge of the overlap and, with the addition of an adhesive fillet, the σ_T stresses are now reduced to about a sixth of those in Design 1, so that if failure is going to occur by transverse fracture of the composites, Design 5, which includes an internal taper and an external fillet, ought to be six times stronger.

The finite element analyses also give the values of the stress components within the adhesive. From these values, the principal stresses (and hence strains) can be determined in both magnitude and direction. Cohesive failure of the adhesive occurs in regions of maximum stress or strain concentration and results in cracks which run at right angles to the direction of these (stress or strain) maxima. The principal stress distributions, therefore, indicate the likely locations and directions of failure in the adhesive. Not only can the joint strength then be predicted, but the fracture surfaces can be interpreted.

In the experimental programme, there was no evidence of joint failure by any form of shear process. Instead, all the joints appeared to fail by interlaminar fracture of the CFRP adherend. Additional tests were carried out to single lap joints. In these joints, alminium or steel adherends were bounded to unidirectional CFRP. Three series of specimens were used which corresponded to Designs 1,4 and 5 in Figure 6. The experimental results, averaged for both types of adherend, each with two different fillet angles, are summarised in Table II.

The results in Table II show enormous differences between the three cases, even though the overlap areas were identical. For the double lap joints, the improvement between Designs 1 and 5 was only 3 times. This was because the double lap configuration tends to reduce the bending effects present in the single lap joint, whereas for the single lap joints the improvement was 5.35 times.

THREE DIMENSIONAL ANALYSIS

It was known from the early work of Adams and Peppiatt[3] that transverse stresses are caused in joints. More recent work, using 3-dimensional finite element analysis, has shown that transverse (anticlastic) bending also occurs in single lap joints, owing to Poisson coupling effects interacting with the local bending (as originally treated by Goland and Reissner[2]). Essentially, this work showed that the maximum transverse stresses in the composite, and the maximum transverse (across the width)

TABLE II
Single lap joint strengths for steel or aluminium bonded to CFRP

Joint design (*cf.* Figure 6)	Description	Failure load (kN)	Ratio
1	Basic	4.85	1
4	Basic + fillet	9.53	1.96
5	Inside taper + fillet	25.93	5.35

stresses in the adhesive, occurred in the middle of the joint, and not at the free edges. In this study, a single lap joint, with composite adherends, and a typical toughened epoxy resin has been considered. Three-dimensional finite element analysis was carried out to gain a fuller insight into the behaviour of the joint.

The single lap joint considered has an overlap length of 12.5 mm, a bondline thickness of 0.2 mm, and was 25 mm wide. Full fillets at 45° to the loading direction were also included. Both adherends were unidirectional fibre reinforced composites, with the fibres oriented parallel to the loading direction. The adherends were modelled as homogeneous, transversely isotropic materials with linear elastic properties as shown in Table III. The values were derived from the fibre and matrix properties using the Halpin-Tsai equations for unidirectional continuous fibre composites.

The adhesive was treated as an elastic-plastic material with the yield criterion being a paraboloidal surface in the principal stress plane. This criterion was used as it accounts for the increase in yield strength with increasing hydrostatic pressure. Uniaxial tensile and compressive bulk data were used to generate the hardening rule for the plastic behaviour within the model.

The finite element model consisted of 8752 elements and 10235 nodes; the majority of elements were 8-noded hexagonals, while 6-noded wedge elements were used at the free edges of the fillet and in areas where mesh refinement is necessary. These elements were chosen in order to minimise the number of degrees of freedom in the model for speed of analysis. Two element layers were used across the adhesive thickness.

Owing to the symmetry of this joint configuration, only half of the joint width was modelled, with the widthwise centre plane being constrained in the transverse direction as appropriate. The gripping conditions were imposed by constraining nodes midway across the thickness at the ends of the adherends, thus allowing full Poisson's ratio contraction.

As large stress gradients were expected in the joint towards the ends of the overlap, mesh refinement was used to concentrate elements in this area. The adherend mesh was also graded towards the adhesive to account better for the rapid change in stresses in this area. Across the width, a finer mesh was employed near the free edge.

Non-linear analyses were performed, with both geometric and material nonlinearity included. The results presented within this paper are for a 5 kN tensile load which, although not a failure load, is sufficient to give an understanding of the joint behaviour.

