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# FAILURE ANALYSISOF ADHESIVELY BONDED HYBRIDTUBULAR LAPJOINTS IN LAMINATED FRP COMPOSITES

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## ABSTRACT:

*Tubular composite structures have wide range of applications in aerospace, marine and chemical, petroleum industries for transportation of various fluids. Adhesive bonded laminated Tubular Single Lap Joints (TSLJ) are one of the most common types of lap joints in these applications. In present paper finite element analysis has been carried out to study the stress and failure characteristics in Hybrid Tubular Lap Joints (HTLJ) with inter-ply hybridization under tensile loading. Effect of varying adhesive thickness on magnitude of stresses and failure index has also been studied in present analysis. Three dimensional stress analysis of the adhesively bonded HTLJ has been carried out through suitable ANSYS Parametric Design Language (APDL) of ANSYS 2020R1. Tsai-wu coupled stress criterion has been used for predicting the onset of joint failures in the HTLJ. A comparative study based on the magnitude of stresses and failure index of TSLJ and HTLJ revealed that marginally effects near within the joint region. From the numerical results it was observed that performance of the joints can be improved by introducing the interlayer hybridization of composite adherends and suggested*

*Key points: HTLJ,TSLJ FRPcomposites*

## 1. INTRODUCTION:

Adhesive bonding is an efficient and convenient method for joining tubular sections. Adhesive bonded laminated tubular lap joints are one of the most common types of lap joints in application of energy and construction industries. Interlayer hybrid Composite pipes have also been utilized in waste water treatment system, power and petroleum productions and other industries for transportation of various fluids. The strength efficiency and life time of adhesively bonded tubular joints can be significantly improved by reducing the stress concentrations at the ends of overlap and distributing the stresses uniformly over the entire bond length. A good amount of literature dealing with the stress analysis of adhesively bonded tubular lap joints of conventional tubular joints are available, However the literature related to hybrid laminated FRP tubular lap joints are very limited. Lubkin and Reissner's [1] analysed the stresses in tubular assemblies subjected to axial loading in which the tubes are considered to be of small thickness for which the thin-shell theory was applied to build stress field. Further it was assumed that the magnitude of shear and peel stresses in the two tubes is negligible relative to that of same stresses in the adhesive layer.  Adams and Peppiatt [2] conducted stress analysis of isotropic tubular lap joints and compared the closed form solution with the finite element method. Y.R Nagaraja et al. [3] Analysed an adhesive tubular joint with the adhesive obeying a nonlinear stress-strain law subjected to an uniaxial load, it was showed that the non-linear behaviour of adhesive in adhesive tubular lap joint adhesive makes it possible to predict a considerable reduction in the maximum stresses at the ends of the joint. An approximate closed -form solution to satisfy equations of equilibrium all stress boundary conditions and stress continuity conditions based on principle complementary energy was presented byY.P.Shi and S.Cheng [4]. It was observed that high shear stress concentrations and maximum normal stress occur at the ends of overlap length. Thomsen [5] analyzed the stress distributions in adhesively bonded with two dissimilar orthotropic laminated cylindrical shell elements. Overlap length, adhesive layer stiffness and adherend stiffness are significantly influence the stress distributions in the adhesive layer. Chihdar Yang.[6] developed analytical model and compared with numerical method of composite pipe joint under tensile load based on laminated anisotropic plate theory. An analytical model for tubular adhesive joints based on the variation principle applied to the potential energy of deformation occurring in the adhesive layer was accomplished by Nemes et al. [7]. The model was capable of detecting the intensity and distributions of stresses in the adhesive layer of a joint composed of isotropic adherends subjected to tensile loading. Effect of hybridization and stacking sequence on the failure behaviour of hybrid filament composite tubes subjected to quasi static indentation was investigated by A.Zuriada et al [8] and stacking sequence will influence strain distributions in hybrid tubes. By varying a modulus graded bond line adhesive the distribution of stresses are reduced in joint region under the tensile loading was performed by S.Kumar [9]. Numerical analysis of laminated FRP composite adherends subjected to tensile load for suitable performance of the joint was performed by R.R. Das B.Pradhan [10]. Suitable overlap length has been determined based on the Tsai-Wu failure criterion. Ch.kannan et al. [11] Performed experiments to study the Hybrid effect in composite tubes under axial compression. It was concluded that with hybrid effect strength and stiffness of hybrid tubes was improved compare to conventional tubes. The effect of stacking sequences and orientation angles influence the stress distributions through thickness direction in hybrid composite tubes  was performed by Ammar Maziz et al.[12]. There are different parameters which influence the stresses in th joint region adhesive thickness, adherend thickness, overlap length, stacking sequence, orientation angles .In  present research is to develop a numerical model of hybrid FRP laminated tubular lap joint using FEM consisting of layered brick elements for the adhesive and adherends. In present analysis the influence of different adhesive thicknesses 0.1mm, 0.15mm, and 0.2mm on stress profiles within the adhesive for overlap length of 20mm were compared in both the joints.

