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Analysis of adhesively bonded triple stepped lap joint in laminated FRP composites subjected to longitudinal loading

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ABSTRACT

The present investigation deals with the static analysis of adhesively bonded triple stepped lap joint in laminated FRP composites using three-dimensional theory of elasticity based finite element method. The finite element model is validated with the available results in the literature for the longitudinal loading of a triple stepped lap joint made of isotropic materials and is extended for the analysis of a triple stepped lap joint made of generally orthotropic laminates subjected to longitudinal loads. Maximum stresses in FRP adherends and Adhesive are computed and the effect of fiber angle on these stresses is studied. The results of the present analysis reveals that the three-dimensional stress analysis is required for the analysis of triple stepped lap joint in laminated FRP composites.

Introduction

Fiber reinforced plastic (FRP) materials have proven to be very successful in structural applications. They are widely used in the aerospace, automotive and marine industries. FRP materials or composites behave differently than typical metals such as steel or aluminum. A typical composite contains layers of aligned fibers oriented at different angles held together by a resin matrix, giving high strength and stiffness in different directions. This anisotropy can cause difficulties when joining two parts together, especially if the two pieces have different stiffness and strength characteristics. The joint can potentially become the weakest link in the structure due to the large amount of load it must transfer. There are wide varieties of ways to join different parts together. Two major methods include mechanical fastening and adhesive bonding. Adhesive bonding of structures has significant advantages over conventional fastening systems. Bonded joints are considerably more fatigue resistant than mechanically fastened structures because of the absence of stress concentrations that occur at fasteners. Joints may be lighter due to the absence of fastener hardware. A major advantage of adhesive bonds is that adhesive bonds may be designed and made in such a way that they can be stronger than the ultimate strength of many metals in common use for aircraft construction.

Delale et.al (1) developed a closed form solution for lap-shear joints with orthotropic adherends using classical plate theory. Nageswara et.al (2) showed that a uniform shear stress distribution occurs with a suitable adhesive thickness along the overlap length of an adhesive single-lap joint except on the free edges. Adams (3,4) predicted strength for lap joints especially with composite adherends by classical linear elastic solution. He also introduced Volkerson's shear lag equation that calculates shear stress in the adhesive. Hart-Smith (5,6) in his extensive work on bonded joints has outlined various aspects of efficient bonded joint design in composite structures that an airframe designer should consider while designing bonded joints between components. He has also made many useful studies to analyse the load transfer mechanism in the adhesive bonded joints and outlined some practical ways to minimize the transverse shear and peel stresses in the adhesive layer. Tsai and Morton (7) stressed that apart from the fillet effect, nonlinear deformation also plays a part in the adhesive stress concentration. Kairouz and Cook (8) investigated the influence of bond line thickness and overlap length on the strength of bonded joints.

Huang et.al (9) has developed an analytical model to determine the stress and strain distributions of single lap adhesive bonded composite joints under tension. They have used laminated plate theory in defining the mechanical behavior of the composite adherends. Li et.al (10) considered the geometrical non-linear effects on the adhesive stress and strain distribution across the adhesive thickness in a composite single-lap joint. They showed that the tensile peel and shear stresses at the bond–free edges changed significantly across the adhesive thickness and became increasingly higher with distance from the center line and the peak near, but not along, the adherend-adhesive interface. Tsai (11) and Morton analyzed a single-lap joint with laminated polymeric composite adherends and with a spew fillet, subjected to tensile loading. They used finite element analysis for this problem to address the mechanics and deformation of such a material and bonding configuration. Tong (12) investigated the strength of adhesive bonded composite double-lap joints. Due to the fact that failure often occurs at the resin-fiber interface adjacent to the adhesive. Tong used a simplified I D model as well as a finite element model in conjunction with several existing and new interlaminar failure criteria to predict the strength of joints. Magalhaes, de Moura, Gon calves (13) presented a two dimensional finite element analysis of composite bonded single-lap joints. They have placed the interface finite elements between the adherends and the adhesive, at the mid plane of the adhesive. The main objective of the interface elements is to obtain stress fields at interfaces between different materials, which is not possible with conventional solid finite elements. They have calculated the

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normalised shear and peel stresses at those interfaces. Panigrahi and Pradhan (14) has developed a three dimensional finite element analysis to compute the out-of-plane normal and shear stresses in an adhesive bonded single lap joint made of specially orthotropic laminates subjected to longitudinal loading. They proved that the three dimensional effects exists in the joint. They also found that the peel stresses are extremely sensitive to the three dimensional effect, but the shear stresses are not.

