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THE STRENGTH OF JOINTS IN FIBRE REINFORCED PLASTICS

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ABSTRACT

This work, mostly theoretical, relating to all aspects of adhesively bonded joints in composite materials is reviewed. The theoretical work is subdivided into classical and finite element methods. General principles and design guidelines are also presented.

The load carrying joints in composite materials can be effected by two basic methods is mechanical fastening or adhesive bonding. This work is seen to be related mainly to theoretical results, derived either from classical analytical or finite element methods. The various approuches are compared with each other and, where possible, with experimental data.

INTRODUCTION

The basic theoretical treatment of bonded joints in metals, based on the classical analytical methods of continue mechanics, was developed some 30-40 years ago. The methods have been modified for composite materials to account where necessary, for their anisotropic nature. The increasingly wide-spread use of digital computer had to effects on the analysis of bonded joints. Firstly, it has enabled solutions to be obtained to what were previously intractable problems. Secondy, it has fostered the development of the discrete or finite, element method, enabling the solution of problems which are totally insoluble by classical methods.

JOINT PARAMETERS

The purpose of a joint is to transfer load, either tensile or shear, between two adherends, as shown in Fig. 1. Analyses usually relate to tensile loading on joints of large width, in which case the stress distribution can be assumed identical at all sections across the joint and edge effects can be ignored.

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Joints can be subdivided into the four basic types shown in Fig. 2. The strength of a given type of joint depends, for a given type of load, on the stress distribution within the joint. This stress distribution depends on the joint geometry, as shown in Fig. 3, and the mechanical properties of the adhesive and adherends. In particular the following parameters can be significant: length of overlap (l); adherend thickness (ta); adhesive thickness (tg); adherend strength and elastic moduli; adhevise strength and elastic moduli and, adhesive stress/strain characteristics. The adhesive is always considered to be isotropic.

FAILURE MODES

Compared to failure in metal joints a larger number of failure modes can be identified for composites, due to their anisotropic nature. In the adherends failure can be tensile, interlaminar or transverse, in the last two cases either in the resin or at the fibre/resin interface. In the adhesive a cohesive mode of failure can occur. These modes are illustrated in Fig. 4.

Additionally there is the possibility of failure at the adherend/adhesive interface. Such failures, which generally happen at a low load, should not occur in a properly prepared joint and can thus be regarded as a quality control problem.

