Nonlinear analysis of adhesively bonded SLJ in laminated FRP composite

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Abstract: The present work deals with 3D Finite Element method to analyze the geometric non-linear response of adhesively bonded Single Lap Joint (SLJ) made of laminated FRP composites. The problem is modelled in ANSYS software. SLJ made of angle-ply FRP adherends bonded with epoxy resin adhesive subjected to uniform longitudinal loading. A uniform load of 10 MPa is applied for linear and non-linear analysis. In the present analysis, width of the joint and adhesive thickness is considered as 100 mm and 0.5 mm. Adherend thickness is varied from 0.5 to 2.0 mm in steps of 0.5 mm. In this work, the effect of adherends thickness on the single lap joint is analyzed and investigated the interlaminar normal stress (σ_{zz}), Inter-laminar shear stress in longitudinal plane (τ_{zx}), and Inter-laminar shear stress in transverse plane (τ_{yz}) at the interfaces of adherends and adhesive, and at the central plane of adhesive. From the analysis it is observed that the magnitude of interlaminar stresses increases as the adherend thickness of the joint increases. The present analysis is used for safe and efficient design of SLJ in FRP composite.

***IndexTerms*-** **SLJ, FEM, Interlaminar Stresses, Non-linear analysis, adherends thickness**.

I. INTRODUCTION

Adhesively bonded joints with laminated FRP composites play an important role in many structural applications especially in space, aircraft and automobile industries. The overlap region of SLJ can potentially become the weakest link in the structure due to the large amount of load it must transfer.

Moreover, this region of the joint is subjected to axial as well as bending due to the offset loading. 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.

Tsai et al. [1] proposed the analytical method for analyzing the distribution of shear stresses on adherend and adhesive of bonded lap joints and compared with experimental and numerical results. Kim and Kedward [2] analyzed the adhesive shear stresses in the bonded joints by closed form stress analysis. Adams and Peppiatte [3] investigated the role of spew at the end of adhesive layer in bonded lap joints. Delale et al. [4] developed closed-form analysis to study the general plane strain problem of bonded joints. Wang and Rose [5] presented analytical solutions for the tri-axial stress analysis of bonded joints and validated with finite element method.

Tsai and Morton [6] evaluated the stress distributions of 3D adherend and adhesive in a SLJ by using linear elastic finite element analysis. Andruet et al. [7] developed the finite element method for analyzing stress distribution and displacement in adhesively bonded joints. Panigrahi and Pradhan [8] developed a three dimensional finite element method for analyzing damages in adhesively bonded SLJ. Vijeta et al. [9] proposed the 3D non-linear finite element analysis for analyzing the interlaminar stresses at the interfaces of single lap joint. K. Senthil et al. [10] studied the presence of closed debonds in the failure of adhesively bonded joints by predicting the debond growth with virtual crack closure technique. F. Kadioglu [11] investigated the performance of SLJ under buckling loading conditions experimentally and compared the results numerically.

The objective of present work is to investigate the interlaminar stresses of SLJ at the interfaces of adherends and adhesive and at the mid plane of adhesive by varying the adherends thickness of the joint.

II. PROBLEM MODELLING AND METHODOLOGY

The present research problem deals with 3D finite element method to analyze geometrically non-linear response of adhesively bonded Single Lap Joint (SLJ) made of laminated FRP composites. 3D analysis is based on theory of elasticity used in the solution of the problem. The model is prepared by using ANSYS software. The dimensions of the SLJ adherends are taken as: length=100mm, width=100mm and thickness is 0.5 to 2.0mm in steps of 0.5 mm. Overlap length of joint and thickness of the adhesive are taken as 12.5mm and 0.1mm respectively. 'SOLID 45' – 3D brick element is used to generate the finite element mesh which used three-dimensional stress-strain relations.

