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Effects of Functionally Graded Adhesive on Failures of Double Lap Joint Made of Laminated FRP Composites

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Abstract: **-- The demand of modern industries to use lightweight assemblies has promoted the use of composite materials. Using traditional joining methods to assemble these materials leads to the introduction of stress concentrations which reduce the strength of the assembly. Adhesive bonding technique is used to overcome this limitation. Stress analysis carried out on double lap joint by previous researchers using mono adhesive layer indicates stress concentrations at the ends of the overlap. The present research is done in the view of reducing the stress concentration at the ends and thus increasing the joint strength. The greater adhesive shear strains at the overlap edges necessitate the use of more ductile adhesive at the edges and less ductile adhesive in the middle. This has been achieved by grading the adhesive layer from stiff in the middle to ductile at the ends using smooth and continuous gradation profiles. Three dimensional finite element analyses are carried out on the double lap joint and the stresses at the various interfacial surfaces have been determined. The onset of failure has been predicted using Tsai-Wu coupled stress failure criterion. The critical location has been found to be present between the main adherent and adhesive layer. The successive numerical simulations carried out using various modulus ratios indicate a considerable reduction in failure index at the critical locations. The results indicate an increase in joint strength using functionally graded adhesive than using mono adhesive layer.**

Index Terms**: Double lap joint, FRP composite, functionally graded adhesive, failure analysis.**

I. INTRODUCTION

Adhesive bonding is a material joining process in which an adhesive placed between the adherend surfaces solidifies to produce an adhesive bond. Adhesive bonded joints have advantage over other joining methods through lower structural weight, lower fabrication cost and improved damage tolerance. A major application of adhesive bonding is therefore found in joining of Fibre Reinforced Polymeric (FRP) composite materials which are widely used in composite structures. The traditional methods involve cutting of fibres, which cause introduction of stress concentrations thereby reducing structural integrity. Adhesive bonding has found applications in various areas from high technology industries, such as aeronautics, aerospace, electronics and automotive to traditional industries such as construction, sports and packaging. No matter what forms of connections are used in any structure, the joints are potentially to be considered as the weakest points. By the use of FRP composite materials, these weakest points increase, which may lead to the loss of structural integrity of the structure. Thus, adhesively bonded structural joints of FRP composite materials must be designed appropriately to meet the specific design requirements.

Safety considerations often require that adhesively bonded structures employed primarily in load-bearing applications, include mechanical fastners (e.g. bolts) as an additional safety precaution. These practices result in heavier and more costly components. The development of reliable design and predictive methodologies can be expected to result in more efficient use of composites and adhesives.

A simple shear lag model for adhesively bonded lap joints with the assumption that the adherends are in tension and the adhesive is in shear only and both stresses are constant across the thickness was presented for the first time in 1938 by Volkersen [1]. However Volkersen solution does not reflect the effects of adherend bending and shear deformation which is potentially significant for composite adherends with a low shear and transverse modulus and strength.

Goland and Reissner [2] extended this study by taking into consideration the effects of adherend bending leading to peel stress in adhesive layer in addition to shear stress. Hart and Smith [3] proposed a simple analytical model by considering that the adhesive layer has perfect elasto-plastic behaviour. He could show the maximum load that an adhesively bonded joint can transfer depends on the shear deformation energy of the adhesive layer, regardless of the stress-strain curve. This approach allows a better prediction of the mechanical behaviour of ductile adhesive layer. The low transverse stiffness that is often present as a result of the high and ultra-high modulus fibres combined with much lower modulus polymer resin is an important characteristic of adhesively bonded joints with composite adherends. Renton and Vinson [4] as well as Srinivas [5] accounted for these low transverse stiffness effects by including first order shear deformation in their analysis. Renton and Vinson [4] developed an analytical solution for a single-lap joint geometry that included shear deformation of composite adherends and determined the linear elastic response for the adherends and adhesive. Srinivas [5] developed a similar method for a single-lap and double-lap joint that included shear deformation as a part of analytical solution while attempting to approximate the non-linear geometric effects.