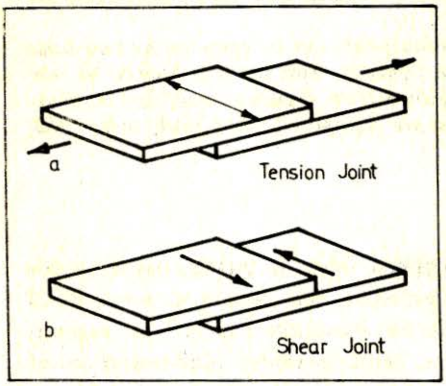

Fig. 1 – Load transfer accross a bended joint

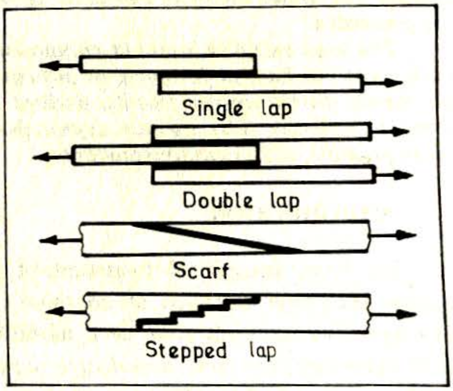

Fig. 2 – Basic types of joints

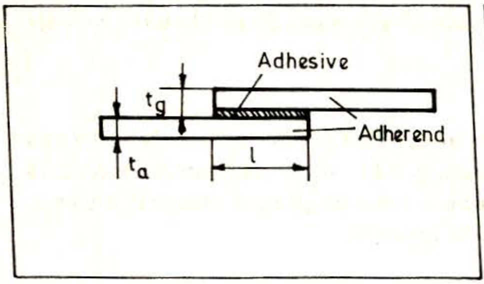

Fig. 3 – Definition of joint dimentions

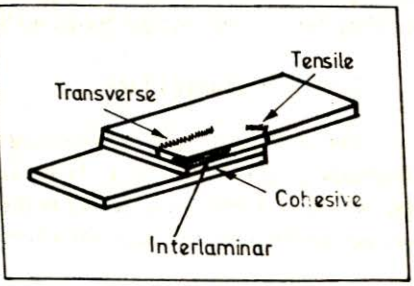

Fig. 4 – Possible failure modes in joints between composite adherends

CLASSICAL ANALYTICAL METHODS APPLIED TO METALS

Most of the basic work in this field, relating to single lap joints loaded in tension, has been reviewed by a number of authors[1-9]. To get a solution it is inevitable that some simplification must be made, the correspondence between the theoretical and experimental results depending critically on which factors are omitted from the analysis.

Linear analyses

The simplest approach is due to Volkersen[10], the so-called "shear lag" analysis. In this analysis the only factors considered are the shear deformation of the adhesive and the elongation of the adherends. It is thus clearly more representative of a double than a simple lap joints since in the latter over all bending of the adherends will occur.

The bending effects in single lap joints were first considered in detail by Goland and Reissner[11] although their importance was recognized by de Bruyne[12]. The results of adherend bending is to induce in the adhesive direct stresses, so-called "peel" stresses, in the through-thickness direction. In addition to the peel and shear stresses, Goland and Reissner also account for the longitudinal direct stress in the adhesive, all these stresses being assumed constant across its thickness which, as in most analyses, is assumed small compared to the adherend thickness.

The bending moment and shear force in the adherends at the ends of the joint, caused by the eccentric load path, are obtained by considering the adherends to be cylindiracally bent plates. In common with most analyses the joint is considered to be wide, ie a plane strain condition. It is shown that as the load increases the peel stress concentration factor decreases due to the decreasing eccentricity caused by the deformation, which ultimately settles to a stable configuration, as shown in Fig. 5. The magnitude of the maximum peel and shear stresses do however increase with load. It is further shown that these stress maxima reach asymptotic values at large overlaps, the maximum shear stress being twice that predicted by Volkersen. Fig. 6 shows typical adhesive stress distributions with the notable feature that the shear stress in non-zero at the ends of the joint. This results violates the stress-free boundary condition and is a consequence, as pointed out by Benson[3], of ignoring the variation of peel stress through the thickness of the adhesive.

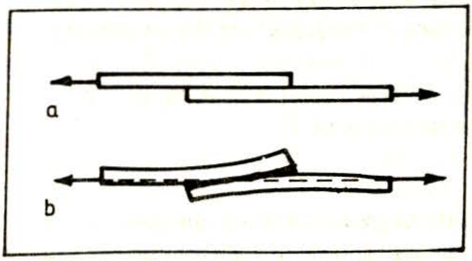

Fig. 5 – Deformation of a single lap joint
a) Loads are initially offsett
b) Loads ultimately align giving stable configuration

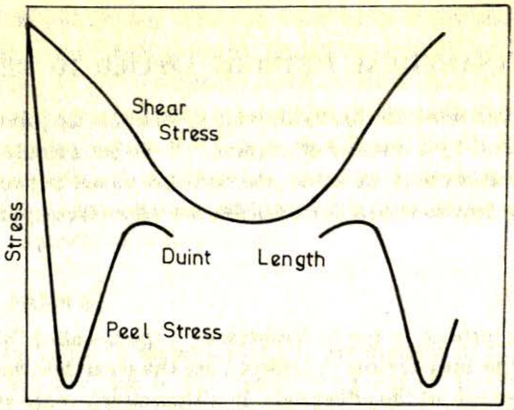

Fig. 6 – Typical variations of shear and peel stress in a single lap joint

The analyses mentioned so far, effectively consider the adherends as thin beams and ignore the through thickness shear and normal deformations in the adherends. As shown by Srinival[13] this only causes significant error if the lap length is small or the adhesive stiffness is large. However, he neglects the variation of stress through the adhesive thickness. A similar analysis is performed by Renton and Vinson[14]. Totally general analyses, including all the above effects, are given by Pirvics[15] an Allman[16] of course, as the situation considered is made more general, the governing equations become increasingly complicated and, almost inevitably, their solution will require the use of a computer.