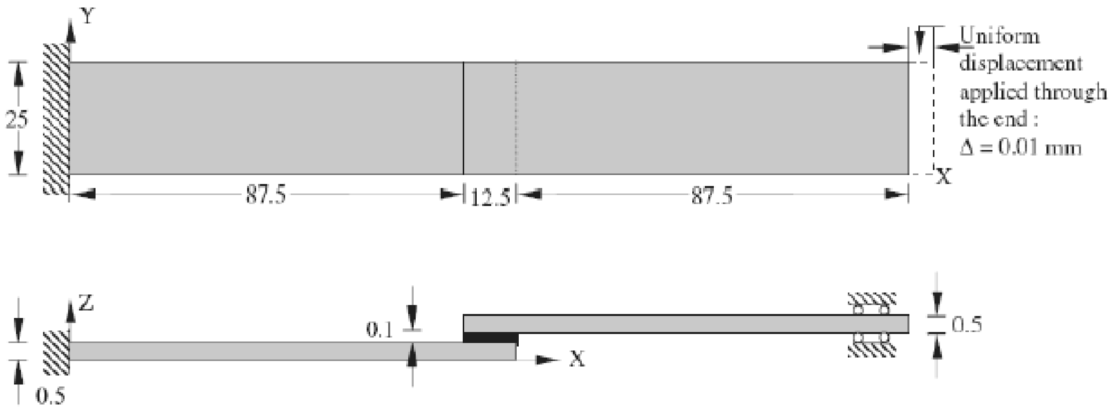


Fig. 1- Details of Single lap joint [8].

In the present work, the finite element model is validated and later this model is extended for geometric nonlinear analysis of SLJ made of angle-ply (30˚/-30˚/-30˚/30˚) FRP adherends bonded with epoxy resin adhesive subjected to uniform longitudinal loading. 10MPa of uniform longitudinal load is used for linear and geometric non-linear analysis. One side of the joint is fixed and the other side is constricted to have only longitudinal displacement. In this work, the effect of adherends thickness on the single lap joint is analyzed through examination of Inter-laminar normal stress (σ_{zz}), and Inter-laminar shear stresses (τ_{zx}, in longitudinal and τ_{yz} in transverse plane) at the interfaces of adherends and adhesive, and at the central plane of adhesive.

The Mechanical properties from the reference [8] are as below.

i) FRP (adherend) T300/934 Graphite/epoxy

E_X = 127.5 GPa; E_Y = 9.0 GPa; E_Z = 9.0 GPa; $\nu_{XY} = \nu_{XZ}$ = 0.28; ν_{YZ} = 0.41;

$G_{XY} = G_{XZ}$ = 4.8 GPa; G_{YZ} = 2.55 GPa

ii) Adhesive (Epoxy)

Young's modulus (E) = 2.8 GPa; Poisson's ration (ν) = 0.4

III. VALIDATION:

Validation of finite element model is done through comparison of stresses at interfaces of single lap joint with the results of reference [8] for linear analysis performed for axial strain loading and reference [9] for linear and geometric non- linear analysis performed for Longitudinal uniform pressure loading. Fig. 2 represents bonded region of SLJ. Table 1 represents the maximum values of the Inter-laminar stresses at Top Interface and Bottom interface. Close agreement between the reference and present values is found.

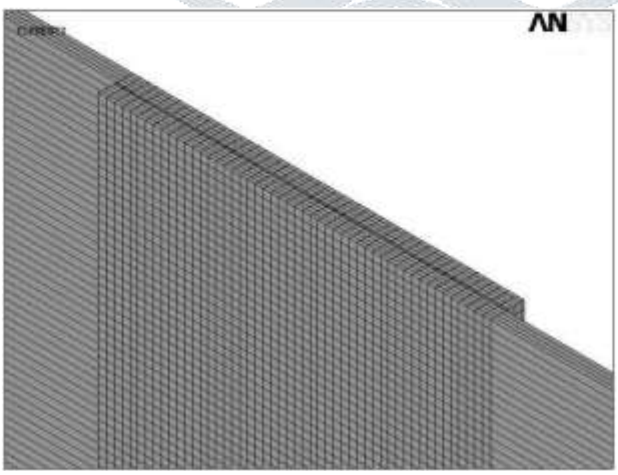


Fig. 2- Bonded region of SLJ.

Table 1: Interlaminar Stress values at Top interface and Bottom Interface

	Normal stress σ_{zz} (Mpa)				Shear stress τ_{zx} (Mpa)			
	Linear		Non-linear		Linear		Non-linear	
Location	Ref [8]	Present	Ref [9]	Present	Ref [8]	Present	Ref [9]	Present
Top Interface	0.40	0.41	1.24	1.25	0.39	0.40	1.16	1.18
Bottom Interface	0.39	0.39	1.25	1.27	0.38	0.39	1.15	1.17