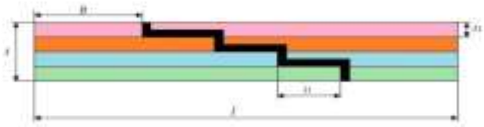
Very few works appear to have been made on the performance of triple stepped lap joint in isotropic materials. No significant work has been reported for the analysis of triple stepped lap joint in FRP composites. In this paper, attempts are made to study the stresses and deformation characteristics of adhesive bonded triple stepped lap joint made of generally orthotropic laminates (FRP) subjected to Longitudinal loading.

The objective of the present paper is to study the three-dimensional stress analysis of adhesive bonded triple stepped lap joint subjected to longitudinal loading with C-F end conditions. The analysis includes the evaluation of normal and shear stresses in the adherends and adhesive of the joint.

Problem Modeling

Geometry.

The geometry of the triple stepped lap joint used is shown in Fig. 1 where the dimensions are taken as $t = 10$ mm, $t_1 = 2.5$ mm, $l = 100$ mm and $l_1 = 16.67$ mm. The width of the plate in the third direction is taken as 25 mm.



All dimensions are in mm

Fig. 1 Geometry of triple stepped lap joint

Finite Element Model

The finite element mesh is generated using a three-dimensional brick element 'SOLID 45' of ANSYS [15]. This element (Fig. 2) is a structural solid element designed based on three-dimensional elasticity theory and is used to model thick orthotropic solids. The element is defined by 8 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions.

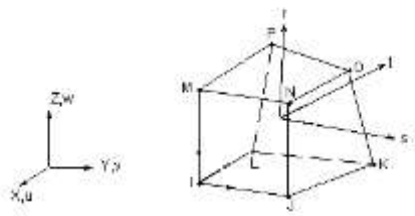


Fig. 2 SOLID 45 Element

Loading and Boundary Conditions

One end of the Joint is fixed and a longitudinal uniform pressure of 19.6MPa is applied at the other end

Material Properties

The following mechanical properties are used for the validation purpose.

Adherend (carbon steel)

Youngs Modulus (E) =206 GPa,

Poissons Ratio (ν) =0.33

Adhesive (Epoxy resin)

Youngs Modulus (E) =3.33 GPa,

Poissons Ratio (ν) =0.34

The following mechanical properties are used for the analysis of triple stepped lap joint.

i) Graphite/epoxy FRP (adherend)

$E_L = 172.72$ GPa; $E_T = 6.909$ GPa; $\nu_{LT} = \nu_{LZ} = 0.25$;

$G_{LT} = 3.45$ GPa; $G_{TT} = 1.38$ Gpa

ii) Epoxy (adhesive)

Youngs Modulus (E) =3.33 GPa,

Poissons Ratio (ν) =0.34

Laminate sequence

Two $+\theta^0/-\theta^0/-\theta^0/+\theta^0$ laminated FRP composite plates are used as adherends for the present analysis. The value of θ is measured from the longitudinal direction of the structure (x-axis) and varied from 0^0 to 90^0 in steps of 15^0.

Results

Validation

Fig. 3 shows the finite element mesh on the overlap region of the triple stepped lap joint. The present finite element model is validated by comparing the stresses obtained for the longitudinal uniform pressure loading in the adhesive region. Table 1 shows the values of the stresses at various steps of the triple stepped lap joint and close agreement is found. Later this model is used for the analysis of triple stepped lap joint of specially and generally orthotropic laminates subjected to longitudinal loading.