Several authors[4,8,9,13,14,17] have undertaken parametric studies to identify the factors that most influence the maximum stresses in a joint. The various merits of single lap and double lap joints are also compared by Srinivas[13]. The following general conclusions may be made for minimizing the maximum stresses: if possible use identical adherends, if not equalize the in-plane and bending stiffness; use as high and adherend in-plane stiffness as possible; use as large an overlap as possible; use an adhesive with low tensile and shear elastic moduli.

As an alternative to using a low modulus adhesive throughout the joint, the maximum stresses can be reduced by using such an adhesive only at the ends of the overlap, in the regions of high stress, a higher modulus adhesive being used in the central region[13]. The same result can be obtained by varying the adherend thickness along the length of the joint[18,19,20].

Adams and Peppiatt[21] discuss the effect of finite joint width and demonstrate the existence of peaks in the adhesive stresses at the corners of the overlap, due to Poisson's ratio effects.

Scarf joints in tension are discussed by Lubkin[22], and in bending by Wah[23], and tubular lap joints are analyzed by Lubkin and Reissner[24].

Nonlinear analyses

All the work so far described refers only to joints for which the stresses stay within the elastic region. Whilst this may be appropriate for joints under fatigue loads, when the stresses in the adhesive are relatively modest, it has long been recognized that such linear analyses always underestimate the ultimate static load of the joint. This is so even for so-called "brittle" adhesives, although the discrepancies will be much more serious for "ductile" adhesives. Experimental evidence of the importance of adhesive nonlinearity is given, among others, by Adams[25]. Grimes[28] describe a nonlinear analysis which includes the effect of transverse shear in the adherends. A nonlinear analysis for tubular joints is discussed by Lubkin[26].

Experimental analyses

As discussed by Sneddon[1], and Niranjan[5], considerable experimental work has been undertaken to verify the various theories mentioned above. In practice it often proves difficult to satisfy the relevant similarity rules, as given for example by Kutscha[2]. Also, reproducing exactly the boundary conditions specified by the theory is sometimes not possible. However, whether using rubber models[27.28] or photoelastic models[9.29.30.31.32] the importance of the end shape of adhesive layer is demonstrated. Stress analysis of this effect is described below.

CLASSICAL ANALYTICAL METHODS APPLIED TO COMPOSITES

Compared to metals, the analysis of joints between composites is complicated by the anisotropy and heterogeneity of the adherends. In particular the effects of the low elastic moduli, both extensional and shear, in the transverse and through-thickness directions may need to be accounted for. A rigorous analysis ought also to include the effect of residual thermal strain arising from curing and thermal mismatch when bonding to metals. Treating the adherends as thin beams, in which case shear deformation is neglected, as in Goland and Reissner's analysis[11] is thus, in general, inappropriate for composites. A complete analysis would include the nonlinear behaviour of the adhesive.

Linear analyses

The linear elastic analyses fall into two parts; those which ignore and those which include through thickness shear in the adherends.

In the former category the work of Erdoğan and Ratwani[33], who consider stepped and scarf joints between an orthotropic and an isotropic plate, is extended by Reddy and Sinha[34] who consider the same joints but between two orthotropic plates. In both cases both plane stress and plane strain are considered, the results being roughly insensitive to these assumptions. It is shown that the maximum adhesive shear stress is less in the scarf joint and the highest adherend direct stress always occurs on the stiffer side of a joint with non-identical adherends. It is conculuded that the elastic properties of the adhesive largely determine the stresses within it.

Wah[35] uses the normal laminate constitutive equations to describe the cylindrical bending behaviour of the adherends in a single lap joint. Unlike the previous two papers the stresses in the adhesive are considered to vary across the thickness. Satisfaction of all the boundary conditions prove impossible without the imposition of an auxiliary problem involving fictitious stresses, although calculations suggest that this is not a significant effect. Also there appear to be computational difficulties in obtaining accurate stress values at the joint ends, arising from the solution of coupled second and fourth order differential equations.