IV. RESULTS AND DISCUSSION

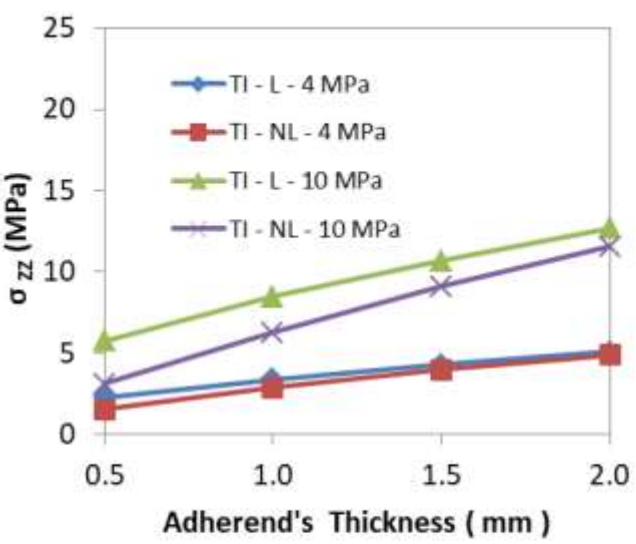
In the present analysis, the adherends thickness of the single lap joint is varied and analyzed the interlaminar normal, shear stresses. Both linear and non-linear analysis is performed on the single lap joint. Analysis is performed at 5 load steps (10MPa). Only at 2 load steps (4MPa & 10MPa), variation of interlaminar stresses w.r.t. adherends thickness are shown in below fig. In the analysis of results, the non-linear analysis results are taken in to the consideration believing that the non-linear analysis is realistic.

Fig. 3 shows the variation of normal stress, σ_{zz} at the Top interface (TI) of adherends and adhesive increases with increase in adherends thickness. Fig. 4 shows the variation shear stress, τ_{zx} at the Top interface of adherends and adhesive increases with increase in adherends thickness. Fig. 5 shows the variation of shear stress, τ_{yz} at the Top interface of adherends and adhesive increases with increase in adherends thickness.

Fig. 6 shows the variation of normal stress, σ_{zz} at the Bottom interface (BI) of adherends and adhesive increases with increase in adherends thickness. Fig. 7 shows the variation of shear stress, τ_{zx} at the Bottom interface of adherends and adhesive increases with increase in adherends thickness. Fig. 8 shows the variation shear stress, τ_{yz} at the Bottom interface of adherends and adhesive increases with increase in adherends thickness.

Fig. 9 shows the variation of normal stress, σ_{zz} at the Mid surface (MS) of adhesive increases with increase in adherends thickness. Fig. 10 shows the variation of shear stress, τ_{zx} at the Mid surface of adhesive increases with increase in adherends thickness. Fig. 11shows the variation of shear stress, τ_{yz} at the Mid surface of adhesive increases with increase in adherends thickness.

From the analysis it is investigated that the magnitude of interlaminar normal stress (σ_{zz}) and interlaminar shear stresses (τ_{zx}, in longitudinal and τ_{yz} in transverse plane) increases as the adherend thickness increases. The reason is as the layer thickness increases the intralaminar forces increases, results in the increase of interlaminar stresses.



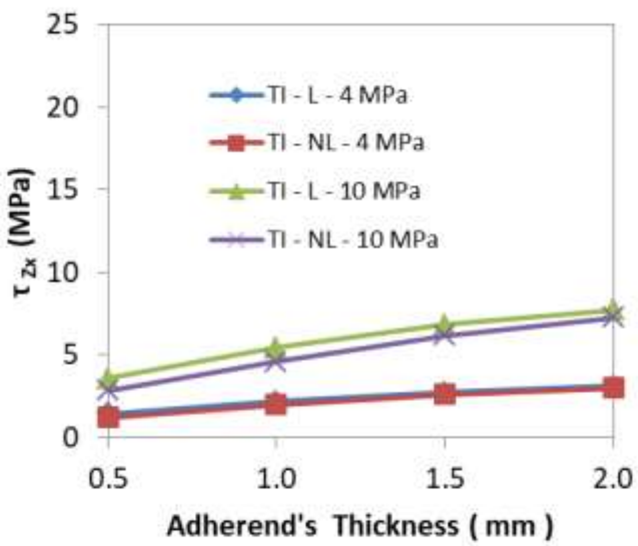
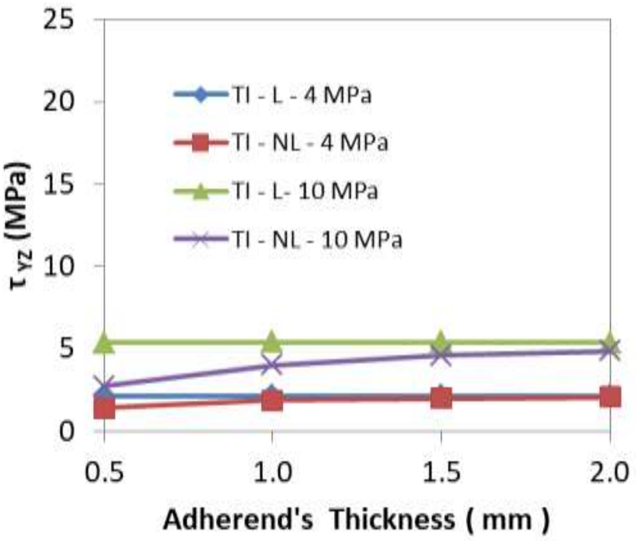


