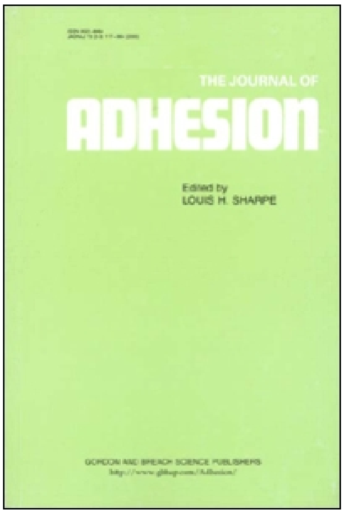

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A. D. Crocombe[a]; I. E. J. Evans[a]
[a] Department of Mechanical Engineering, University of Surrey, Guildford, England

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The Interaction of Adhesive Joint Strength and Adherend Cladding†

A. D. CROCOMBE and I. E. J. EVANS

Department of Mechanical Engineering, University of Surrey, Guildford GU2 5XH, England.

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The paper presents the results of an investigation concerning the effect of the cladding layer on the strength of a bonded joint. This has been carried out by combining the results from both experimental and analytical studies. The former involved a direct comparison of clad and unclad joints, providing data for the analytical work which was achieved through detailed non-linear finite element analysis of both clad and unclad configurations. Good estimates for failure strengths were found and, although adhesive yielding characteristics for both configurations were similar, the key to the differences in joint strength appear to be due to the presence of the adhesive fillet at the ends of the overlap.

INTRODUCTION

Aluminum alloys have, for some considerable time, often been given a thin surface coating of pure aluminium to enhance their environmental integrity and resistance to corrosion. Although thin, typically less than 0.1 mm, the weight of this cladding may still be a significant portion of the whole, say 10%. As the cladding is essentially a pure aluminium its strength is minimal and thus will reduce the specific load carrying capacity of the adherend. This basic reduction of adherend strength is accepted in practice and may be accomodated in the design process.

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However, there is reason to believe that, as well as reducing the strength of the alloy, the cladding can have a deleterious effect on the adjacent layer of adhesive in a bonded joint and thus affect the joint strength. This aspect is much more difficult to accomodate in the basic design and the object of this study was to investigate the interaction between the adhesive and cladding layers and thus the effect on joint strength in more detail.

Joint strength dependence was investigated by carrying out a programme of standard double lap joint tests on joints manufactured using both clad and unclad aluminium. Both visual and microscopy techniques were used to study the failed joints in order to quantify the cladding layer and the mode of failure. The strengths found from these tests were then used as boundary conditions for a non-linear finite element analysis of both the clad and unclad double lap joint configurations. These analyses in turn produced data defining the state of stress and deformation in the joint which could be used to investigate criteria for failure and establish the causes of any strength reduction that might be found in the experimental tests. In this study all parameters except the cladding layer have been kept constant. A future publication is planned which combines results obtained from varying the cladding layer with those obtained by varying the adhesive thickness. This will show how the concept of global yielding, introduced in this paper, governs the strength of a range of joints where the 'thickness effect' is active.

BACKGROUND

There does not appear to have been very much work carried out examining the effect of the cladding layer on joint strength. Communication with several workers, however, has revealed that after joint failure the cladding layer can often be seen to have exhibited extensive yielding. It is not unreasonable to assume that such behaviour may significantly affect the stress developed in the adhesive layer and hence the strength of the joint. It is, of course, essential to accommodate non-linear behaviour as, in a linear analysis, the performance of the cladding and core alloy would be identical. Thus an approximate numerical technique, such as the finite element method, is necessary. In order to model the detail of the thin cladding layer a large and complex model is necessary and this is probably the main reason why so little work has been carried out.

Adams[1] has included a primer layer in an earlier elastic finite element analysis of axisymmetric butt joints and obtained reasonable results. However, although the finite element method has been applied successfully to analyse the non-linear response of various joint configurations,[2,3] a non-linear analysis including the cladding layer does not yet appear to have been undertaken. Thus one of the objectives of this work was to investigate the validity and viability of such an approach.