For double lap joints Grimes[36] uses a shear-lag analysis in conjunction with classical lamination theory to support a largely experimental programme.

Sinha and Reddy[37] extend the work of Reddy and Sinha[34] to include the effect of stresses induced by the curing process. It is shown that a residual shear stress will exist in the adhesive making the critical end of the joint dependent on the direction of the applied load. Of the more general analyses the work of Allman[16], Srinivas[13] and Renton and Vinson[14] already mentioned above, includes joints with composite adherends.

Dickson[38] compare a general approach with that of Goland and Reissner[11] and show that neglecting through-thickness direct strains is likely to be most significant. The Goland and Reissner results are conservative. It is also shown that residual thermal strains can cause a large increase in adhesive shear stress.

Parametric studies[39] indicate the same trends as already outlined for metals. The adhesive stresses become less and more uniform as the adhesive moduli are reduced, the adherend stiffness is increased and the overlap length is increased. For composite adherends the ply lay-up and stacking sequence are additional variables. It appears that the lay-up has more influence on the adhesive peel stress than on the shear stress. Also for large overlaps adherend failure becomes increasingly likely.

Nonlinear analyses

An analysis which included through-thickness adherend strain as well as the nonlinear behaviour of the adhesive would almost certainly be too cumbersome to be useful. However, several authors have shown that the effects of nonlinearity are generally so much more significant than those due to trough thickness strain, that the latter are almost invariably ignored.

Dootson and Grant[40] and Grant[41] modify simple shear-lag theory, ie neglecting adherend bending, and account for nonlinear adhesive elastic properties. The governing equation is re-written in finite difference form and solved iteratively.

The prediction of failure load is based on a limiting value of the maximum adhesive shear strain.

Corvelli[42] also uses a simple linear analysis and modifies the results to account for adhesive nonlinearity. The maximum shear stress in the adhesive is obtained via a stress concentration factor which is dependent on the secant shear modulus at failure. A rigorous nonlinear analysis shows this modified linear approach to be acceptable.

In addition to adhesive nonlinearity, adherend bending and nonlinear elasticity is considered by Grimes[26.43]. Deformation theory of plasticity, based on a secant modulus, effective stress and a Ramberg-Osgood approximation to the stress/strain law, is used to account for nonlinear elasticity.

The work of Dickson[38] also accounts for adhesive nonlinearity by a variety of methods. They conclude that a technique based on numerical integration is prubably best although this is not pursued in detail. They also examine an approach similar to that used by Hart-Smith.

The most extensive work is that of Hart-Simth who analyses in detail double lap[44], single lap[45] and scarf and stepped joints[46]. This work is also presented in summary form[47]. Adhesive nonlinearity is based on an idealized, elastic/perfectly plastic (ie non-work-hardening), shear stress/strain curve as shown in Fig. 7a. For double lap joints[44] it is shown that the adhesive strain energy in shear is the only significant quantity affecting joint strength. By adjusting the elastic strain (γ_e) and keeping the maximum plastic strain (γ_p) the same for the actual and idealized states, as seen in Fig. 7, the strain energy is made the same for both cases. Thus, with the same adherends, all adhesives having the same strain energy, failure stress and failure strain will produce joints with identical strength provided the interfacial bond strength is unchanged. Increasing γ_p will increase the strength of the joint. The shape of stress/strain curve affects only distribution, along the joint, of adhesive shear stress. The analysis is similar to the classical work of Volkersen[10], but is unusual in including the effect of peel stresses. Thermal effects are also included in the analysis and it is shown that reduction in joint strength, due to thermal mismatch, increases as adherend thickness and/or stiffness increases. Also the critical end of the joint is different for tensile and compressive loading. Joints loaded in shear will have a lower load capacity than those loaded in tension since the strength depends on shear modulus rather than elastic modulus.