Fig. 3 – Normal stress (σ_{zz}) at Top Interface



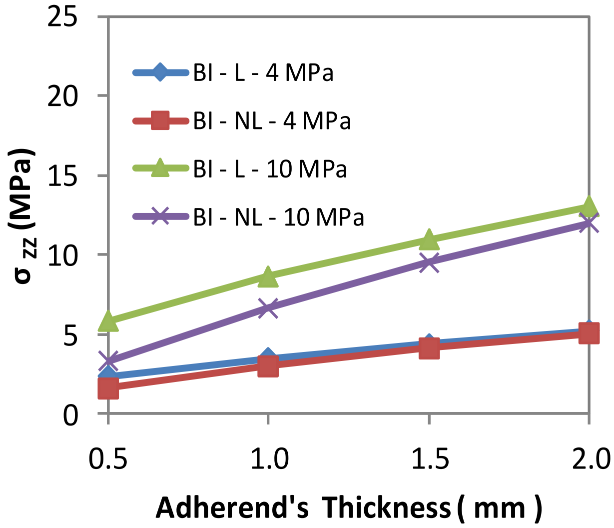
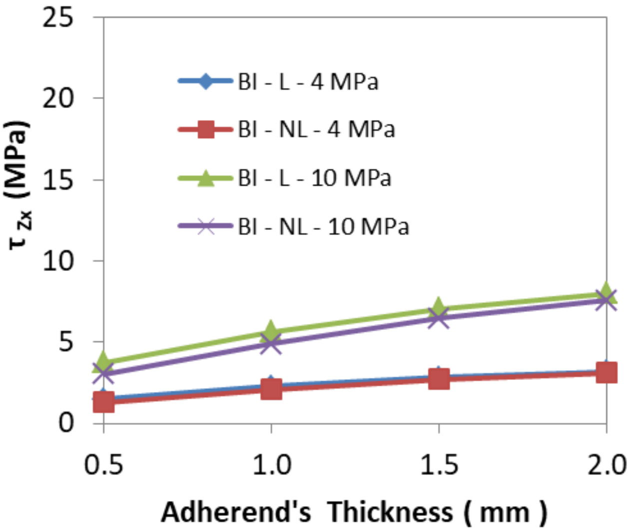


