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Stress distribution of adhesively bonded double lap joints in FRP laminated composites using FEM

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Abstract
Adhesively bonded joints are increasingly being used in joining various structural components made of FRP laminated composites. Adequate understanding of the behavior of adhesively bonded joints is necessary to ensure efficiency, safety and reliability of such joints. While single lap joint has received considerable attention, very little work has been carried out on the double lap joint configuration. The present investigation deals with the static analysis of adhesively bonded double lap joint in laminated FRP composites using three-dimensional theory of elasticity based finite element method. The finite element model is validated with the theoretical concepts. The double lap joint made of generally orthotropic laminates subjected to longitudinal loading is analyzed. The out-of-plane normal and shear stresses are computed at the interfaces of the adherend and adhesive, and at mid surface of the adhesive for different ply orientations in the double lap joint are considered for the analysis. It was predicted that when the fiber angle increases the stiffness of the plate in the longitudinal direction decreases and the interlaminar stresses at joint interfaces increases due to the effect of coupling and also the longitudinal displacement increases.

Keywords: Double lap joint (DLJ), Finite element method (FEM), Fiber-reinforced polymer (FRP), interlaminar stresses, Adhesive thickness.

1. Introduction
Fiber-reinforced polymer (FRP) composites are increasingly replacing metals in primary load-carrying members, resulting in many advantages, but also introducing new challenges. Because no structure is built as a single monolithic unit, various members must be joined adequately to ensure the structure's safety and performance. Unlike metals, structural thermoset-FRP members cannot be welded, and lack the ductility needed for efficient mechanical fastening, making adhesive-bonding the only efficient alternative. However, an adequate understanding of the behavior of adhesively bonded joints is necessary to ensure not only efficiency, but also safety and reliability.

The overwhelming majority of the work on the subject of adhesive bonding has focused on the single-lap configuration. The use of mechanical fasteners to join composite structures is widespread in the aerospace industry. The tolerance to environmental effects, the ease of inspection and assembly, and the possibility of part replacement are the main advantages of this technique. However, even for optimized combinations of laminate lay-up, stacking sequence and joint geometry, low efficiencies, defined as the ratio between the notched and unnotched strength of the laminate, occur. The low efficiency is due to high stress concentrations, and to the brittle nature of most fiber-reinforced composites. Low efficiencies lead to weight and cost penalties in composite structures.

In adhesive bonding, two parts or substrates are joined by some kind of adhesive in several configurations. In general, loads are transferred from one substrate to another by shear stress. However, since in most cases loads are not applied concentrically with the joint, moment can create normal stress in joint, resulting in lower strength. This problem can be eliminated by using double lap joint, which transfer force only by shear stress. In general, adhesive bonding can fail in four modes- failure of the adherend, Shear strength failure of the adhesive, a mode associated with the failure of the adhesive under a peel load and failure by delaminations of the fibrous composite adherends. Adhesive bonding has many advantages over mechanical joints. First, since the load is distributed over an area of adhesive bonding, this results in a more uniform distribution of stresses and higher resistance to flexural, fatigue, and vibrational stresses. Second, it is more applicable to join irregular surfaces than mechanical joints. Third, it is less expensive and faster than mechanical joints. 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.