Tong [6] used a simplified one dimensional model as well as finite-element model to predict the strength of adhesively bonded double-lap composite joints. He showed that the failure loads predicted by the non-linear model were in good agreement with the measured failure loads, whereas those given by the linear model were about half of the measured loads. First, Hart-Smith [7] extended the elastic solution of Volkersen considering adhesive plasticity, adherend stiffness imbalance, and thermal mismatch between the adherends. He devoted a significant effort to the concept of using a high modulus adhesive in the central region of the joint and low-modulus adhesive in the outer regions where the relative displacements between the adherends exceed the strain capabilities of the high-modulus adhesives. He found that this concept had no practical merit in comparison to a ductile adhesive alone while it did offer advantages over a brittle adhesive alone, and by softening the end zones of the joint an increase in strength was obtained. Srinivas [5] showed that the maximum peel and shear stresses in the bond-line could be reduced by using a combination of flexible and stiff adhesives for single-lap, flush and double-lap joints, and advised a flexible and ductile adhesive around the free edges of the overlap region, where the peak stress occurs and a rigid and brittle adhesive in the middle of overlap region, where low stresses exist uniformly.

Pires et al. [8] used two adhesives with different stiffness's along the overlap region of an adhesive lap joint where a stiff adhesive was applied in the middle portion of the overlap and a less stiff adhesive was applied towards the edges prone to stress concentrations. The experimental, linear and non-linear analyses indicated a measurable increase in strength of the bi-adhesive bonded joints in comparison to those in which single adhesive was used over the full length of the bond line.

Fitton and Broughton [9] described a practical method for joint optimisation using an adhesive layer with variable modulus. They achieved significant changes in the failure modes and improvement in the joint strength of lap joints in comparison to a single-modulus adhesive which is typically used to bond unidirectional carbon fibre-reinforced plastics. They achieved most significant improvements in the joint strength whereas failure occurred in un-optimised single adhesive joints at stresses considerably less than the shear strength of the adhesive and were dominated by peel stresses.

Temiz [10] applied bi-adhesive concept to double-strap joints subjected to bending moments in order to reduce stress concentrations around the adhesive free edges with an expectation to increase the failure load levels of the adhesive joint. He used a stiff adhesive in the middle portion of the overlap and a flexible adhesive around the free edges of the overlap region, and his results showed that the adhesive joints with two different adhesives carried higher loads and had higher strength as compared to single-adhesively-bonded joints.

Kumar and Pandey [11] carried out two- and three-dimensional non-linear (geometric and material) finite element analyses of adhesively bonded single lap joints having modulus-graded bond line by modelling adhesives as an elasto-plastic multilinear material and the substrates as both linear elastic and bi-linear elasto- plastic material. The static strength was higher for joints with bi-adhesive bond lines compared to those with single adhesives in bond line, and a higher joint strength was possible for an optimum bi-adhesive bond line ratio.

From the above discussion it clear that the use of bi-adhesive in bonding of the double lap joint leads to reduction in stress concentrations at the overlap. In this paper this technique is implemented to further reduce the stress concentrations by using functionally graded adhesive with appropriate material gradation profile along the overlap length. Numerical simulations are successively carried out for functionally graded adhesive with various modulus ratios. Tsai- Wu coupled failure criterion is used to predict the location of damage initiation.

II. FINITE ELEMENT ANALYSIS

A. Modelling of double lap joint

The double lap joint specimen considered for the present analysis is shown in Fig.1. The length of joint is taken as L = 230 mm, top and bottom adherend thickness h1 = 2 mm, main adherend thickness h2 = 4mm, thickness of adhesive layer ta = 0.5 mm, width W = 20 mm, distance along the bond length 2c = 50 mm.

The top and bottom adherend is made up of [0]8 graphite/epoxy composite laminates and the main adherend is made up of [0]16 graphite/epoxy laminates. The thickness of each ply in all the adherends is taken as 0.25 mm. Mechanical properties of the composite laminates are given in Table I. Two types of adhesives are used in the present analysis. The first one is mono-modulus adhesive and the second one is functionally graded adhesive. The mechanical properties of the mono-modulus adhesive are given in Table II. The details of functionally graded adhesive is given in the next section.