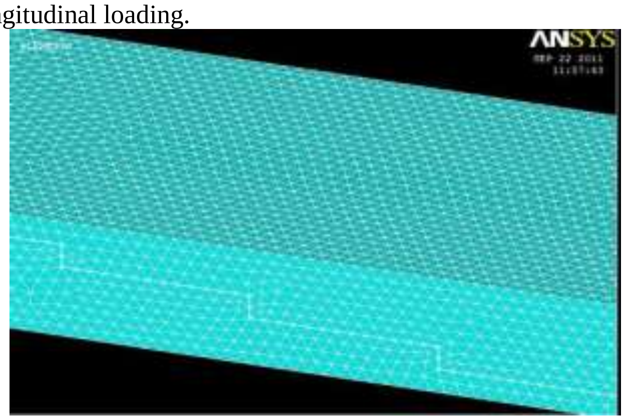


Fig. 3 Finite Element Mesh of Triple Stepped Lap Joint

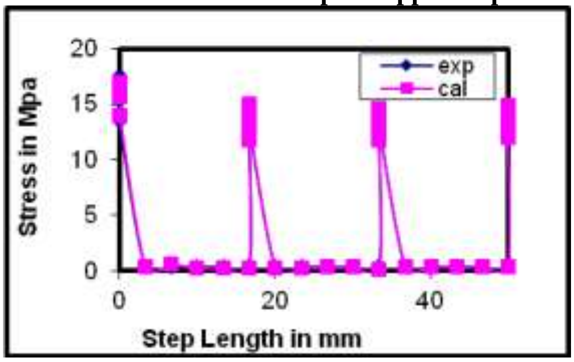


Fig. 4 Validation Graph

Variation of the stresses along steps of triple stepped lap joint

Figs. 5-8 show the variation of longitudinal normal stress (σ_{xx}) in the adhesive portion along the overlap region of the joint for four different thickness values of adhesive. It is observed that this stress is maximum near the ends, which drastically falls in other portion of each step. The un-symmetry in variation of the stress within the step may be due to the nature of constraints and loading. It is also observed that this stress increases with increase in fiber angle. This is due to the reduction in mismatch of longitudinal stiffness of adhesive and adherends.