As the cladding layer yields at low levels of stress it will significantly increase the flexibility of the bondline region behaving in many respects as an extension to the adhesive layer. This observation has led Adams *et al.*,[4] to postulate that the effect of the cladding layer would be similar to an increase in the adhesive thickness. An elementary joint analysis would show that this would reduce peak stresses and hence increase the strength of the joint. Experimentally, however, the converse is usually noted and it was not until recently that a full explanation of this thickness effect was presented.[3] It transpired that, although yielding occurs first in joints with thin adhesive layers, subsequent yield takes place at lower levels of adhesive shearing and at a faster rate in the thicker joint. Thus this work was carried out to see whether the same thickness effects were present when the cladding layer yielded.

Preliminary data, presented at the conference, showed results obtained from a commercial analysis package. This however was rather limited in approach and the present paper presents a more detailed analytical study, incorporating additional non-linear features, using an analysis package developed on a previous programme of work.[2]

ADHESIVE JOINT TESTING

The double lap joint, made to British Standard 5350, was used as the primary investigative configuration. A programme which involved the controlled manufacture and testing of both clad and unclad versions of this joint was undertaken. This provided comparative data on the strength of clad and unclad joints, appropriate sets of boundary conditions for the analysis program and afforded an opportunity to study the mode of failure and failed surfaces on both types of joint.

The object of this programme was to subject the cladding to as high a level of shear loading as possible in order to accentuate any effects there might be on the joint strengths. This was achieved using high strength components. The clad and unclad aluminium alloys were to British Standard specifications BS3L73 and BSL157 respectively, and had a 0.2% proof stress of about 400 MPa, while the adhesive, a toughened film epoxy, Redux 308 A, had a maximum shear stress of around 70 MPa. The double lap joint was used in preference to the single lap joint as this reduced the mode I loading on the adhesive and thus caused failure at higher loads and, hence, enhanced cladding deformation.

The double lap joints were jig bonded in batches of ten. Each adherend set, consisting of two pre-slotted 2 mm thick outer adherends and one pre-slotted 4 mm thick centre adherend, was treated to a standard chromic acid etch and then immediately bonded with the film adhesive under nominal pressure at 150°C for one hour. The adhesive thickness was controlled at 0.2 mm by the use of ballotini; varying amounts were used and no noticeable effect on joint strength was noted. The resulting bonded plates formed a series of double lap joints connected over parts of the free adherend length. These were separated using a bandsaw and then tested to destruction.

The specimens were loaded to failure in a 100 kN screw driven Instron universal testing machine. Due to the large shear strains anticipated in the cladding layer it was thought likely that the adhesive would be subject to different rates of straining in the clad and unclad joints. In order to investigate any strain rate dependency both clad and unclad joints were loaded at two different crosshead speeds.

The results from the tests are summarised in Figure 1. The horizontal bands represent the scatter in the failure loads, which was always less than 2%. Two main conclusions can be drawn from these test results. Firstly, an unclad joint is stronger than its clad counterpart, the increase in the average, measured failure load being about 6%. Secondly, although present, the strain rate effect

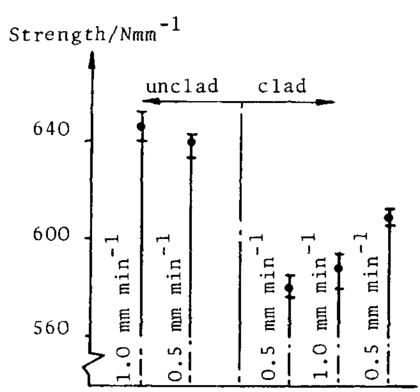

FIGURE 1 Measured double lap joint strengths.

was not significant, a doubling of the crosshead speed resulting in an increase of failure load of only about 1%.

The narrow band of scatter in the failure loads can be attributed to the common mode of failure exhibited by every specimen. This consists of a locus of failure completely within the adhesive on one face and regions of failure close to the interface on the other. It is conjectured that failure within the adhesive must occur initially on one face (cohesively), the joint then abruptly becomes an unbalanced single lap joint, undergoing sudden joint rotations with associated increases in the adhesive transverse direct or peel stresses causing failure close to or on the interface at the remaining bondline.