The stresses induced at the interfaces of the adherends and adhesive play an important role in the design of adhesively bonded joints in FRP composites. Hence, these stresses are required to be analyzed most accurately. The behavior of idealized bonded joints such as double-lap shear joints was first studied by Volkersen [1]. He developed simple closed-form solutions for the shear stress distribution in the adhesive bondline assuming the shear deformations to be confined to the adhesive bondline while the adherends deform in response to a tensile load only by stretching. This provided useful insight into the fundamental behavior of bonded joints. Later, it was realized that, in particular for single-lap joints, the deformations of the adherends are not only axial, and that bending offered by the eccentric nature of lap joints causes transverse tensile stresses at the edges of the bondline. Goland and Reissner [2] took into consideration the effects of the adherends bending and the peel stress, as well as the shear stress, in the adhesive layer in a single lap joint. Hart-Smith [3, 4] modified the shear lag model to include the adhesive plasticity. Kim and Kedward [5] used finite difference method for the analysis of adhesively bonded joints. Penado and Dropek [6] used finite element method for the analysis of adhesively bonded joints. Abdolmajid and Tahani [7] developed an analytical method for stress analysis of symmetric adhesively bonded homogeneous and heterogeneous double-lapjoints (DLJs).They studied the effect of inhomogeneity of the adherends on distributions of interfacial peel and shear stresses along the length and through the thickness of the bonding regions. Adams and Peppiatte [8] analyzed a bonded joint using a two dimensional linear elastic finite element method with plane strain assumption. Panigrahi and Pradhan [9] studied a single lap joint with the adherends made of especially orthotropic laminates for the evaluation of the tri-axial stress field using finite element analysis and proved the necessity of three-dimensional stress analysis of single lap joint. Panigrahi and Pradhan [10] carried out Three-dimensional non-linear finite element analyses for graphite/epoxy laminated FRP composite double lap joints to study the onset and growth of adhesion failure and delamination induced damages. Panigrahi and Pradhan [11] carried out Three-dimensional non-linear finite element analyses to study the effects of through-the-width delaminations on delamination damage propagation characteristics in adhesively bonded single lap laminated FRP composite joints. Ascione [12] presented a numerical investigation on double-lap and symmetrical single-lap joints subjected to shear/bending moment and axial force. De Castro and Keller [13] performed Quasi-static axial tension experiments in laboratory environment on adhesively-bonded double-lap joints from pultruded GFRP laminates. Chen and Nelson [14] presented some insight and tools to understand the stress distribution in a bonded joint induced by thermal expansion of dissimilar materials. Osnes and McGeorgeb [15] studied the interfacial stress distribution in overlaminated double-lap joints is investigated. Analytical models are derived for the shear and transverse case. They demonstrate the critical failure mode for the transverse normal stresses in the joint related to the peel stress. Gustafson and Waas [16] developed a thermo-mechanical analytical model and a corresponding macroscopic bonded joint finite element for the analysis of orthotropic double lap joints subjected to combined thermal-mechanical loads. Mokhtari *et al* [17] studied the effects of composite layer stiffness, thickness and ply orientations on stresses in the adhesive layer of a double lap bonded joint are investigated using three-dimensional finite element analysis. Non-linear behavior of the adhesive is considered for different ply orientations to find the maximum stress in adhesive joints. Choupani [18] carried out a finite element study to understand the stress fields and stress intensity factors over the behavior of cracks in adhesively bonded double-lap joints. From the finite element results it was found that the patch materials of low stiffness, low adhesive module and low tapering angles are desirable for a strong double-lap joint aerospace structure. Vallee *et al* [19] carried out the experimental and numerical investigations were carried out on adhesively bonded full-scale double lap joints composed of pultruded GFRP profiles with relatively thick adhesive layers. The influence of different geometric parameters on the joint strength was investigated for different adhesive layer thickness, the fillet radius and the overlap length. Kim *et al* [20] present the behavior of a two-part epoxy adhesive bonded to a steel substrate subjected to cold region environment. Experimental tests are conducted for various specimens using double-lap shear joints in wet–dry and freeze–thaw conditions to examine the durability performance of the joint, including load-carrying capacity, interface deterioration, and failure mode.

The overwhelming majority of the work on the subject of adhesive bonding has focused on the single-lap configuration. Very few works appear to have been made on the performance of double lap joints in isotropic and orthotropic materials. The stresses induced at the interfaces of the adherends and adhesive play an important role in the design of adhesively bonded joints in FRP composites. Hence, these stresses are required to be analyzed most accurately. As part of the analysis the present work, attempts to study the interfacial stress characteristics of adhesive bonded double lap joint made of generally orthotropic laminates (FRP) subjected to axial loading. The analysis includes the evaluation of (i) Interlaminar normal stress (σzz) (ii) Interlaminar shear stress in longitudinal plane (τzx) and (iii) Interlaminar shear stress in transverse plane (τyz) at the interfaces of the adherend and adhesive, and at the middle plane of the adhesive.