## 2. SPECIMEN GEOMETRY AND BOUNDARY CONDITIONS:

The geometry, loading, and boundary conditions for the bonded HTLJ specimen considered in the present research have been taken from the work Das and Pradhan [10]. As shown in Fig.1

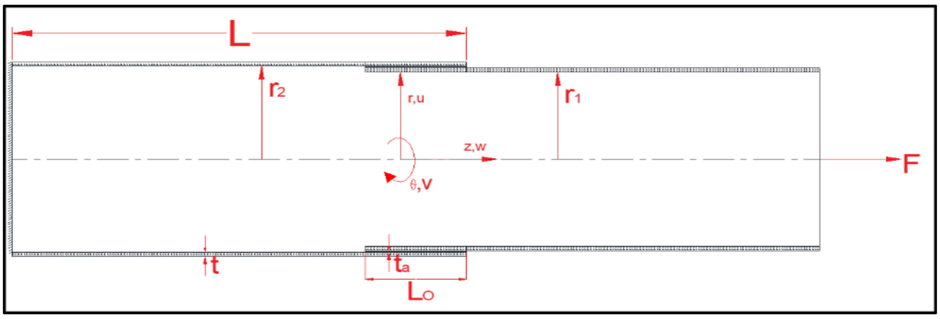


**Fig.1 Sectional view of tubular lap joint**

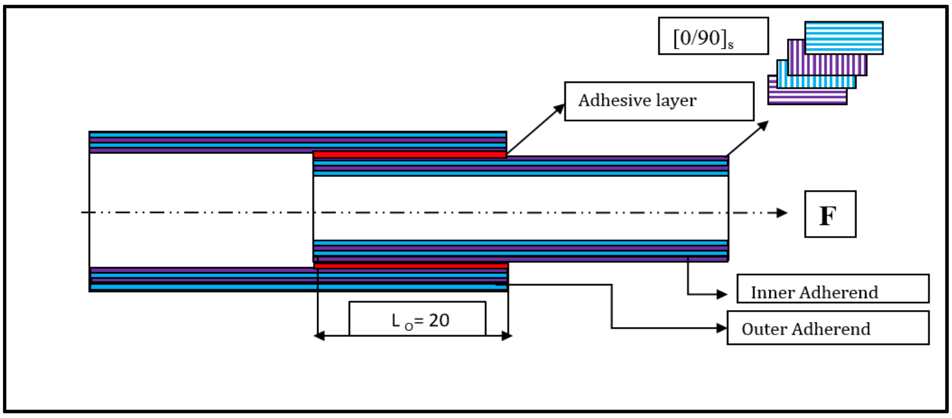


**Fig.2 Sectional view of Hybrid Tubular lap joint**

The bonded HTLJ along with loading and boundary conditions are shown in Figure 2. In present analysis detailed stress analysis of laminated bonded HTLJ subjected to tensile loading of 10 MPa applied at the end of inner tube. The material properties of Hybrid FRP tubular adherendsand isotropic epoxy adhesive are given in Table 1 and geometrical parameters as shown in Table2.