As can be seen from Figure 8, showing the transverse (widthwise) deformation of the adherends, there is significant shrinkage of the loaded adherend at the end of the

TABLE III
Composite Adherend Mechanical Properties

$E_{11}, E_{22}, E_{33} (GPa)$	v_{12}, v_{23}, v_{13}	$G_{12}, G_{23}, G_{31} (GPa)$
164	0.285	6.99
9.71	0.296	3.75
9.71	0.285	6.99

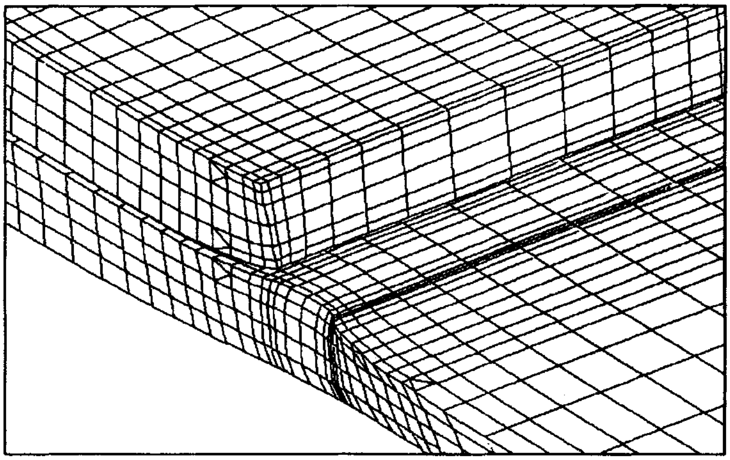

FIGURE 8 Lateral deformation of single lap joint with unidirectional CFRP.

overlap. This is a clear indication that Poisson's ratio effects are significant in the behaviour of composite single lap joints. The transverse deformation of the loaded adherend is then constrained by the upper "unloaded" adherend within the overlap length, thus enhancing the stresses in the loaded adherend. It must be pointed out that the magnitude of the deformations has been greatly exaggerated for ease of visualisation.

Stress/strain distribution from within the composite adherends are also available from the analyses and one such result is shown in Figure 9 with the stresses normal to the loading direction (peel stresses) within the first ply plotted. The darker shaded area is where these stresses are greatest, and free edge effects are clearly present. It must be noted that this area represents a range of stresses and does not locate precisely the actual maximum.

Thus, 3-dimensional analysis, although being computationally expensive, gives a more detailed description of the general behaviour of the single lap joint.

CONCLUDING REMARKS

With composite adherends, there are two possible mechanisms of failure. In one case, transverse tensile stresses at the edge of the joint close to the interface result in interlaminar failure of the CFRP. In the other case, concentrations of the principal stresses in the adhesive result in tensile (cohesive) failure. The cohesive failure results in cracks which run through the adhesive to the interface, after which the composite will fail transversely in an interlaminar manner. However, it may not be clear in the first instance which mechanism is responsible for failure from studying only the fractured surfaces of the joint. By applying suitable failure criteria to the finite element results for the adhesive and the adherends, the load required for failure by either mechanism can be predicted. It has also been shown that a full 3-dimensional

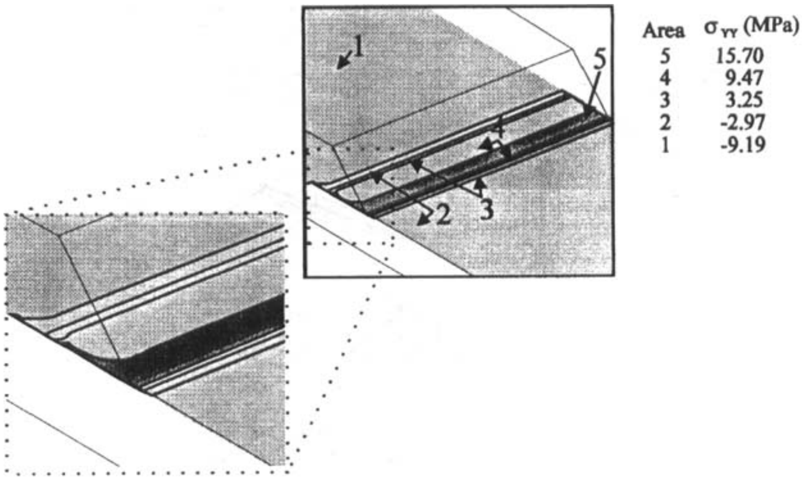

FIGURE 9 Distribution of transverse (σ_{yy}) stresses in the top ply of the lower composite adherend.

finite element analysis is necessary if transverse (across width) stresses are to be considered.

Thus, by using finite element techniques, it is possible to predict the strength of joints from fundamentals together with the mode of failure. This greatly assists not only the design process but also the post-failure analysis of joints, as it otherwise is difficult, if not impossible, to decide where the failure initiated.

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