2. Problem modeling

The details of geometry, finite element model with validation, stacking sequence of the laminate, type of load applied along with boundary conditions and material properties used for the analysis of double lap joint are as follows.

2.1 Geometry

The geometry of the double lap joint used for the present analysis is as shown in Fig.1. (All the dimensions are in mm).

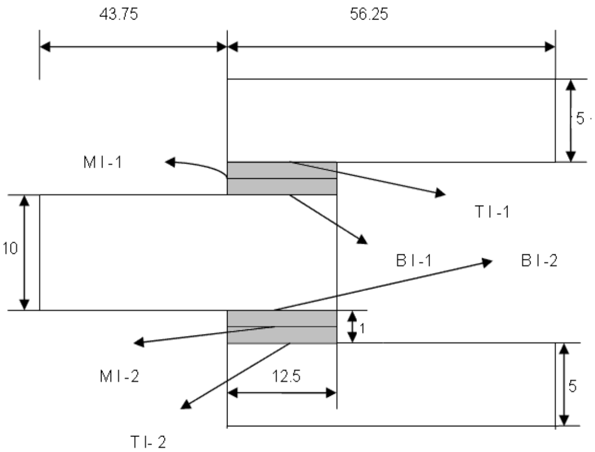

Fig 1: Geometry of the double lap joint

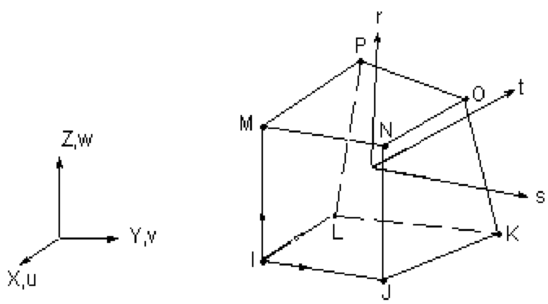

Fig 2: SOLID 45 Element

The total length of the adherend is taken as 100mm and width of the adherend is taken as 25mm. The adhesive thickness as 1mm.The overlap length for the geometry taken as 12.5mm.The value of thickness of the adherent (t_{an}) is determined from the length to thickness ratio (s) equal to10.

In Fig.1 TI-1, TI-2,BI-1 and BI-2 represents the adherend and adhesive Interfaces at top and bottom of the double lap joint about middle adherend.MI-1 and MI-2 represents the Interfaces at middle of the adhesive at top and bottom of the double lap joint about middle adherend. According to these dimensions a geometric model is prepared by using ANSYS software and Finite Element mesh is done as per the geometric modeling.

2.2 Finite Element Modeling

The finite element mesh is generated using a three-dimensional brick element 'SOLID 45' of ANSYS [17]. This element (Fig. 2) is a structural solid element designed based on three-dimensional elasticity theory and is used to model thick orthotropic and isotropic solids. The element is defined by eight nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. SOLID45 element is used for the structural analyses of the joint considered for the present analysis.

2.3 Loading and Boundary Conditions

The following types of loads and boundary conditions are applied for prediction of the response of the structure in the analysis.

2.3.1 Loading: A uniform longitudinal axial pressure load of 10Mpa is applied for the present finite element model.

2.3.2 Boundary Conditions: One end of the joint is clamped and the other end is restricted to move in the transverse direction. A uniform longitudinal load of 10Mpa is applied at non-clamped end of the joint.