Fig. 4 – Shear stress (τ_{zx}) at Top Interface

Fig. 5 – Shear stress (τ_{yz}) at Top Interface

Fig. 6 – Normal stress (σ_{zz}) at Bottom interface



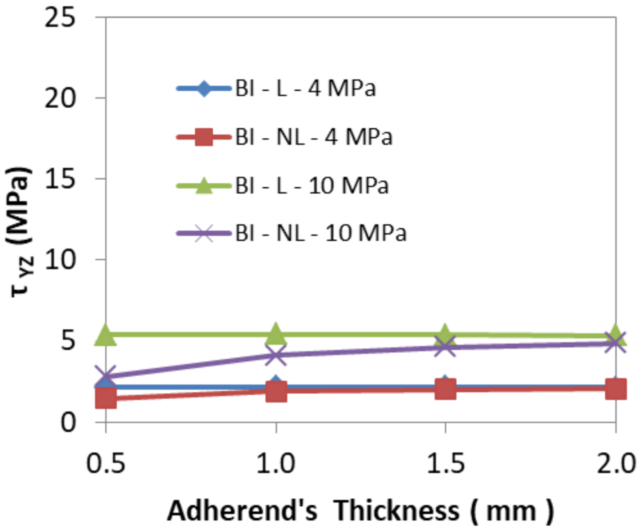


Fig. 7 - Shear stress (τ_{zx}) at Bottom Interface

Fig. 8 - Shear stress (τ_{yz}) at Bottom Interface

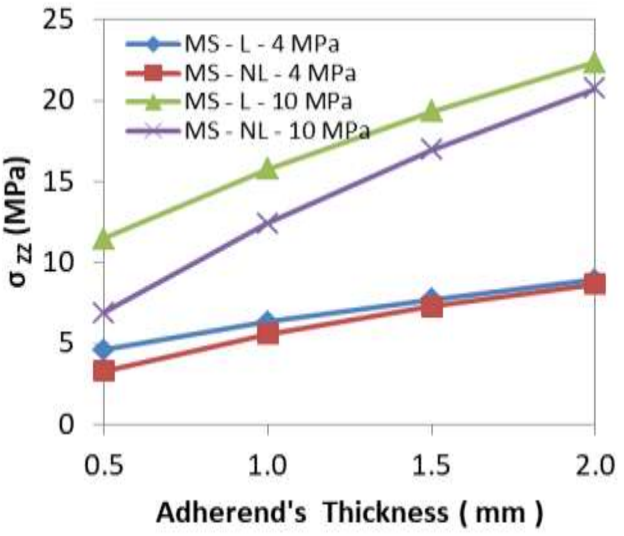


Fig.9 –Normal stress (σ_{zz}) at Middle of adhesive

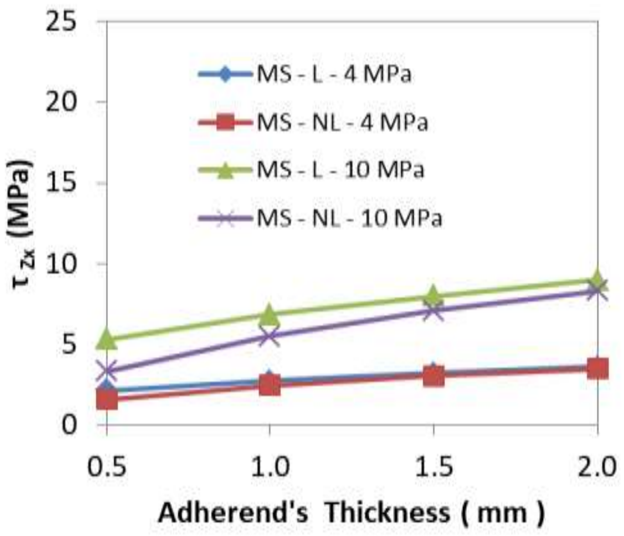


Fig.10 –Shear stress (τ_{zx}) at Middle of adhesive

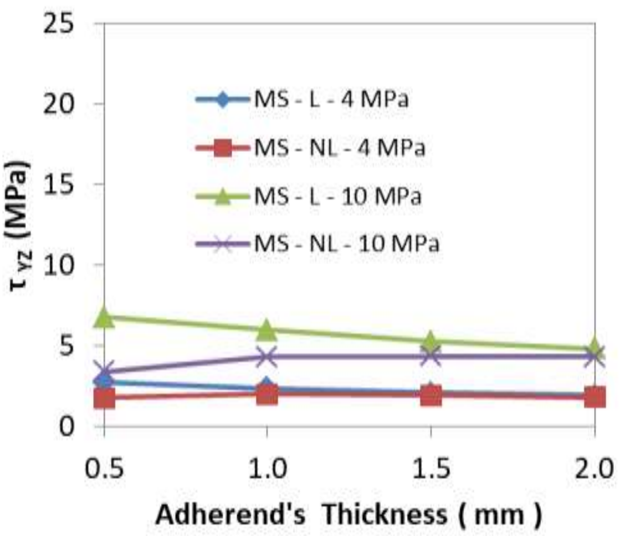


Fig. 11 – Shear stress (τ_{yz}) at Middle of adhesive

V. CONCLUSIONS

The 3D Finite element model is prepared and performed the geometric non-linear analysis by changing the adherends thickness of the joint to evaluate the interlaminar stresses at the bonding region of Single Lap Joint. From the analysis, it is found that the magnitude of interlaminar normal stress (σ_{zz}) and interlaminar shear stresses (τ_{zx}, in longitudinal and τ_{yz} in transverse plane) increases as the adherend thickness increases. The reason is as the layer thickness increases the intralaminar forces increases, results in the increase of interlaminar stresses. The present analysis is useful for safe and efficient design of SLJ in FRP composite. The interlaminar stresses (normal & shear) need to be analyzed very accurately as it plays an important role in the design of adhesively bonded joints in FRP composites.

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