In an attempt to establish the existence of, and quantify, the cladding layer of pure aluminium on the clad joints after the etching and bonding process, a number of manufactured joints were sectioned across the thickness, mounted and subsequently polished. The adhesive-adherend interface region was thence examined using various techniques of microscopy. By using a light microscope a surface layer on the aluminium was noted that appeared to be different from the core alloy, the size of this layer typically being a little less than the adhesive layer. The elements present in this surface layer were determined using an energy dispersive X-ray analysis technique known as electron probe micro-analysis. Using this technique it was shown that, as anticipated from the aluminium specification, the core alloy contained 93% aluminium and 5%

copper while the surface layer was essentially pure aluminum. Thus verification of the cladding layer was achieved and it remained to show, through non-linear stress analysis, the mechanism by which this layer might reduce the strength of a bonded joint by the amount found in the testing programme.

ADHESIVE JOINT MODELLING

The finite element analysis requires the component being analysed to be subdivided into a regular mesh. The chosen degree of refinement in the mesh used is generally limited by computer time available, a range of refinements being used to establish convergence of the results. The basic mesh used in this work is shown in Figure 2 and is based on a mesh developed for single lap joint analysis discussed in an earlier publication.[3] In all, a total of 2007 nodes and 624 quadratic, isoparametric, plane strain elements were used. The quadratic elements accomodate a linear variation of strain and thus further enhance the accuracy of the solution. A

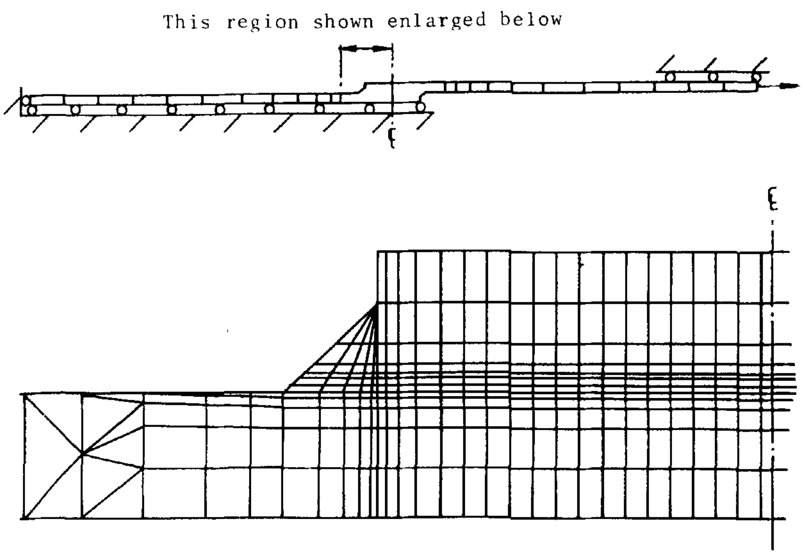

FIGURE 2 Double lap joint finite element mesh.

typical non-linear analysis required about 1000 seconds on a CRAY 2 supercomputer. Although essentially a full single lap joint model, double lap joint conditions can be achieved by appropriate constraint of the nodes which represent the (centre) line of symmetry in a double lap joint. Other loads and constraints representing the action of the grips are as shown in Figure 2. The mesh shown was used to model both clad and unclad joints. This was achieved simply by assigning the thin layer of elements adjacent to the adhesive layer the appropriate material properties.

The analysis was to accomodate full non-linear behaviour of all the constituent materials. The finite element package used was developed during an earlier programme of work[2] and is capable of modelling both material and geometric non-linearitites and also includes a hydrostatic sensitive yield criterion (a function of both the first and second stress invariants, developed particularly to model yielding in polymeric materials) as well as the more usual von Mises criteria (a function only of the second stress invariant). Further details of this are outlined in the publications cited earlier.

