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Strength of Adhesive-Bonded Lap Joints in Composite Structures

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Abstract: Many fiber-reinforced composite structures are made up of a number of modules for ease of manufacturing and handling. Modular construction requires some form of jointing system that will transmit the applied loading between the different modules and give adequate performance over the service life of the component. This paper reviews the different analytical approaches used to study bonded joints and presents a simple analysis to predict failure loads for a specific type of bonded joints, namely the lap joint. The present analysis is compared with two more rigorous analyses and found to give good results. Experiments were also carried out on glass fiber specimens and it is concluded that the present approach compares well with test results.

Key Words: Bonded Joint, Lap Joint, Composite Joint

Introduction

Modern synthetic adhesives offer a jointing technique in a wide range of engineering applications. Recently, the use of these adhesives as a method of jointing parts made of fiber reinforced composite materials is escalating, especially in Glass Fiber Reinforced Polymers (GFRP).

The term "bonded joints" is used here to mean joints that are made between two fiber reinforced composite parts which have already cured.

Bonded joints have some advantages over other jointing techniques (such as mechanical connections where bolts and rivets are used). These advantages include: continuous input of load, absence of holes, fluid tightness, and elimination of stress concentration. However, the strength of bonded joint depends, to a large extent, on the skill and care of the workman and the quality of the joint. This presents disadvantage for bonded joints and requires careful attention during bonding.

This paper is concerned about one type of bonded joints, namely the single lap joints between two fiber reinforced composite parts as shown in Fig. 1. The theoretical analysis used here is based on the theory of elasticity. The experimental investigation is conducted on test specimens made of GFRP where the jointing is done by polyester resin.

Previous Investigations: Previous investigations of bonded lap joints fall into two classes: these based on the classical strength of materials and those based on fracture mechanics. The formers usually utilize a maximum stress or maximum strain failure criterion: Hart-Smith (Hart-Smith, 1985), for instance, proposed maximum strain criterion that has been used in the aerospace industry. Other examples of stress- or strain-based criteria are given in Refs. (Harris and Adams, 1984; Adams, 1986; Crocombe *et al.*, 1990; Pickett *et al.*, 1982; Chun and Sun, 1980 and Pickett and Hollaway, 1985).

The fracture mechanics of adhesive joints has been studied by many investigators (Hamaush and Ahmad, 1989; Mall and Johnson, 1986; Mall and Kochlar, 1988; Suo, 1990; Fernlund and Spelt, 1991; Groth, 1988; Fraisse and Schmit, 1993 and Fernlund *et al.*, 1994). According to Fernlund *et al.* (1994), however, many of these studies give contradictory results, and some of these suffer from the fact that they are too idealized and cannot be applied easily.

This paper is based on the theory of elasticity in which the strength of the bondline is predicted taking into account not only the properties of the adhesive, but also the properties of the adherends. The applicability of the present method is demonstrated with comparison between predicted and experimental results for single lap joint geometry.

Outline of the Method: The analysis is relatively simple and easy to use. It is based on the theory of elasticity where the equilibrium equations and strain compatibility conditions lead to one equation that gives the adhesive shear stress distribution.

Fig. 2 shows the three components of the joint drawn as free body diagrams. These are adherend 1 (of thickness t_1 and modulus in x-direction E_{x1}), adherend 2 (of thickness t_2 and modulus in x-direction E_{x2}) and the adhesive layer (of thickness t_a and shear modulus G_a).

Fig. 3 shows the equilibrium of an element of length dx taken from adherend 1 within the joint.

The equilibrium equation of this element gives:

$$\frac{\partial F_1}{\partial x} dx = \tau b dx \tag{1}$$

where b is the joint width (out of plane dimension) and τ is the adhesive shear stress. Equation (1) leads to:

$$\tau b = \frac{\partial F_1}{\partial x} \tag{2}$$

Similarly, for an element of adherent 2, Fig. 4, the following equation is obtained:

$$\tau b = -\frac{\partial F_2}{\partial x} \quad (3)$$

The overall equilibrium of the joint from x to the end of adherend I, Fig. 5, gives:

$$F_1 + F_2 = P \quad (4)$$

where P is the tension force applied to the joint.
The compatibility conditions, which exist in the displacements of the element of the joint, can be derived from Fig. 6 as follows:

$$t_a \frac{\partial \gamma}{\partial x} dx = (1+\varepsilon_1)dx - (1+\varepsilon_2)dx \quad (5)$$

or

$$\frac{\partial \gamma}{\partial x} = \frac{1}{t_a}(\varepsilon_1 - \varepsilon_2) \quad (6)$$

where the direct strains ε_1 and ε_2 and the shear strain γ are:

$$\varepsilon_1 = \frac{F_1}{bt_1E1}, \varepsilon_2 = \frac{F_2}{bt_2E_2}, \gamma = \frac{\tau}{G_a} \quad (7)$$

substituting from (7) into (6) and noting that τ is function of x only leads to:

$$\frac{d\tau}{dx} = \frac{G_a}{t_a}\left(\frac{F_1}{bt_1E_1} - \frac{F_2}{bt_2E_2}\right) \quad (8)$$