Table I. Graphite/epoxy FRP composite lamina material properties [12, 13]

Elastic constants	
E_x	127.5 GPa
E_y	9.0 GPa
E_z	4.8 GPa
$\nu_{xy} = \nu_{xz}$	0.28
ν_{yz}	0.41
$G_{xy}=G_{xz}$	4.8 GPa
G_{yz}	2.55 Gpa
Strengths	
Z (interlaminar normal strength)	49.0 MPa
S (out of plane shear strength)	2.55 MPa

The joint is subjected to tensile load of 10 kN. In the present analysis three dimensional twenty-node layered volume element SOLID186 is used to model laminated FRP composite. The nodes at the location x = 0, are constrained by using the boundary condition, u = v = w = 0, where u, v and w are the displacements along x, y and z directions respectively.

B. Modelling of functionally graded adhesive layer

A number of adhesive layers with different values of elastic modulus have been created along the overlap length. This is done in such a way that the adhesive at the ends of the overlap is more ductile compared to the adhesive in the middle. The overlap length is divided into two regions. The smooth and continuous variation of elastic modulus have been expressed by the following linear profile,

$$E(\mathrm{m}) = E_1 + (\mathrm{E}_2 - \mathrm{E}_1)\frac{m}{c} \qquad (1)$$

$$E(\mathrm{m}) = E_2 + (\mathrm{E}_1 - \mathrm{E}_2)\frac{m}{c} \qquad (2)$$

Where m is the variable varies from 0 to c. Equation (1) is used to calculate material properties for overlap length ($90 < x < 115$). Similarly equation (2) is used for overlap length ($115 < x < 140$).

Table II. Epoxy adhesive material properties [12,13].

Elastic constants	
E	2.8 GPa
ν	0.4
Strengths	
Y_T	65.0 MPa
Y_C	84.5 MPa

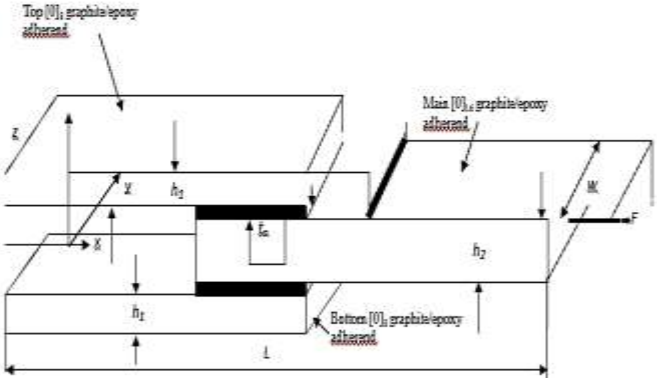

Fig.1. Double lap joint specimen of laminated FRP composites.

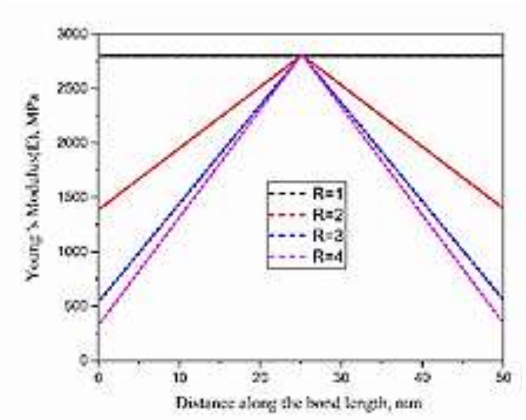

Fig.2. Elastic modulus gradation for different modulus ratio along bond length.

Material gradients have been evaluated in terms of modulus ratio *R*, expressed as,

$$R=\frac{E_2}{E_1} \tag{3}$$

The continuous variation of the elastic modulus with respect to the overlap length for different values of modulus ratio is shown in the Fig. 2. The upper bound elastic modulus E_2 is held constant, while the lower bound elastic modulus is varied according to the modulus ratio *R*.