The various material stress-strain characteristics can be modelled to any degree of accuracy using a normalised cubic B-spline

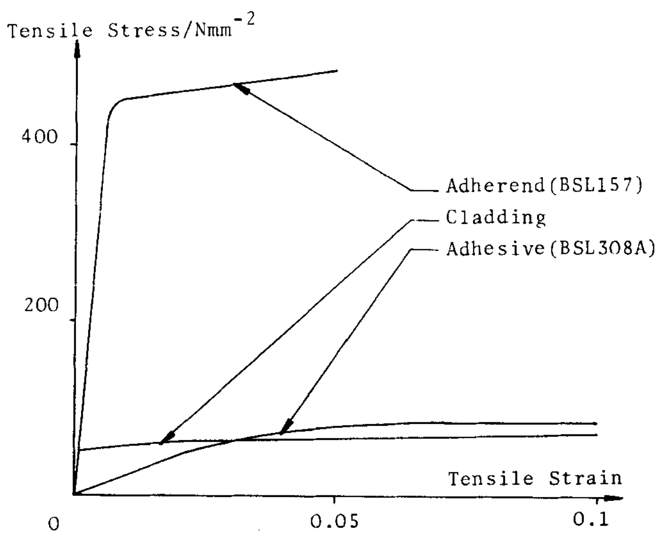

FIGURE 3 Stress-strain characteristics of double lap joint materials.

representation. Appropriate curves for the core aluminium alloy, the adhesive, and the cladding layer were constructed and are shown in Figure 3. Data for the former was obtained by carrying out uniaxial tensile tests on strain gauged aluminium specimens. The adhesive behaviour was derived from published shear stress-strain curves[5] while the properties of the cladding layer were taken as those applicable to 99.9% pure aluminium, the purity specified by BSL157.

ADHESIVE JOINT ANALYSIS

An initial, elastic anlaysis of both joints was carried out. Under such conditions the clad and unclad joints and their resulting stress distributions were identical. Elastic analyses of double lap joint configurations have been the subject of many publications and are thus very well documented. The adhesive stresses at the gauss points (points of numerical integration within each element) nearest the adhesive centre-line are shown in Figure 4 and are typical of a double lap joint. Note that due to the relatively high stiffness mismatch the shear stress distribution is fairly flat. The peel stress

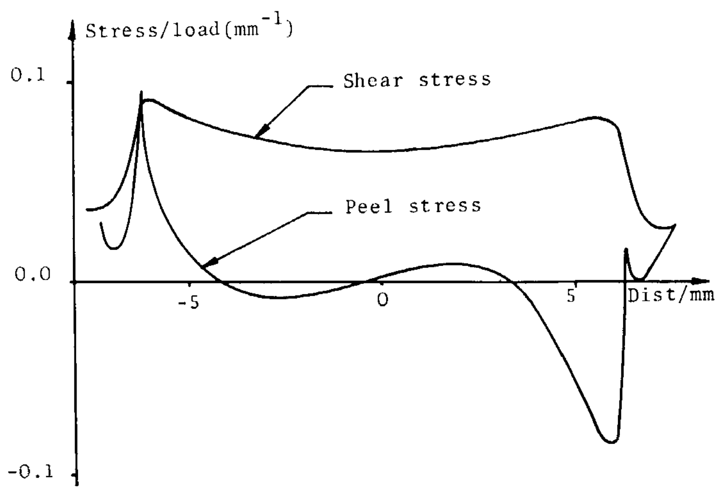

FIGURE 4 Variation of adhesive elastic stresses with distance from the centre of the overlap.

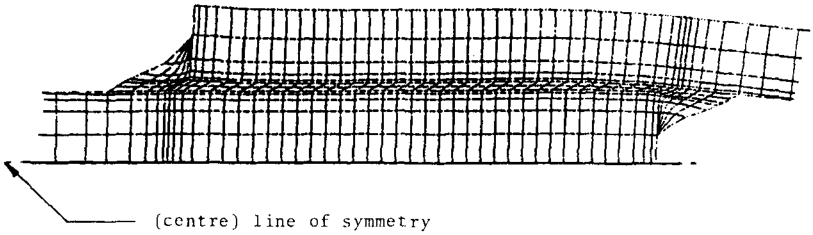

FIGURE 5 Elastic deformation of the overlap region of a double lap joint.

has a region of tension near the free end of the outer adherend and compression at the other; this is due to the flexural deformation of the outer adherend which is shown, much magnified, in Figure 5. The peel stress distribution has a significant effect on the spread of the yield zone in the adhesive. Using a hydrostatic sensitive yield criteria has the effect of suppressing the yield in regions of compression and promoting the yield in regions of tension. Clearly, then, the yield zone is likely to spread predominantly from the free end of the outer adherend. In fact, the results from the non-linear analyses reported later show that the yield is fairly constrained near the free end of the centre adherend. This is a feature that any non-linear analysis using only a standard yield criteria would not be able to model.