From (1):

$$\frac{d\tau}{dx} = \frac{1}{b}\frac{\partial^2 F_1}{\partial x^2} \quad (9)$$

Substituting from (4) and (9) into (8) gives:

$$\frac{\partial^2 F_1}{\partial x^2} - \lambda^2 F_1 = -aP \quad (10)$$

where:

$$a = \frac{G_a}{t_a t_2 E_2} \quad (11)$$

$$\lambda^2 = \frac{G_a}{t_a}\left(\frac{1}{t_1E_1} + \frac{1}{t_2E_2}\right) \quad (12)$$

The solution of (10) is:

$$F_1 = C\cosh\lambda x + D\sinh\lambda x + \frac{aP}{\lambda^2} \quad (13)$$

in which C and D are determined from boundary conditions. These conditions are: $F_1=0$ when x = 0 and $F_1= P$ when x = L.
Using these conditions and also equation (1) the following equation is obtained which gives the adhesive shear stress distribution:

$$\tau = \frac{P}{b}\left[\left(\lambda + \frac{a}{\lambda} + \frac{a}{\lambda}\cosh\lambda L\right)\frac{\cosh\lambda x}{\sinh\lambda L} - \frac{a}{\lambda}\sin\lambda x + \frac{a}{\lambda^2}\right] \quad (14)$$

Experimental Investigation: The experimental investigation was conducted on specimens made of glass fiber reinforced polyester. The adhesive used is also polyester resin. A total of 30 specimens were tested. All specimens were made of the same fiber and resin and were bonded using the same adhesive. The adhesive properties were supplied by the manufacturer and they were G_a=1.35 GN/m^2 and S=28.9 MN/m^2 where S is the ultimate shear stress. The composite properties were calculated from the lamination theory and were also obtained from simple tension tests carried out on specimens made of the same material. The modals of elasticity in the x-direction for the composite was found to be E_x=40.9 GN/m^2. The two adherends for all specimens were of the same material, same thickness and same fiber stacking and orientation. The average thickness was 12 mm for the adherends and 0.1 mm for the adhesive. The specimen width b and the bonded length L were slightly different from one batch to another, but they were in around b=40 mm and L=25 mm as will be detailed later.

Results and Discussion

'The adhesive shear stress distribution along the bonded length as given by equation (14) is shown in Fig. 7.
The stress distribution is given in a normalized manner where it is divided by the average shear stress which is given by:

$$\tau_{av} = \frac{P}{bL} \quad (15)$$

The Fig. is drawn for the data given in paragraph (4) above.
The results of finite element analysis (Pickett and Hollaway, 1985) are also shown in the same figure for comparison. Also shown in the same figure are the results taken from complicated analysis (Pickett and Hollaway, 1985) called flexible joint analysis in which the overall joint bending deformations are taken into account. This figure shows that the present simple analysis gives good comparison with both the finite element analysis and the so called flexible joint analysis.
It is clear from Fig. 7 that the present analysis predicts higher maximum adhesive shear stress than the other two analyses, hence it is conservative.
If τ in equation (14) is replace by S, the ultimate shear stress for the adhesive, and the equation is inverted, then the applied tension load, P, that causes failure of the joint can be predicted. It is clear from Fig. 7 that the maximum shear stress occurs at x=0 or