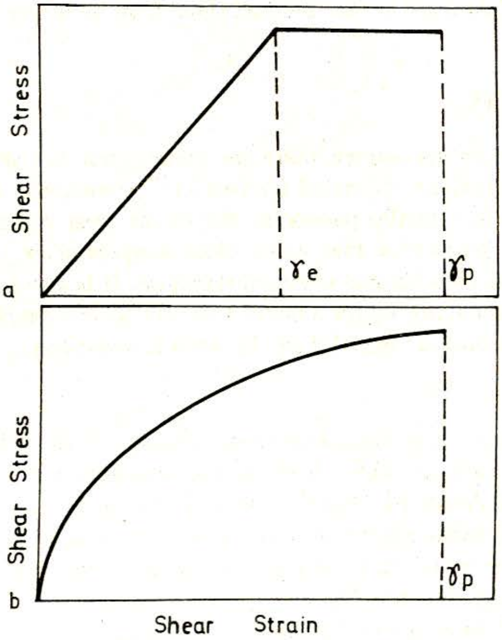

Fig. 7 – Adhesive shear stress/shear strain curve
a- Idealized elastic/perfectly plastic
b- Actual (Reference 50)

Hart-Smith's work on single lap joints[45] is based on that of Goland and Reissner[11] but corrects their value of adherend bending moment at the ends of the joint. Also unlike the work of Grimes[26] and Dickson[38] he considers both geometric and stress/strain nonlinearity. The shear behaviour of the adhesive proves to have little influence on joint strength, the latter depending largely on adherend properties and peel stresses. In contrast to double lap joints the overlap length has a significant effect of joint strength. Thermal effects are again shown to be important.

In analyzing scarf joints[46] Hart-Smith adopts a similar approach and obtains equations containing the same variables as for the double lap joint. It is shown that the adhesive stress is essentially uniform if the adherends are identical. If non-identical adherends are used the adhesive shear stress distribution becomes increasingly non-uniform as the mismatch between the extensional stiffnesses of the adherends becomes greater. The relative thermal mis-match can vary independently of the stiffness mis-match it is shown that the critical end of the joint depends on lap length. These effects are further complicated by the direction of applied load, thus if thermal effects alleviate stiffness mis-match for tensile load they will aggravate things for compressive load.

The analysis of stepped joints[46] ignores overall load eccentricity and also peel stress on the grounds that the end steps should be so thin that no significant peel stresses are induced.

The solution which is based on an iterative approach, proves to be very sensitive to the precision of the initial values. This largely a consequence of the physical behaviour of a stepped joint in that the first three steps dominate the load transfer process.

TEST RESULTS

Where test results are quoted these are usually, but not always, compared with theoretical predictions. As noted by Grimes[28] comparison between the various sets of results in virtually impossible due to the great variety of adherends, adhesives and joint geometries that exist. Most workers show the variation of joint strength with lap length and adherend thickness. It is also apparent that the lay-up and stacking sequence of the adherend, as well as the ductility of the adhesive, are extremely important and of these the latter is overriding.

Static tests

Theories, such as shear lag, which ignore bending of the adherends seem to agree well with test data o double lap joints, provided adhesive nonlinearity is accounted for. This is shown by Grant[41] for joints in CFRP, Corvelli[42] for joints between BFRP and metal adherends and Hart-Smith, who compares his theory with extensive experimental data presented by Lehman and Hawley[48] for a large variety of adherends, as shown in Fig. 8.

The need to include adherend bending in the analysis of simple lap joints is emphasized by the poor comparison between test and theory shown by Grant[41], using only a simple shear-lag analysis and, in contrast, the very good correlation demonstrated by Hart-Simth[47] as shown in Fig. 9.

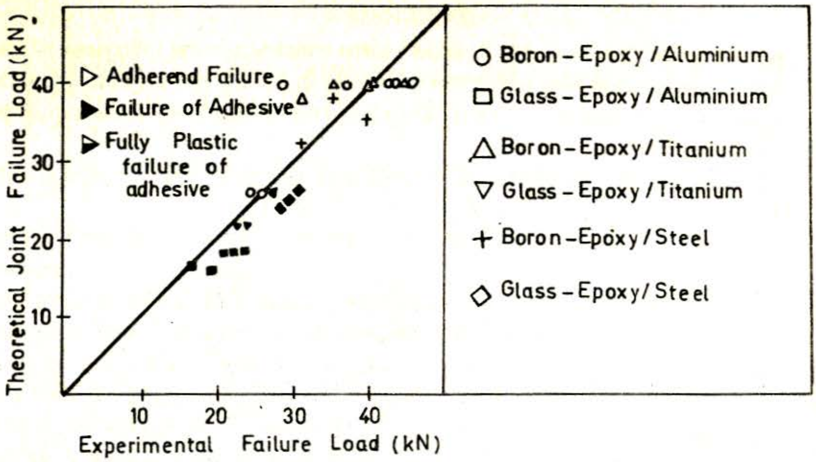

Fig. 8 – Comparison of theoretical and experimental failure loads for double lap joints (Reference 50)