III. DAMAGE PREDICTION IN DOUBLE LAP JOINT

The double lap joint bonded by adhesive experiences two types of failures; (i) adhesion failure which occurs the interfaces of the adhesive and the adherends and (ii) cohesion failure which takes place within the adhesive layer. Three surfaces are considered for the failure analysis, (i) between the top adherend and adhesive layer, (ii) main adherend and adhesive layer and (iii) within the adhesive layer. The damage onset is predicted on the three surfaces using Tsai-Wu coupled failure criterion. The failure surface in the stress space is represented in the following form:

$$f(\sigma_k) = F_i\sigma_i + F_{ij}\sigma_i\sigma_j = 1 \tag{7}$$

where *i*, *j*, *k* = 1,2,3……..,6 and F_i and F_{ij} are the strength tensors.

The out of plane peel and stress components are responsible for the initiation of failure in the double lap joint. Hence only these stress components are used to determine the failure index values *e* and are given by,
(i) Interfacial failure in tension for $\sigma_z > 0$

$$\left(\frac{\sigma_z}{Z_T}\right)^2 + \left(\frac{\tau_{xz}}{S_{xz}}\right)^2 + \left(\frac{\tau_{yz}}{S_{yz}}\right)^2 =^{e^2} \begin{cases} e \geq 1 & failure \\ e < 1 & no\ failure \end{cases} \tag{4}$$

(ii) Interfacial failure in compression, for $\sigma_z < 0$;

$$\left(\frac{\sigma_z}{Z_c}\right)^2 + \left(\frac{\tau_{xz}}{S_{xz}}\right)^2 + \left(\frac{\tau_{yz}}{S_{yz}}\right)^2 =^{e^2} \begin{cases} e \geq 1 & failure \\ e < 1 & no\ failure \end{cases} \tag{5}$$

Similarly the failure index at the middle of adhesive layer is evaluated by cohesive failure philosophy. As given by Adams [14] the parabolic yield criterion is used for the isotropic adhesive layer, which is expressed as

$$\begin{aligned} &(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \\ &+2(\left|Y_c\right| - Y_T)(\sigma_1 + \sigma_2 + \sigma_3) = 2\left|Y_c\right| Y_T e \end{aligned} \tag{6}$$

Using the equations (4) and (5) the failure indices have been evaluated at the interface between top adherend and adhesive layer and main adherend and adhesive layer. Equation (6) is used in evaluating the value of failure index at the adhesive layer. Thus, based on the magnitude of the failure index the critical location for the onset of damage is determined.

IV. RESULTS AND DISCUSSIONS

Three dimensional finite element analysis have been carried out on the double lap joint made of laminated FRP composites. Out-of-plane stresses (σ_z, τ_{xz} and τ_{yz}) are evaluated on various surfaces, (i) top adherend and adhesive layer, (ii) main adherend and adhesive layer and (iii) at the middle of adhesive layer. Tsai-Wu coupled failure criterion is used to evaluate the failure indices at the interfacial surfaces and the parabolic yield criterion is used to evaluate the failure index at the adhesive layer. The three dimensional nature of variation of the failure index along the overlap length for the critical surfaces of the double lap joint with mono modulus adhesive are shown in Fig.3 . It is observed that the peak value for the failure index occur for the surface between the main adherend and adhesive layer. Hence failure is likely to initiate from this location. The maximum value of failure index at the adhesive layer is less compared to that at other interfaces; hence cohesive failure will not take place.