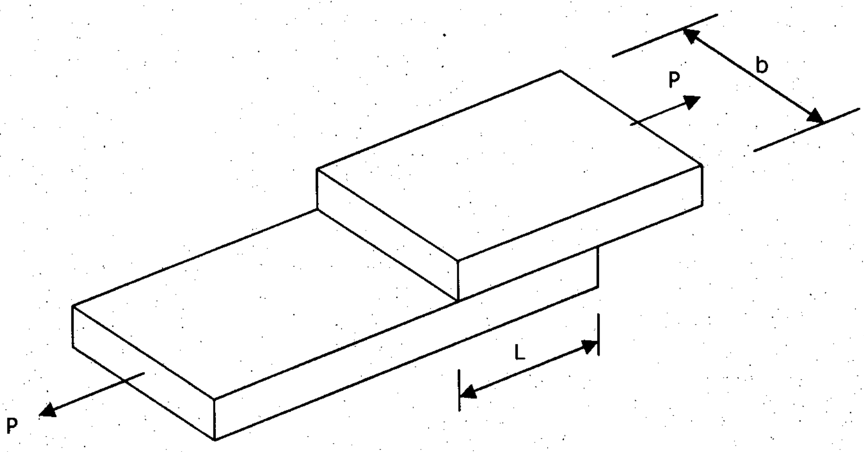

Fig.1: Single Lap Joint

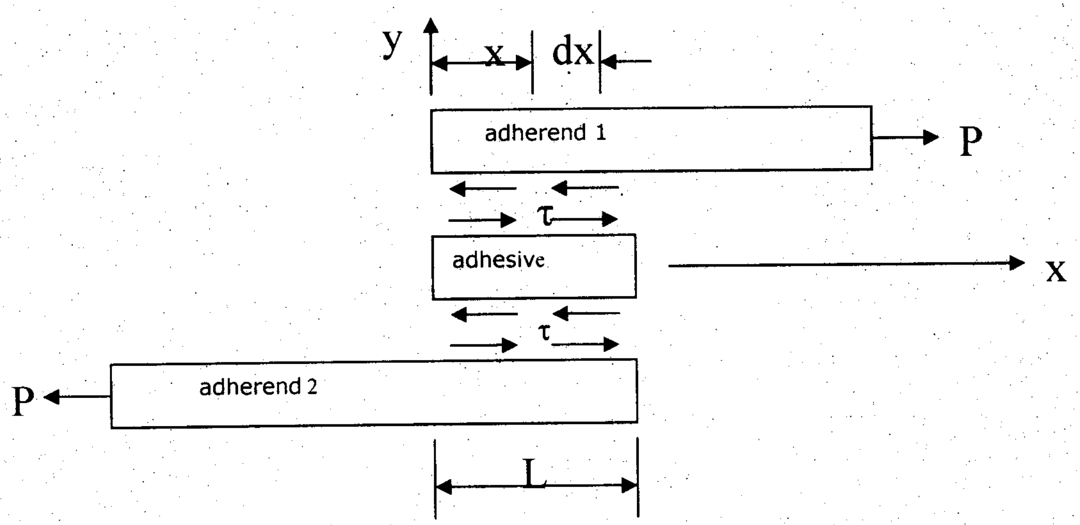

Fig. 2: Free Diagrams of Joint Components

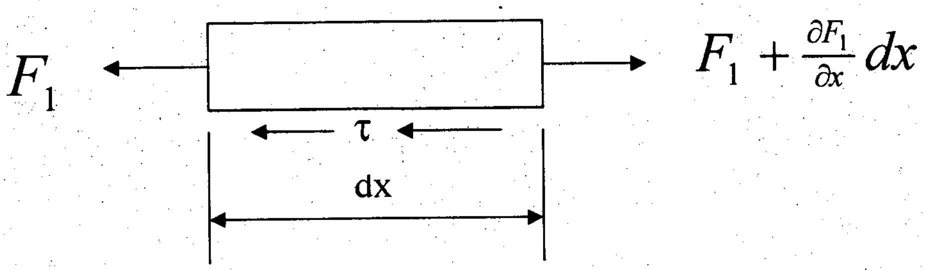

Fig. 3: Equilibrium of Element of Adherend 1

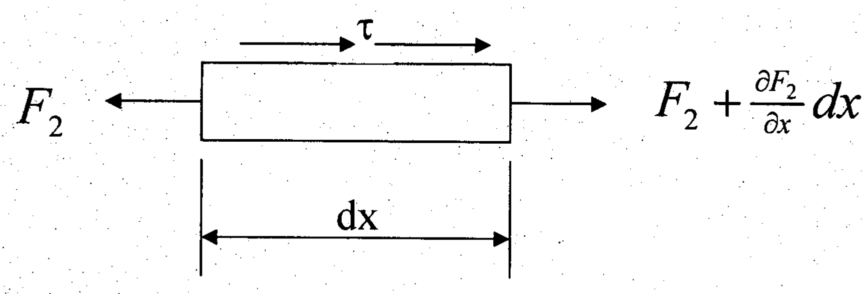

Fig. 4: Equilibrium of Element of Adherend 2

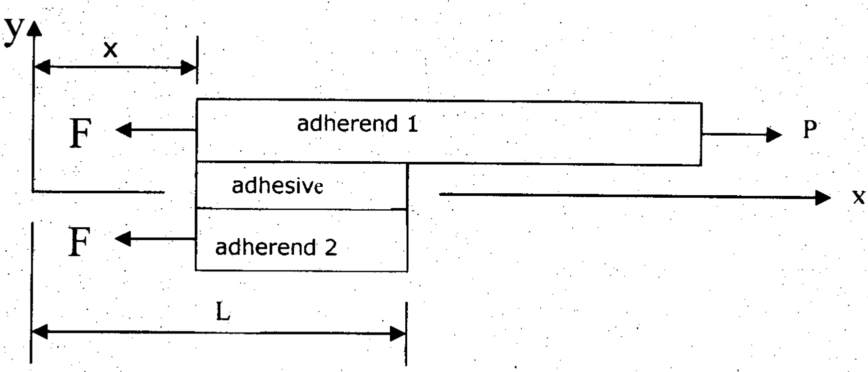

Fig. 5: Overall Equilibrium

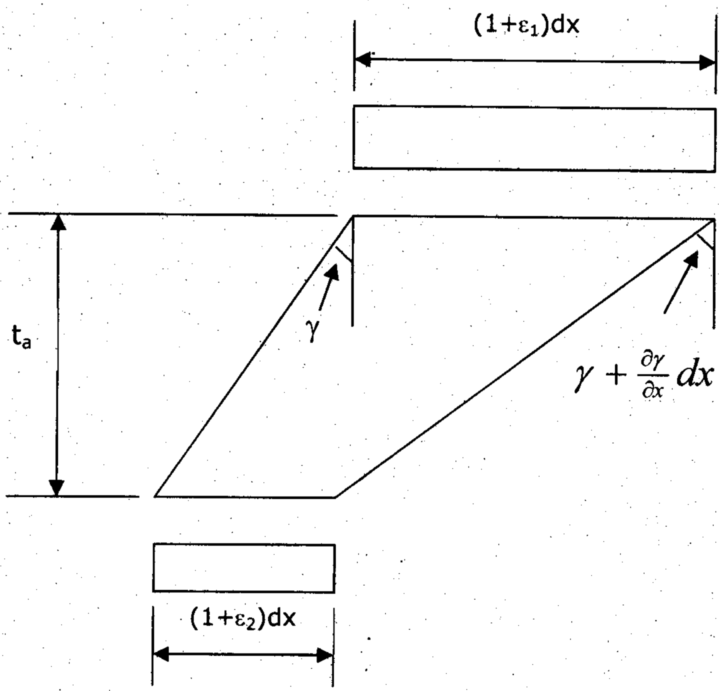

Fig. 6: Compatibility Conditions

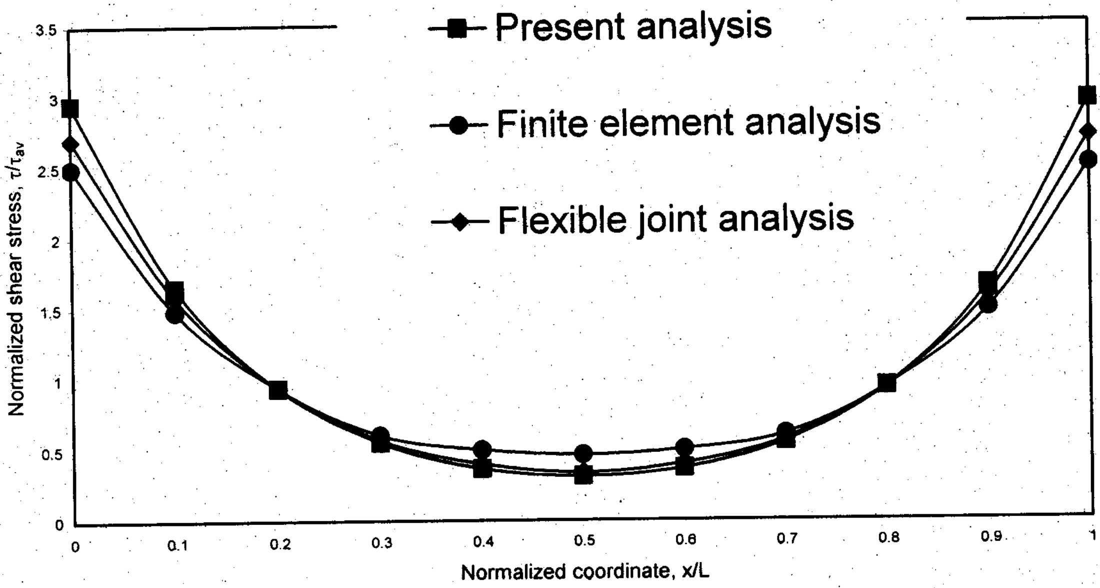

Fig. 7: Shear Stress Distribution

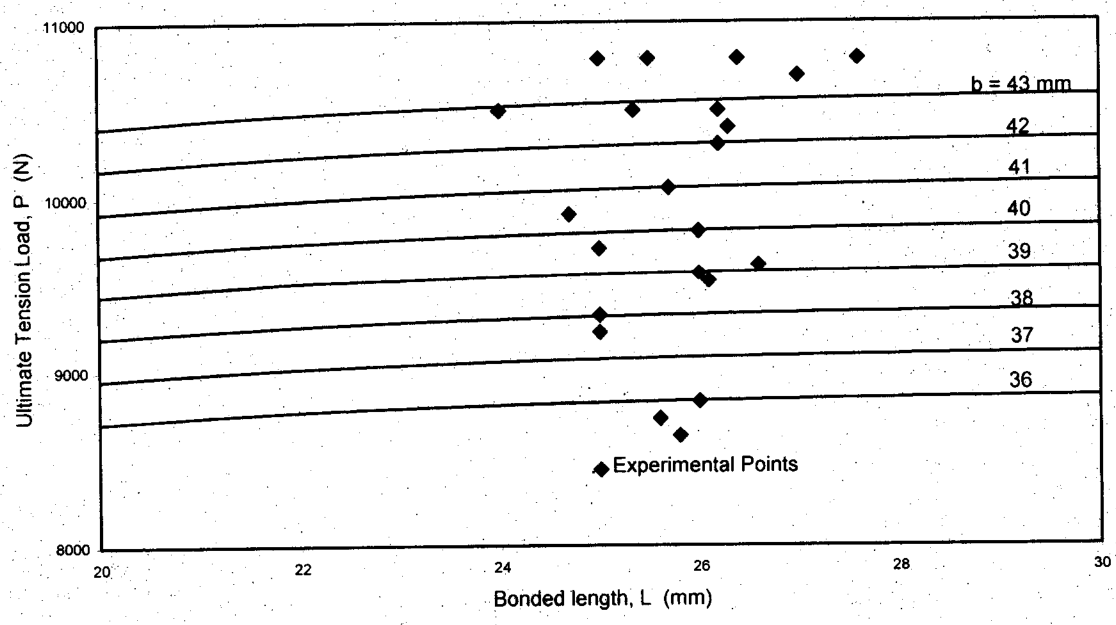

Fig. 8: Ultimate Tension Load

x=L for the joint geometry under consideration. If, however, some factor of safety is used for S, the inverse of equation (14) gives the allowable applied load that can be used safely on the bonded joint without causing failure.

Fig. 8 shows the predicted ultimate tension load, P, that causes failure in the joint as function of the bonded length, L, and the specimen width, b.