Considering first the non-linear analysis of the unclad configuration, Figure 6 shows the spread of the yield zone as the load is increased. The numbers between any two contours give the level of loading (Nmm^{-1}) by which the enclosed material yielded. As suggested above, initial yield does occur near the free end of the outer adherend, adjacent to the corner. The first adhesive gauss point yields at a load of around 250 Nmm^{-1}. Subsequent yielding then spreads predominantly along the overlap region and not out into the fillet of the adhesive. Although yielding begins shortly after at the other end of the joint it spreads more slowly from this end, as anticipated. However the bulk of the overlap has yielded at a load of around 500 Nmm^{-1} and even at this level of loading the greater part of the adhesive fillet remains elastic. Further increases in the applied load see the gradual spread of the yield zone into the fillet until at a load of around 650 Nmm^{-1} a path of yielded adhesive exists through the fillet. Due to the lack of any significant strain

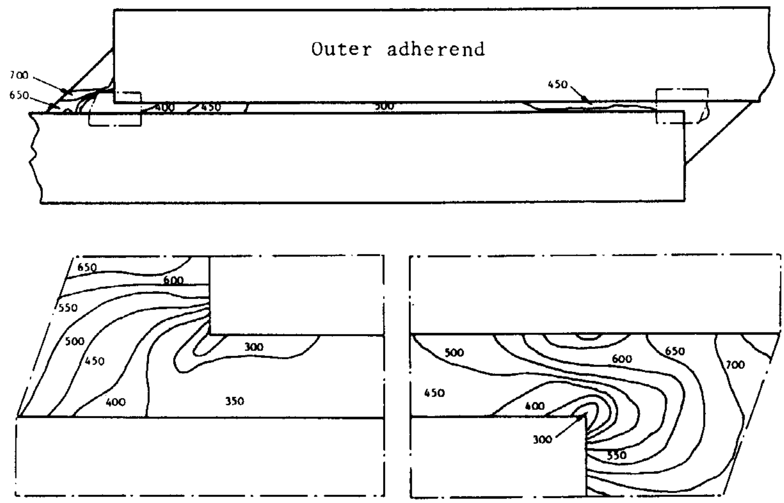

FIGURE 6 Spread of the yield zone in the unclad double lap joint.

hardening in the adhesive, once a path of yielded material exists there will not be any significant increase in the level of the adhesive stress and hence in the load carrying capacity of the joint. Thus the analysis would suggest that an effective lower bound on the failure load would be about 650 Nmm^{-1} and, by comparison with the measured failure loads for the unclad joints, this is shown to be a good estimate.

This criterion for joint strength, based on GLOBAL YIELDING rather than LOCAL RUPTURE of the adhesive, was used with considerable success in the analysis of single lap joints in an earlier paper[3] where good joint strength predictions for various adhesive thicknesses were obtained. It would thus appear to have much to commend its use in appropriate joint configurations.

To illustrate further the variation of stress with applied load, consider Figure 7. This shows the adhesive shear stress distribution along the gauss points closest to the centre-line at various levels of loading. A number of points arise from this. The level of stress in the adhesive fillet, although increasing, still remains substantially below the level of stress in the overlap region. As the load increases the stress distribution tends to become smoother. This, of course, is caused by the yielding in the adhesive tending to redistribute the

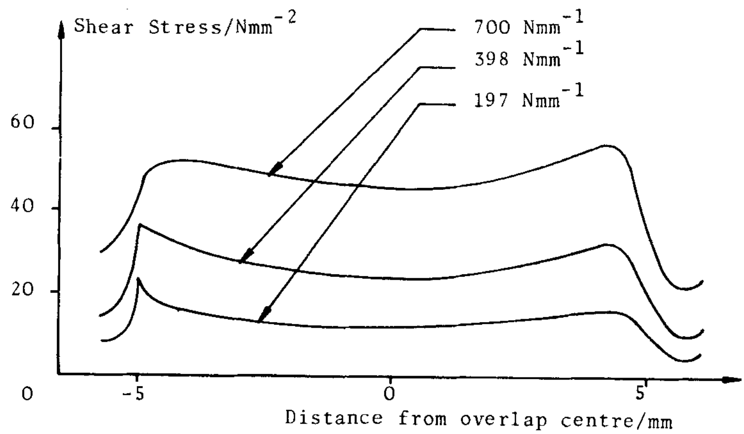

FIGURE 7 Variation of the adhesive shear stress with distance from the overlap centre at various loads in the unclad double lap joint.