**Table 1. Material properties of composite adherends and adhesive.**

| Joint materials | Material properties |
|---|---|
| 1. T300/934 graphite/epoxy | $E_r$= 127.5GPa$E_\theta$= 4.8 GPa$E_z$= 9GPa<br>$\upsilon_{rz} = \upsilon_{\theta z}$= 0.28$\upsilon_{r\theta}$=0.41<br>$G_{rz}$= $G_{\theta z}$= 4.8GPa$G_{r\theta}$=2.55GPa |
| 2. E-Glass/epoxy | $E_r$=41.4GPa$E_\theta$= $E_z$=10.4GPa<br>$G_{r\theta}$= $G_{rz}$= 5.1GPa$G_{2\theta}$=4.1GPa<br>$\upsilon_{r\theta}$=$\upsilon_{rz}$=0.24 $\upsilon_{\theta z}$=0.21 |
| 3. Epoxy adhesive(isotropic) | $E$=2.8 GPa<br>$\upsilon$= 0.4 |

**Table .2.Geometric parameters of composite adherends**

| Stacking sequence | $[0^0/90^0]_s$ |
|---|---|
| Adherend lengths | L=80mm |
| Overlap length | $L_O$=20mm |
| Adhesive thickness | ta=0.15mm |
| Adherend thickness | t = 1mm |
| Inner radius of inner Adherend | $r_1$=18.9 mm |
| Inner radius of outer Adherend | $r_2$=20.05 mm |

## 3. Finite element modelling

The bonded HTLJ has been modelled using the Finite Element codes of ANSYS 2020R1. Solid 185, 8-node brick elements have been used for modelling the adherends and adhesive layer. The FEA model of HTLJ and mesh model of tubular lap joint without hybridization and with hybridization HTLJ and has been shown in Fig.3(a). These elements provide the advantage of simulating both structural and layered composite structures. Critical bond line interfaces and portions of the composite tubular portions lying within the overlap length region have been considered a failure prone regions. Three different bond line interfaces: (i) the interface of inner adherend and the adhesive, (ii) the mid surface of the adhesive and (iii) the interface of outer adherend and adhesive in the overlap region of the joint are the critical regions and lay up sequence as shown in Fig 4(a) and (b). A very fine mesh has been adopted to take care of high stress gradients at the free edges of the joint. For better results the meshing pattern has been made comparatively finer towards the joint and course towards the free and fixed edges which has already shown in Fig.5(a) and (b). Appropriate restrained boundary conditions have been taken for simulating pure axial loading in the HTLJ. U=V=W=0, for all nodes along at the clamped end of the outer tube, and U=0, for all nodes along at the loaded end of the inner tube. In order to validate the FE modelling and simulation technique developed for the bonded HTLJ analytical results of Thomsen [5] and pradan [10] have been considered in the present analysis.