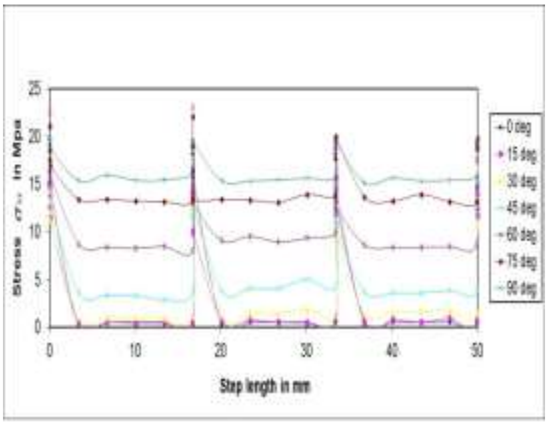


Fig: 5Variation of σ_{xx} along Step Length for Adhesive thickness of 0.05 mm

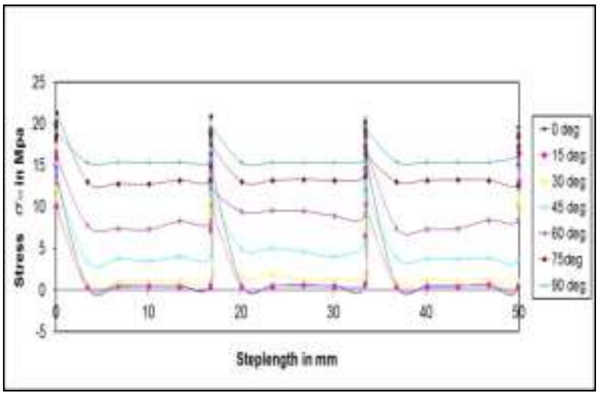


Fig:6 Variation of σ_{xx} along Step Length for Adhesive thickness of 0.1 mm

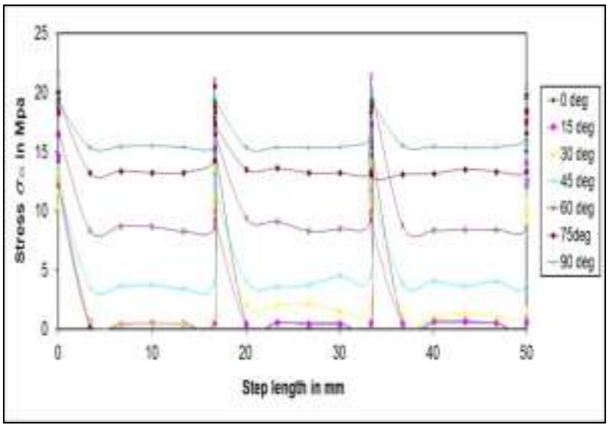


Fig:7 Variation of σ_{xx} along Step Length for Adhesive thickness of 0.15 mm

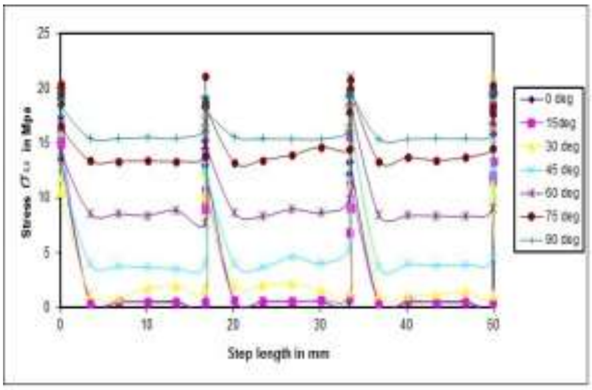


Fig:8 Variation of σ_{xx} along Step Length for Adhesive thickness of 0.2 mm

Variation of the maximum stresses with respect to the fiber angle θ

Figs. 9 to 14 show the variation of magnitude of maximum stresses in adherends with respect to the fiber angle in the laminate. In-plane normal stresses and shear stresses increase up to 45^0 of θ followed by a drop except τ_{xy} for 0.2 mm thickness which continuously increases with θ. Out of plane normal stress increases up to 60^0 of θ and later decreases. The variation of stresses is due to the variation in internal stiffness in the adherends due the change in fiber angle. The interlaminar effects at the interfaces of adherends also influences the stresses.