The experimental results obtained from the present work are also shown on the same figure. The experimental results are scattered around the theoretical results, and in some cases the experimental results are higher than the predicted results. The reason for this is that the predicted failure load was based on the ultimate shear stress as compared with the maximum shear stress from the distribution of Fig.

7, which occurs at x=0 and x=L. Clearly, when the stress at these regions reaches its maximum valve the stress away from there will be much lower. On the other hand, it has already been pointed out that the present analysis is conservative in predicting the maximum shear stress as compared with the finite element method.

There are some specimens, however, failed at loads lower than the predicted loads. The reason for this is the quality of the bond. The specimens were bonded manually and therefore the quality of the bond depends very much on the skill and care of the technician who produced the specimens. However, overall comparison shows that the present analysis gives fair results.

Conclusion

The present simple analysis for prediction of failure load in single lap bonded joints was found to correlate well with two more rigorous analyses, namely the finite element analysis and the flexible joint analysis. The present approach was also found to correlate well with experimental data.

The closed form nature of the present solution as compared with the other two solutions makes it well suited to the design of bonded joints. The finite element analysis requires too much input of data and may require long run-time on the computer. The flexible joint method, being complicated, requires numerical solution of the governing differential equations, which also necessitates using of computer. The present approach is, therefore, computationally much faster.

However, discrepancies in the predicted results and test results are noted, and these were attributed to the quality of the bonded joints which was noted to be only fair.

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