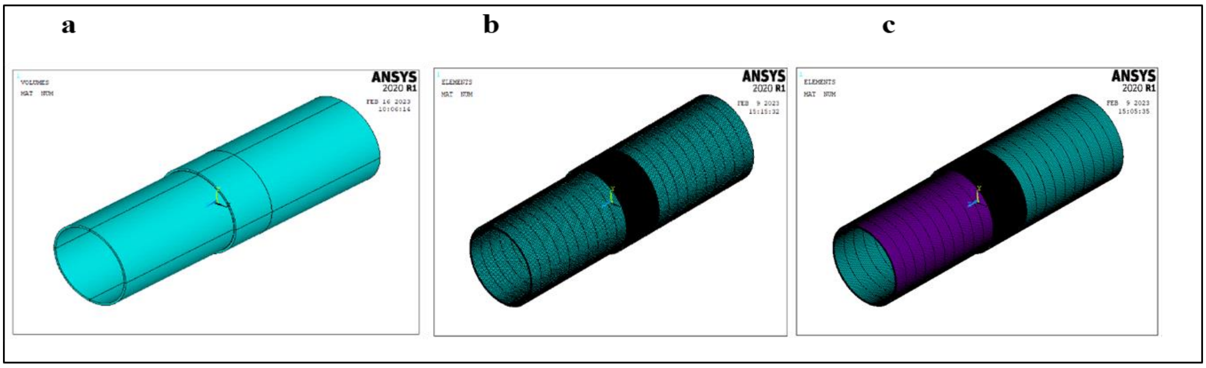
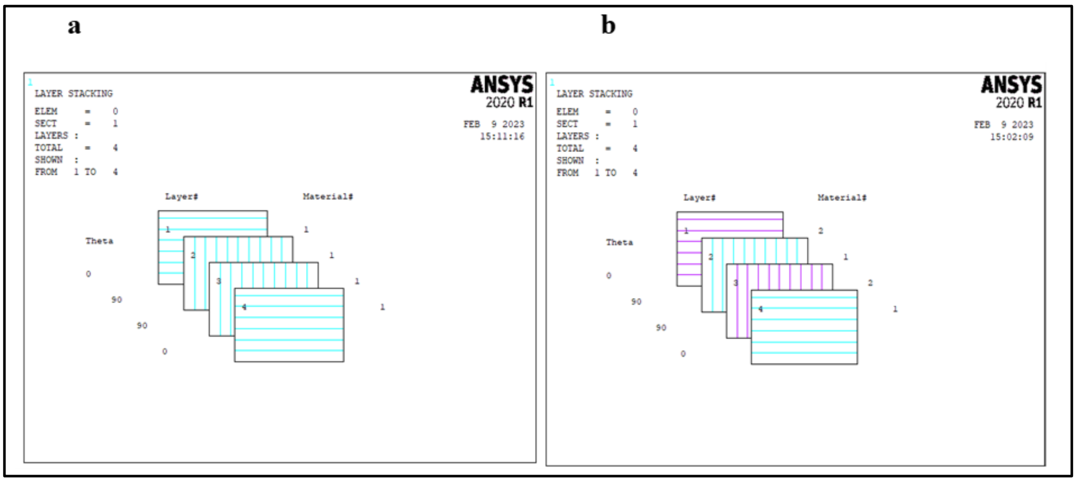


Fig. 3 Finite element model of bonded TSLJ (b) finite element mesh of TSLJ without hybridization and (c) finite element mesh of HTLJ with hybridization.



a

LAYER STACKING
ELEM = 0
SECT = 1
LAYERS :
TOTAL = 4
SHOWN :
FROM 1 TO 4

| Layer# | Theta | Material# |
|---|---|---|
| 1 | 0 | 1 |
| 2 | 90 | 1 |
| 3 | 90 | 1 |
| 4 | 0 | 1 |

b

LAYER STACKING
ELEM = 0
SECT = 1
LAYERS :
TOTAL = 4
SHOWN :
FROM 1 TO 4

| Layer# | Theta | Material# |
|---|---|---|
| 1 | 0 | 2 |
| 2 | 90 | 1 |
| 3 | 90 | 2 |
| 4 | 0 | 1 |