2.4 Material Properties

The following mechanical properties are used for the present analysis of double lap joint.

i) Epoxy (adhesive)

E = 5.171 GPa; $\nu = 0.35$;

ii) Graphite-Epoxy (adherends)

$E_1 = 172.72$ GPa, $E_2 = E_3 = 6.909$ GPa

$G_{12} = G_{13} = 3.45$ GPa, $G_{23} = 1.38$ GPa, $\nu_{12} = \nu_{13} = \nu_{23} = 0.25$

2.5 Laminate sequence

$+\theta^0/-\theta^0/-\theta^0/+\theta^0$ 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.

3. Results and Discussion

3.1 Validation

Fig.3shows the finite element mesh on the overlap region of the double lapjoint. The finite element mesh divisions on the non-overlap regions are same as that given for overlap region across thickness, but along the length coarse mesh is considered to limit the number of nodes without losing the accuracy of the solution. The present finite element model is validated by comparing the stresses obtained for the double lap joint of specially orthotropic laminates with the theoretical concepts. A few computed values of stresses on free surfaces of the present finite element model are obtained after conducting number of convergence tests by varying mesh size. The values of interlaminar stresses are observed tobe nearly equal to zero at all free surfaces.

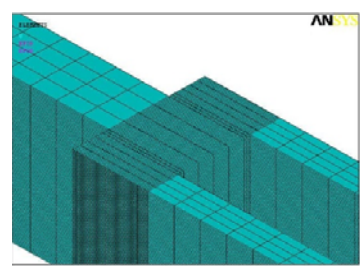

Fig 3: Finite element mesh on the overlap region of the double lap joint

3.2 Variation of out of plane Normal & Shear Stresses with Fiber Angle θ

Figs. 4-7show the variation of out of plane normal and shear stresses and displacement w.r.t to θ for longitudinal loading. The out of plane normal stresses σ_{zz} (Fig.4) increases with increase in θ upto 45^0 and later decreases at all the interfaces considered for the analysis. The magnitude $\sigma_{zz}$is more at mid interface followed by bottom interface and top interface. As the fiber angle increases the stiffness of the plate in the longitudinal direction decreases and the stress increases.

Fig. 5 shows the variation of τ_{yz} w.r.t to θ. This stress also increases upto45^0, and later decreases. The magnitude τ_{yz} is more at mid interface followed by bottom interface andtop interface. However the magnitudes of the stresses at $\theta=45^0$ are less at all interfaces when compared to σ_{zz}.

Fig. 6 shows the variation of τ_{zx} w.r.t to θ. This stress at the interfaces increases up to $\theta = 45^0$, and later decreases. The magnitude τ_{zx} is more at mid interface followed by top interface and bottom interface. The magnitude of stresses at the interfaces is more for σ_{zz} and τ_{zx} when compared to τ_{yz}

Fig. 7 shows the variation of longitudinal displacement 'u' w.r.t to fiber angle. There is a slight increase in 'u' upto 30^0, and increases at a greater rate between 30^0 and 60^0followed by a slight increase. The increase in longitudinal displacement is due to the reduction of stiffness with increase in fiber angle. Figs. 8-11 represents the deformed shapes of the double lap joint for the fiber angle of $\theta = 45^0$

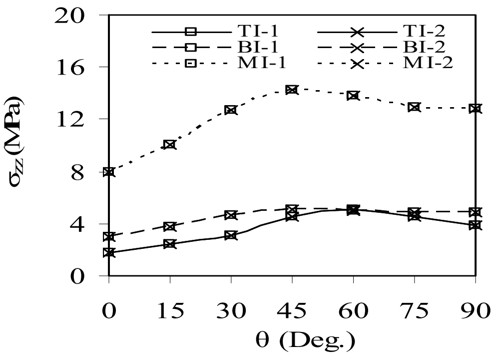

Fig 4: Variation of σ_{zz} with θ (t_{an} = 8mm)