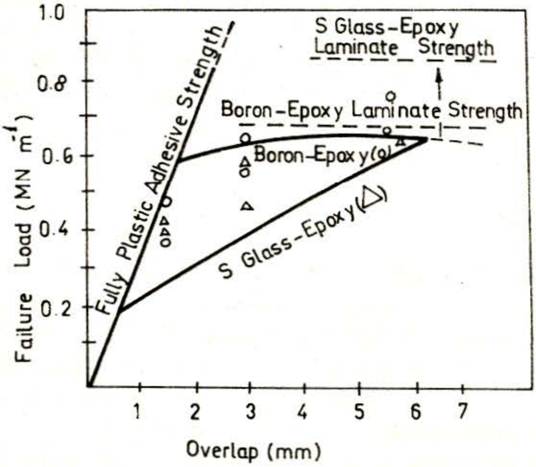

Fig. 9 – Comparison of theory and experimental for single lap joints at room temperature (Reference 50) Lay-up: (0°/± 45°/0°)

ADHESIVE PROPERTIES

As stated by Kutscha[2] and Kutscha and Hofer[4], among others, one the greatest draw backs to predicting the strength of bonded joints has been the lack of reliable data on the mechanical properties of adhesives. An extensive review of the methods available for mechanical testing is given by Niranjan[5], and a limited collection of data is in the MIL Handbook[48].

If correction is not made for Poisson's ratio constraints, the behaviour of the adhesive in thin layer form appears different to that in bulk form. Because of this it is often suggested that specimens for determining mechanical properties should be of thin-layer configuration.

There still remains the difficulty of obtaining the pure shear or pure tensile stresses needed to determine the corresponding properties.

A stepped single lap joint between thick stiff adherends is favoured by Renton[49] ve Guess[50] as a method for obtaining properties in shear. However, analyses show that even under these circumstances the shear stress in the adhesive is not uniform along the length of the joint. The apparent shear strength is seen to depend on the joint geometry. A preferable method, adopted by Sage[51] is probably the, so-called, napkinring test, in which the specimen is loaded in torsion. Even with this method pure torsion cannot be assured due to difficulties in aligning the two halves of the specimen. Whichever method is used the properties derived depend on the thickness of the adhesive layer which, it appears, is difficult to measure accurately.

The adhesive properties in tension are probably even less reliable than those in shear although, fortunately, their influence on joint behaviour is not so marked as are the shear properties. Butt joints between flat or ring specimens are the preferred methods and aligment appears to be more critical than for shear tests. Also the distribution of stress throughout the adhesive is certainly non-uniform, and the strains in the adhesive layer are too small to be measured accurately. In this case tests on bulk material are to be preferred. Kuenzi and Stevens[52] give detail of tensile, as well as shear, tests.

CONCLUSIONS

Clearly adhesive bonding is a viable technique for joining composite materials although the low interlaminar shear and tensile strengths limit the joint efficiency. Simple methods of analysis are valuable in pointing out the important parameters affecting joint strength. To predict failure loads it is essential that the nonlinear behaviour of the adhesive is accounted for. Also, thermal strains should be included in ony analysis. It is possible that, as a design tool, the finite element method may be too expensive when compared to classical analytical approaches. In general, joint strength is improved (stress reduced) as adherend stiffness is increased and adhesive moduli are decreased. Effort should be made, by tapering the adherends for example, to reduce peel stresses. A ductile adhesive is preferable to a brittle adhesive in that static and fatigue strength is increased although, of course, creep strength will be reduced.

ACKNOWLEDGEMENT

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