Fig.4(a) lay-up sequence of TSLJ (b) lay-up sequence of HTL

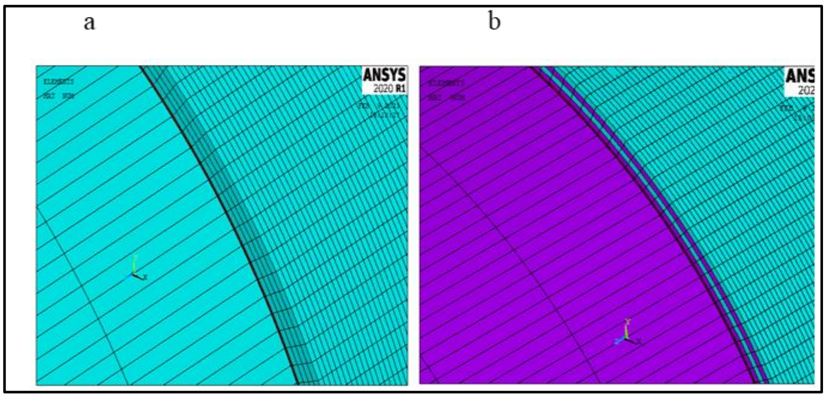


Fig. 5(a) Overlap region of TSLJ (b) Overlap region of HTLJ

It can be clearly observed from Fig. 6. Stress values in the mid-surface of the adhesive which compares well with the available literature that the numerical results are in good agreement with that of the analytical ones proving the compatibility and adaptability of the developed Finite Element based modelling and simulation technique.

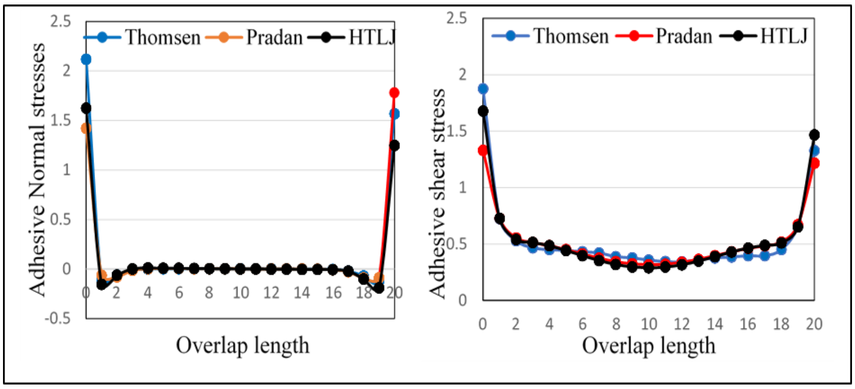


Fig.6 Normal and shear stress distributions along the adhesive mid-plane in tubular lap-joints subjected to uniform tensile load.

## 4. Criteria of Adhesive Joint Failures.

Under three-dimensional stress states, the initiation of adhesion failures occurs at the interfacial surface between the tubes and adhesive generally can be evaluated by the Tsai-Wu coupled stress criterion. Which takes into account the interaction of all six stress components at the critical and ply interfaces given by.

$$\frac{\sigma_r^2}{R_T^2}+\frac{\sigma_\theta^2}{\theta_T^2}+\frac{\sigma_Z^2}{Z_T^2}+\frac{\tau_{\theta r}^2}{S_{\theta r}^2}+\frac{\tau_{zr}^2}{S_{zr}^2}+\frac{\tau_{z\theta}^2}{S_{z\theta}^2}+\sigma_r\left(\frac{1}{R_T}-\frac{1}{R_C}\right)+\sigma_\theta\left(\frac{1}{\theta_T}-\frac{1}{\theta_C}\right)+\sigma_Z\left(\frac{1}{Z_T}-\frac{1}{Z_C}\right)+f_{\theta r}\sigma_\theta\sigma_r+ f_{zr}\sigma_z\sigma_r+\ f_{z\theta}\sigma_z\sigma_\theta=\ e^2\{e\geq\ 1,\quad failure\ e<\ 1, no failure$$ -------------- **(1)**

Where, R<sub>T</sub>, ϴ<sub>T</sub>, Z<sub>T</sub> are the allowable tensile strengths and R<sub>C</sub>, ϴ<sub>C</sub>, Z<sub>C</sub> are the allowable compressive strengths in the three principal material directions, respectively. $S_{\theta r}$, $S_{zr}$ and $S_{z\theta}$ are the shearing strengths of the orthotropic layer in various coupling modes. The coupling coefficient reflecting the interaction between r, ɵ and z directions are given by $f_{\theta r}$, $f_{zr}$and $f_{z\theta}$respectively. Failure index (e) is defined as the parameter to evaluate the condition whether the bonded pipe joint is likely to fail or not. If e ≥ 1 failure occurs, else there is no failure.