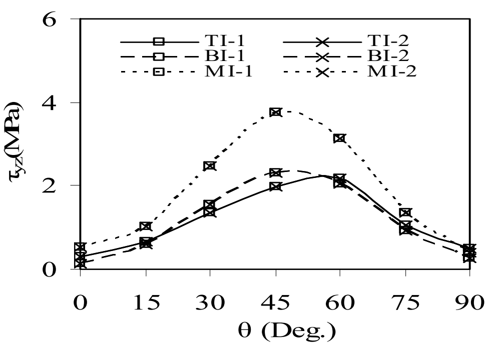

Fig 5: Variation of τ_{yz} with θ (t_{an} = 8mm)

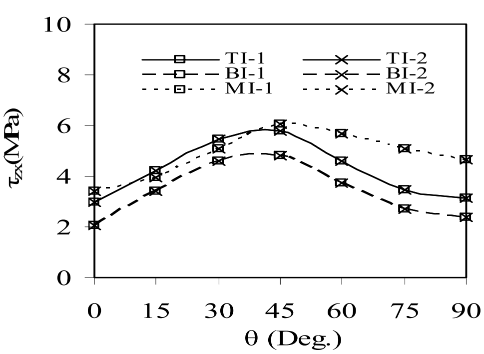

Fig 6: Variation of τ_{zx} with θ (t_{an} = 8mm)

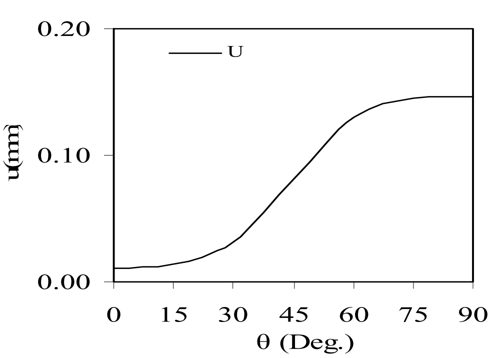

Fig 7: Variation of withθ (t_{an} = 8mm)