load. The effect of the hydrostatic compression near the free end of the centre adherend suppresses yield and thus allows higher levels of shear stress to be sustained.

Figure 8 shows, from the analysis of the clad joint, the spread of the yield zone, the dashed line showing the extent of the cladding layer. As before, the numbers between any two contours give the load level by which the enclosed material has yielded. As anticipated (from the simple tensile loading in the aluminium) yielding begins first in the cladding layer at the loaded ends of each adherend, occuring at a load of about 100 Nmm^{-1}. As the load is increased the yielding spreads down the overlap from each end, spreading a little more quickly on the outer adherend as this is subject to both bending and tension while the centre adherend is in tension only. The yielding in the cladding preceeds that of the adjacent adhesive layer. This is because, in addition to the shear and transverse direct stresses, which are common to both cladding and adhesive (on the interface), the cladding layer also experiences considerable in-plane direct stresses, from both tension and bending in the adherend.

Considering now the yielding of the adhesive, this initiates at the same location, adjacent to the unloaded corner of the outer adherend. Yielding occurs at a slighly higher level of loading, caused by the yielded cladding layer increasing the apparent

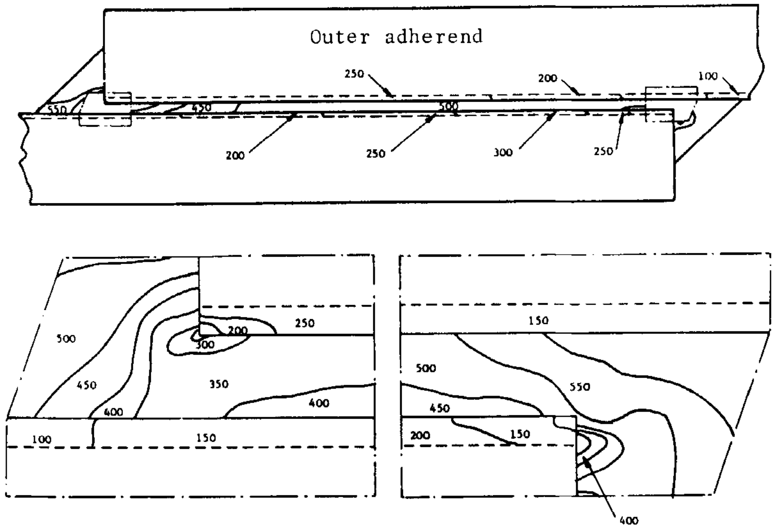

FIGURE 8 Spread of the yield zone in the clad double lap joint.

flexibility of the adhesive locally and thereby reducing the level of stress. However, by comparing Figures 6 and 8 it can be seen that yielding through the overlap is very similar for both clad and unclad joints. By a load of about 500 $\mathrm{Nmm^{-1}}$ the overlap region is once again completely yielded. The difference, however, can be seen by the spread of the yield zone into the adhesive fillet, adjacent to the free end of the outer adherend. It can be seen that, unlike the unclad joint, by the time the overlap has yielded a substantial portion of the fillet has yielded also, indicating that the level of stress in the fillet is much higher. From Figure 8 it can be seen that a path of yielded material through the adhesive fillet exists at a load of about 550 $\mathrm{Nmm^{-1}}$. Once again, using the concept of GLOBAL YIELDING, this would explain why the clad joint is weaker than its unclad counterpart.

This behaviour can once again be illustrated by considering the shear stress distribution curves at different levels of applied load, Figure 9. Immediately, on comparison with Figure 7, the high relative levels of stress in the adhesive fillets can be seen and it is suggested that it is the absence of the load carrying capacity of the fillet that reduces the strength of the joint.