Generally, the stresses ($\sigma_r$ ,$\tau_{r\theta}$, and $\tau_{rz}$) are majorly responsible for the initiation of joint failures. Hence, only the inter laminar shear stresses ($\tau_{r\theta}$ and $\tau_{rz}$) and through-the-thickness normal or peel stress ($\sigma_r$) are required to predict the joint fracture initiation. Therefore, the Tsai-Wu criterion given in Eq. (1) reduces to the form as.

$$\left(\frac{\sigma_r}{R_T}\right)^2+\ \left(\frac{\tau_{\theta r}}{S_{\theta r}}\right)^2+\left(\frac{\tau_{zr}}{S_{zr}}\right)^2=e^2\{e\geq 1\quad failure\quad e<1\ no\ failure$$ ------------

------------------- (2)

Where $R_T$ is the interlaminar normal strength and $S_{\theta r}$ and $S_{zr}$ are the inter laminar shear strengths, respectively among the two orthogonal shear coupling directions. However, the parabolic yield criterion for isotropic materials proposed by Raghava et al. [13] has been used to evaluate the failure index of the adhesively bonded TSLJ within the adhesive layer. The criterion is given by:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 2(|Y_C| - Y_T)(\sigma_1 + \sigma_2 + \sigma_3) = 2|Y_C| Y_T e \text{ -----------------} \qquad (3)$$

Where $\sigma_1$, $\sigma_2$ and $\sigma_3$ are the principal stresses in the isotropic adhesive material causing yield and $Y_C$ and $Y_T$ are the absolute values of the compressive and tensile yield strengths respectively. It may be noted that when $Y_C$ and $Y_T$ are equal the above yield criterion reduces to the most familiar Von-Mises yield criterion.

## 5. Results and discussion.

### 5.1 Stress distributions within the adhesive mid layerin TSLJ and HTLJ with effect of varyingadhesive thickness.

It can be observed from Figure 7(a)-(c).The Normal stress profiles have similar trend in both TSLJ and HTLJ where the magnitude of stresses 2% increase 0.1mm adhesive thickness and 1% increase for 0.15 and 0.2 of adhesive thickness in HTLJ.