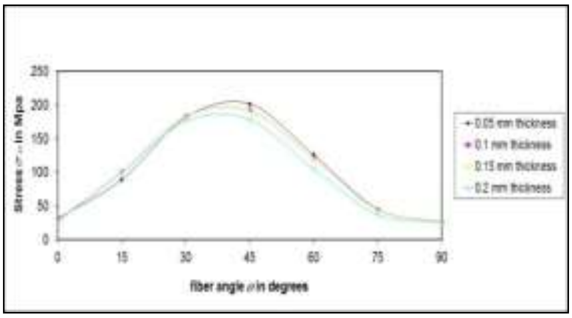


Fig:9 Variation of σ_{xx} w.r.t θ

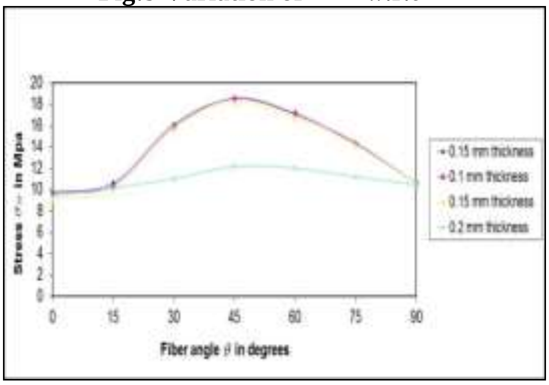


Fig:10 Variation of σ_{yy} w.r.t θ

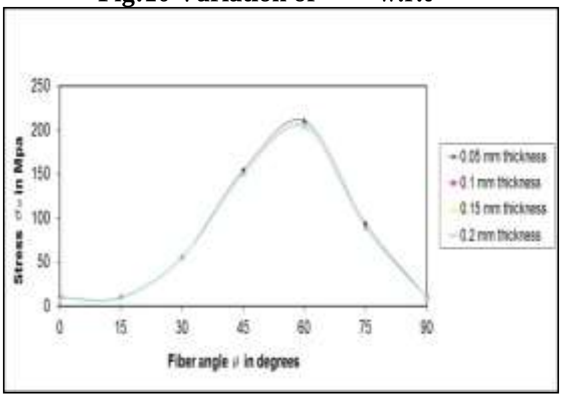


Fig:11 Variation of σ_{zz} w.r.t θ

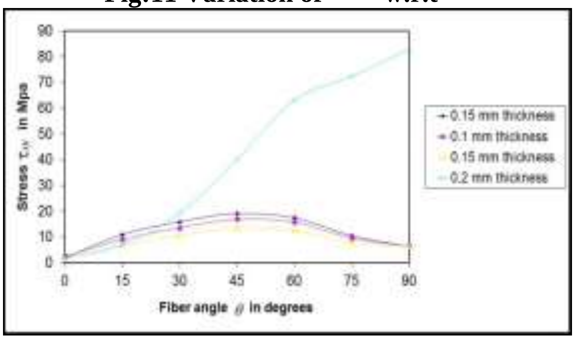


Fig:12 Variation of τ_{xy} w.r.t θ

Validation table: 1

0-0		0-1		1-1		1-2		2-2		2-3		3-3	
cal	exp	Cal	exp	cal	exp	cal	exp	cal	exp	cal	exp	cal	exp
17.0	17.5	0.3	0.4	11.7	12.8	0.2	0.4	11.7	12.8	0.3	0.4	13.0	12.8
16.5	16.5	0.6	0.4	14.8	13.5	0.2	0.4	14.8	13.5	0.4	0.4	13.8	13.5
16.9	15.4	0.2	0.4	15.0	14.2	0.3	0.4	14.7	14.2	0.4	0.4	14.8	14.2
15.7	14.2	0.31	0.4	13.9	13.5	0.3	0.4	13.8	13.5	0.3	0.4	13.1	13.5
13.9	13.5	0.3	0.4	12.9	12.8	0.2	0.4	12.8	12.8	0.3	0.4	12.0	12.8

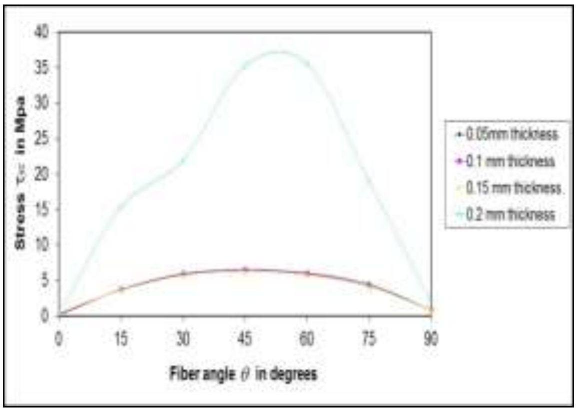


Fig:13 Variation of τ_{yz} w.r.t θ

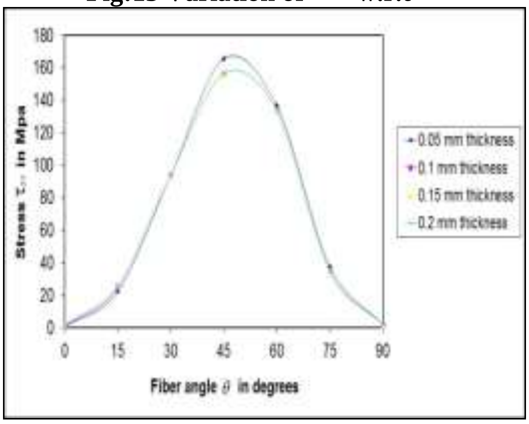


Fig: 14Variation of τ_{zx} w.r.t θ

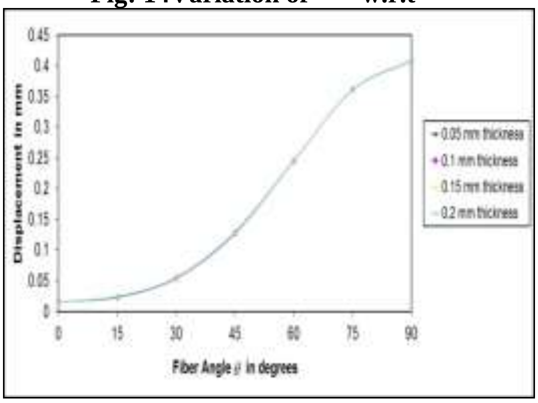


Fig:15 Variation of Displacement w.r.t θ

Conclusions

Three-dimensional finite element analysis has been taken up for the evaluation of the stresses in adherends and adhesive in Tripple stepped lap joint made of FRP laminates of generally orthotropic nature subjected to longitudinal loading. The following conclusions are drawn:

- Variation of the stresses in the width direction is significant and therefore three- dimensional analysis is necessary.
- Maximum intensity of longitudinal normal stress σ_{xx} is found between 15^0 and 45^0 which results in interfacial failure. The fiber angle range from 0^0 to 15^0 or 75^0 to 90^0 is recommended as the stresses are observed to be minimum in that range.
- It is also observed that the coupling effect in the laminate influences the deflection and stresses, and causing for the increase in their magnitudes up to some value of fiber angle and then decreasing of the values later.
- The displacement of the structure is increasing with the increase of fibre angle θ for longitudinal loading

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