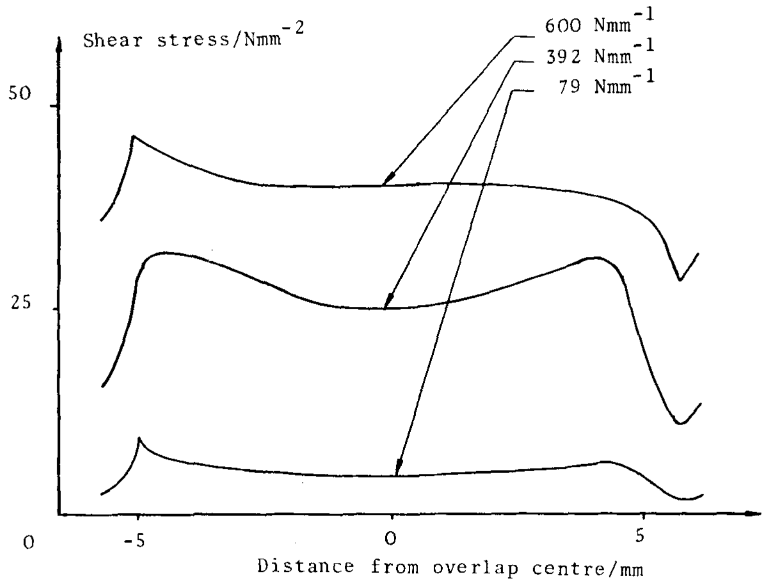

FIGURE 9 Variation of the adhesive shear stress with distance from the overlap centre at various loads in the clad double lap joint.

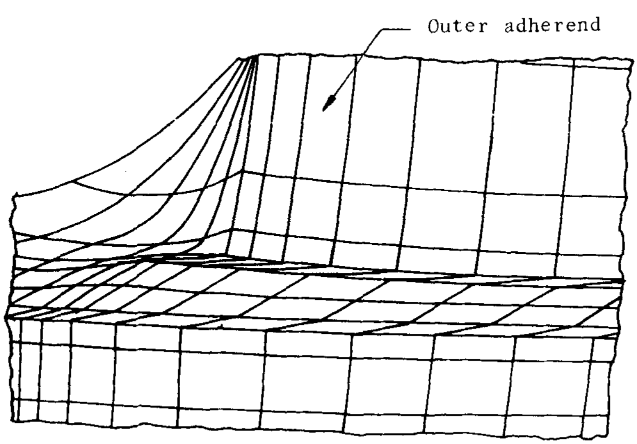

FIGURE 10 Deformation of the tensile end of the clad double lap joint overlap region predicted from the full non-linear analysis.

The cause of the high stress in the adhesive fillet is largely due to the increase in the shear deformation of the joint. This can be most clearly seen by considering Figure 10 which shows a plot of the predicted deformed mesh (scaled up for clarity) for the clad joint at its maximum load. The excessive shearing in the cladding layer is immediately apparent along with the associated deformation it causes in the adhesive fillet.

CONCLUSION

Adherend cladding is a thickness parameter and hence is likely to affect the strength of an adhesive joint. Experiments on both clad and unclad variants of the same double lap joint show that, for the configurations concerned, cladding reduces the joint strength and that the anticipated resulting decrease in strain rate is not sufficient to account for this strength reduction. At the levels of loading applied the cladding will yield excessively and thus a non-linear stress analysis of both unclad and clad joints was carried out. Analysis of the former showed that yielding occurred first at the tensile end of the joint and spread down the overlap region. Yielding occurred at higher loads at the compressive end, suppressed by the hydrostatic level of stress. At still higher levels of load, the yielding spread into the fillet region and the strength of the joint could be predicted by assuming failure to occur when a complete path of yielded adhesive existed, a concept termed GLOBAL YIELDING. Analysis of the clad joint showed a similar pattern for yielding in the overlap region but the adhesive fillets were stressed to a much higher level by the excessive deformation of the cladding layer. Yielding through the adhesive thus occurred at lower loads and by using GLOBAL YIELDING as a criterion for failure again it was shown that the measured reduction in clad joint strength could be theoretically predicted.

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