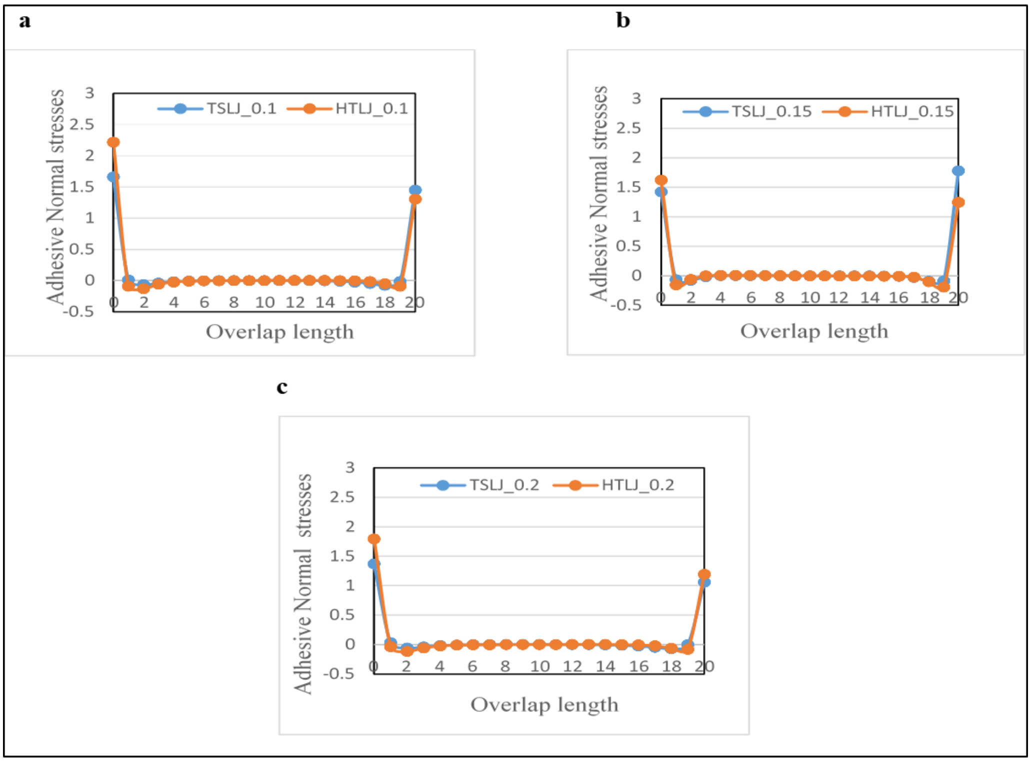


Fig.7 Normalstress distribution in mid adhesive layer in TSLJ and HTLJ

### 5.2 Shear stress distributions within the adhesive mid layer in TSLJ and HTLJ with effect of varying adhesive thickness.

From the Fig.8 (a)-(c).The shear stress profiles are similar but magnitude values are increase 2% for 0.1mm adhesive thickness and 1% increase for 0.15 and 0.2 of adhesive thickness in HTLJ.