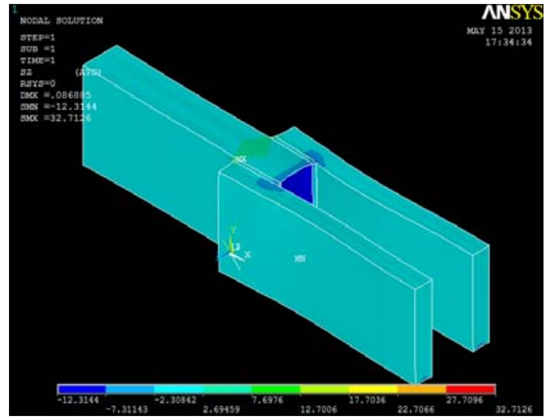

Fig 8: Normal stress in σzz direction

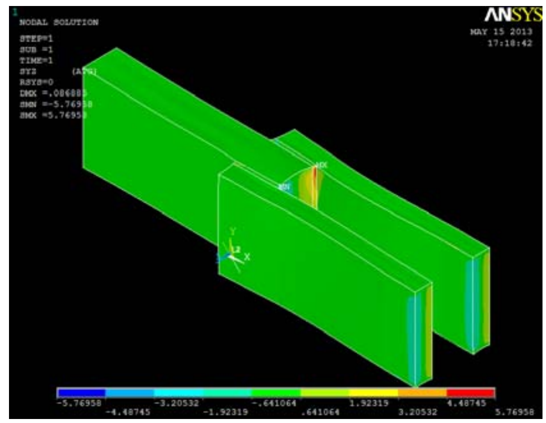

Fig 9: Interlaminar shear stress in τ_{yz} direction

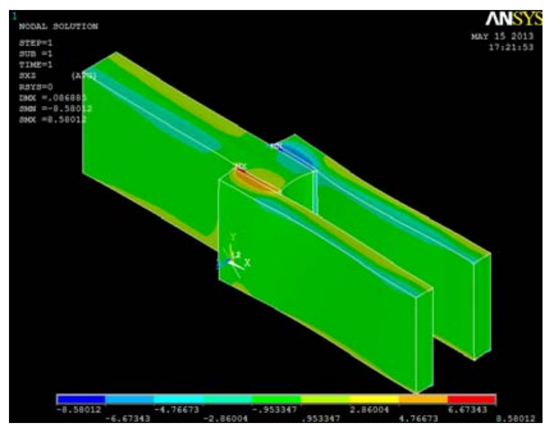

Fig 10: Interlaminar shear stress in τzx direction

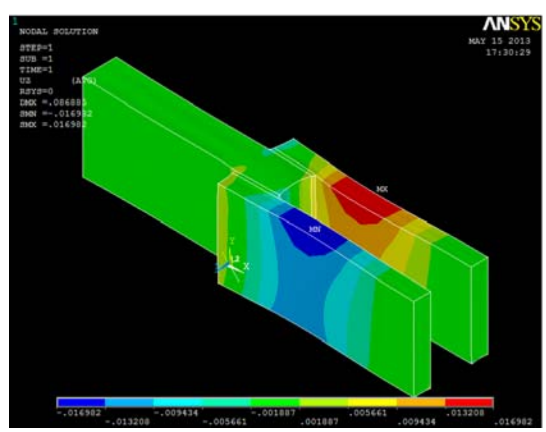

Fig 11: Longitudinal displacement in z direction

4. Conclusions

Three dimensional theory of elasticity based finite element analysis has been carried out for the static analysis of adhesively bonded double lap joint in laminated fiber reinforced plastic (FRP) composites. In the present analysis the effect of Inter laminar normal stress (σ_{zz}), inter laminar shear stresses (τ_{yz}, τ_{zx}) and displacement in angle-ply laminates is determined for the different cases of variation in width of the double lap joint. From all the above cases it was predicted that maximum value of the interlaminar stresses for the joint regions occurs particularly at fiber angle $\theta = 45^0$.The following reasons are concluded from the part of this analysis.

- The magnitude of stresses $\sigma_{zz,}$ τ_{yz} and τ_{zx} increases up to $\theta = 45^0$ and later onwards it decreases. As the fiber angle increases the stiffness of the plate in the longitudinal direction decreases and the stress increases. The reduction of the stresses beyond $\theta = 45^0$ may be due to the effect of coupling.
- The increase in the longitudinal displacement is due to the reduction of the stiffness with increase in fiber angle. Variations up to 30^0 and beyond 60^0 may be due to the effect of coupling.
- The magnitude of stress at all the interfaces is more for σ_{zz} and τ_{zx} when compared to $\tau_{yz.}$
- The magnitude of stresses $\sigma_{zz,}$ τ_{yz},τ_{zx} and 'u' increases with increase in thickness of the adherend. A similar trend is maintained by the stresses σ_{zz}, τ_{yz} and τ_{zx} for all the values of adherend thickness under consideration.
- The increase in longitudinal displacement and stresses is due to the reduction of stiffness of the plate in the longitudinal direction with increase in fiber angle.
- The peel stress, σ_{zz}, found to be the deciding parameter in design of adhesive bonded double lap joints as the magnitude of this stress is greatest when compared to other stresses.
- The fiber angle θ influences the stresses due to the mismatch in layer properties at the interfaces leading to delamination.

5. Nomenclature

$E_L = E_1$ Young's modulus of the lamina in the fiber direction
$E_T = E_2 = E_3$ Young's modulus of the lamina in the transverse direction of the fiber
$G_{LT} = G_{12} = G_{13}$ Shear modulus in the longitudinal plane of the fiber
$G_{TT} = G_{23}$ Shear modulus in the transverse plane of the fiber
$\nu_{LT} = \nu_{12} = \nu_{13}$ Poisons ratio in the longitudinal plane of the fiber
$\nu_{TT} = \nu_{23}$ Poisons ratio in the transverse plane of the fiber
t_{an} Adherend Thickness
θ Fiber Angle

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