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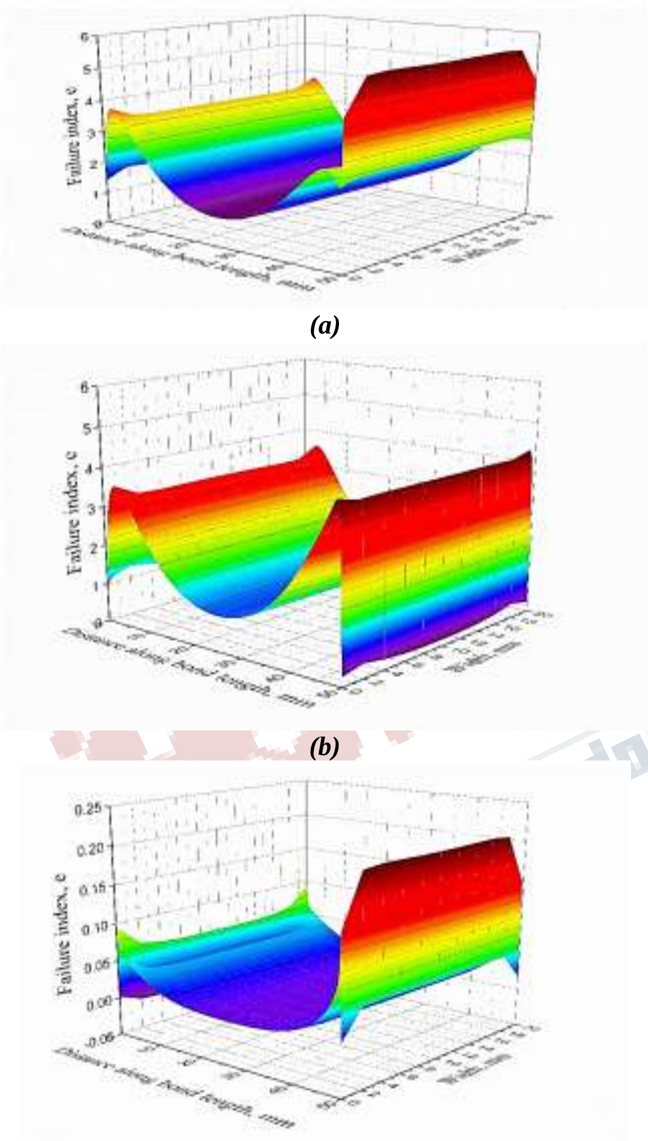
Using functionally graded adhesive with smooth and continuous gradation of elastic modulus along the overlap length the damage is attempted to mitigate. The variation of failure index along the overlap length with varied modulus ratio is shown in Fig.4. It is observed that there is considerable decrease in failure index with increase in modulus ratio, thus increasing the joint strength and delaying failure.



(a)

(b)

(c)

Fig.3. Variation of failure index e, along the overlap length of double lap joint: (a) at the interface of main adherend and adhesive layer, (b) at the interface of top adherend and adhesive layer, and (c) at the middle of adhesive layer

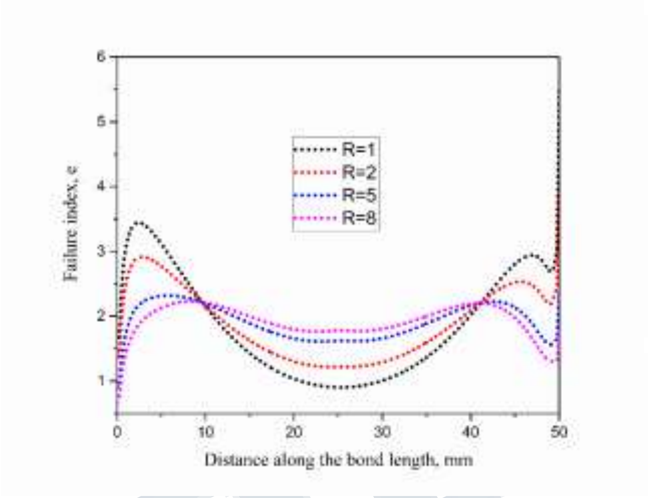


Fig.4. Effect of functionally graded adhesive with various modulus ratios on the failure index at the interface between the main adherend and adhesive layer

V. CONCLUSION

The numerical simulation carried out on double lap joint with functionally graded adhesive indicates considerable decrease in failure index at the critical layer thus, improving the joint strength. Hence the use of functionally graded adhesive is recommended for bonding double lap joint to increase the joint performance.

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