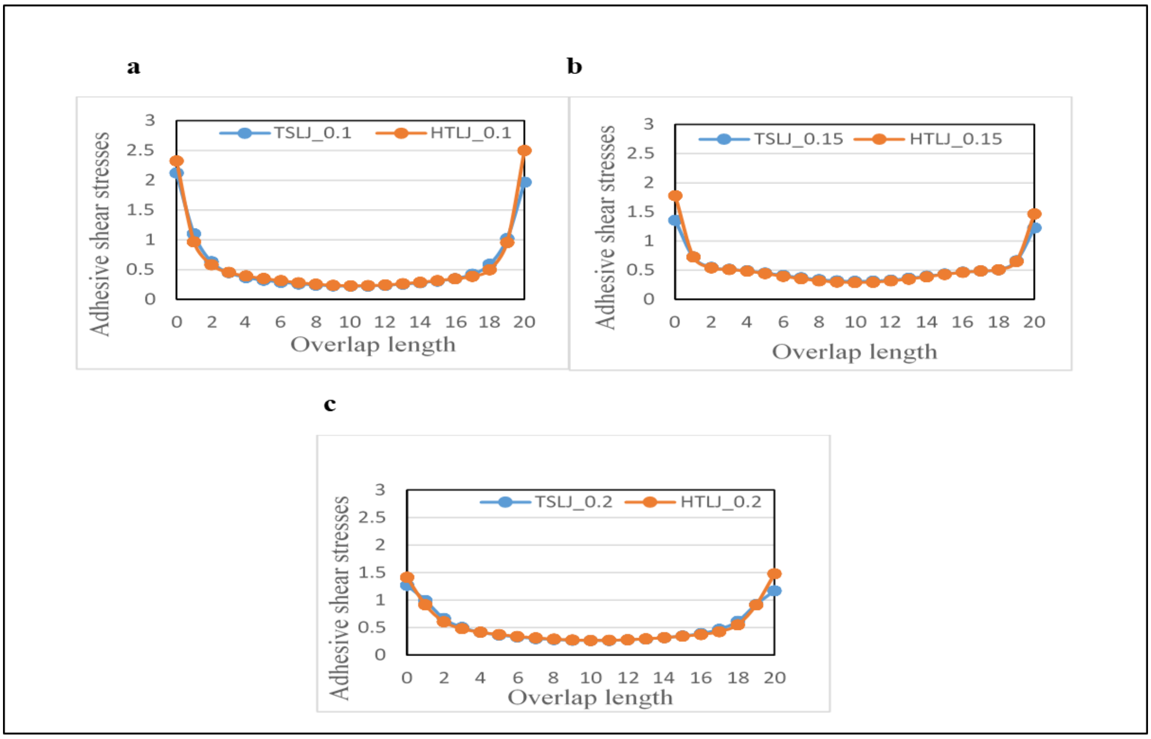


Fig.8 Shear stress distribution in mid adhesive layer in TSLJ and HTLJ

### 5.3 Failure initiation in adhesive mid layer in TSLJ and HTLJ with effect of varying adhesive thickness.

The failure index profiles for TSLJ and HTLJ for varying adhesive thickness has shown in Figure 9(a)-(c).The Parabolic yield criteria based failure index profile shows similar in both the joints by varying adhesive thickness. But the magnitude of failure index value at loaded end it shows increased to 1 for HTLJ for 0.1 mm adhesive thickness and for 0.15 and 0.2 mm adhesive thickness the values are below the limit.

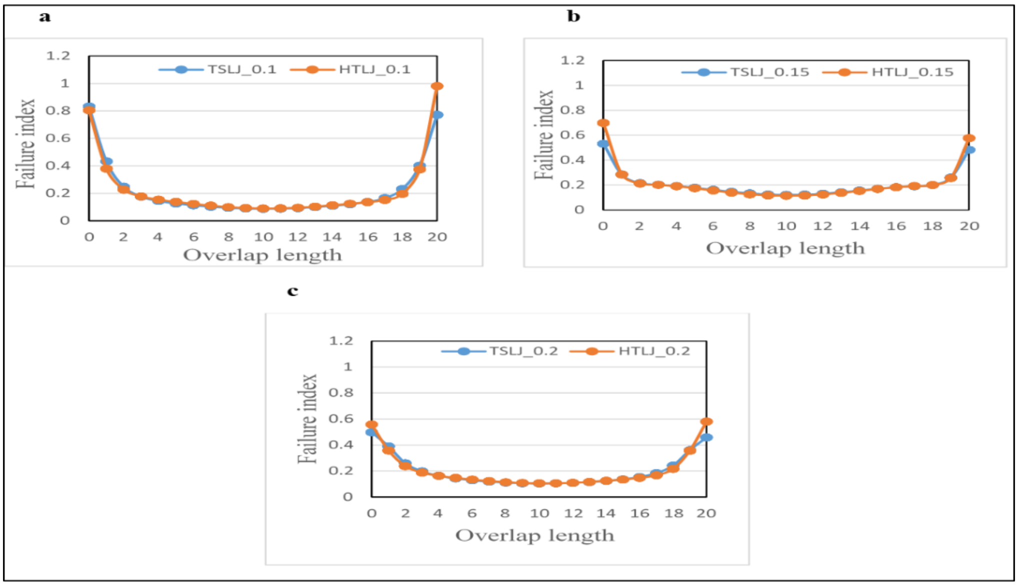


Fig.9 Failure index in mid adhesive layer of TSLJ and HTLJ

## 6. Conclusions:

Three-dimensional stress and failure analysis under tensile loading with effect of varying adhesive thicknessin TSLJ and HTLJ have been studied out in the present research. The parabolic yield criteria have been implemented for predicting the cohesion failure mode in adhesive bonded joint respectively. Numerical model of HTLJ was developed through ANSYS APDL. Normal stress components ($\sigma_r$) and radial-axial shear stress component ($\tau_{rz}$) have been observed all the bond line interfaces of the bonded HTLJ. The magnitude of stresses in HTLJ they are of negligible magnitudes compare to TSLJ. By comparing the failure index values of TSLJ and HTLJ.Failure index values attains maximum for HTLJ for 0.1 mm adhesive thickness. Whereas for 0.15mm and 0.2 mm adhesive thickness the values are within the limit. The suitable adhesive thickness has been determined by parabolic yield criteria. From it was observed by introducing hybridization by increasing the adhesive thickness reduction in the longitudinal shear stress and peel stress.

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