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Stress and Failure Analysis of Hybrid FRP Laminated Tubular Joints

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Abstract

Composite tubes have been used in transporting corrosive fluid in petro chemical and paper industries. [Fiber reinforced Polymers] FRP Composite Pipes are even becoming popular in the offshore oil and gas industry. Bonded joints with tubular adherends are finding applications in various piping industry. In the recent times Hybrid Tubular Bonded Lap Joints (HTLJ) have been extensively used to optimize the cost and to enhance the performance of the joint. Overlap length and adhesive thickness and stacking sequence are the parameters which outstandingly effect distribution of stress within the adhesive layer of the joint region. The existence of adhesively bonded tubular lap joints can be materially progress and reduce the stress concentration at the ends of overlap there by transmit the uniform stress for the entire bond line. The aim of this study is to estimate the interlaminar stresses build in adhesive layer in joint region by varying stacking sequence subjected to tensile loading to find the performance of the joint using finite element method. The onset of joint failures in the HTLJ has been estimated using the stress-criterion Tsai-Wu integration. Additionally presuming that the adhesive thickness is minimal in relation to the adherends. Tubular adherends with three material properties of Carbon/epoxy and E-glass /epoxy Kevlar 49/epoxy were considered. Numerical results good agreement is compared with available literature In this paper finite element analysis of hybrid FRP tubular lap joints have been performed.

Keywords: HTLJ, Tsai-Wu criteria, FRP composites, FEA, Inter-laminar stresses.

INTRODUCTION

Adhesive bonding has established and efficient method for joining tubular sections, finding common use in construction and energy industries. The adhesive bonding of tubular joints represents a prevalent type of lap joint, which is vital in applications involving the transportation of various fluids, particularly within interlayer hybrid composite tubes utilized for wastewater treatment, power generation, and petroleum production. The strength of bonded tubular joints can be enhanced by minimizing stress concentrations at the ends of the overlap and promoting a uniform stress distribution across through bond length. While a significant available literature discusses stress analysis in conventional adhesively bonded tubular lap joints, there exists a notable gap in the analysis of hybrid laminated fiber-reinforced polymer (FRP) tubular lap joints. For instance, Lubkin and Reissner [1] explored the stress distribution in tubular sections subjected to axial loading by applying thin-shell theory to analyze the stress field in tubes of small thickness. Adams and Peppiatt [2] conducted a comparative study on isotropic tubular lap joints, analyzing stress using closed-form solutions and finite element methods, offering insights into the behavior of such joints under loading. Furthermore, Y.R. Nagaraja et al. [3] examined the performance of bonded tubular lap joints under uniaxial loads, taking into account the nonlinear behavior of adhesives and highlighting

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the reduction in maximum stresses at the joint ends. Based on the complementary energy principle, an estimated closed-form solution & equilibrium equations, continuity conditions and stress boundary conditions was presented by Y.P. Shi and S. Cheng [4], demonstrating that maximum normal & high shear stresses typically occur at the overlap length ends. Thomsen [5] expanded the analysis to include adhesive bonded joints of dissimilar orthotropic laminated cylindrical shell elements, demonstrating that factors such as adherend stiffness, adhesive stiffness, and overlap length play critical roles in influencing stress distributions within the adhesive layer. These insights underscore the complexity of stress interactions in bonded tubular structures and highlight the need for further research, particularly in the realm of hybrid laminated FRP systems where existing studies are limited. Chihdar Yang. [6] An analytical model for tubular adhesive joints that use the potential energy of deformation and the variational principle was established by Nemes et al. [7]. This model provides a foundation for understanding the mechanical behavior of adhesive joints.A. Zuriada et al. [8] explored the influence of stacking sequence and hybridization on the behavior of failure of hybrid composite filament tubes, indicating that these factors significantly affect strain distributions. S. Kumar [9] highlighted that the modulus variation of the bond line adhesive can reduce stress concentrations in adhesive joints under tensile loading, which is essential for optimizing joint design. The Tsai-Wu failure criterion, employed by R.R. Das and B. Pradhan [10], serves as a benchmark for evaluating the suitability of overlap lengths in adhesive joints under tensile loads. Ch. Kannan et al. [11] investigate the hybrid effect enhances the strength and stiffness of composite tubes compared to conventional designs, reinforcing the need for comprehensive modelling to capture these benefits. Effects of Hybridization and Stacking Sequence Research by Ammar Maziz et al. [12] demonstrated that orientation angles and stacking sequences which influence stress distributions through the thickness of hybrid composite tubes, further emphasizing the importance of these parameters in joint performance. Developing FEM-based numerical model to analyze hybrid FRP laminated tubular lap joints. Forecasting the 3D stress distributions in the adhesive layer under tensile loading. Identifying failure-prone regions within the bonded joints to evaluate design improvements.

NUMERICAL METHOD

Stress Analysis of HTLJ

To evaluate the stress distributions in HTLJ the 3dimensional FEA is performed to calculate the out-of-plane stresses (σ_r, τ_{zr}) adhesive mid layer in the overlap region. The material properties and geometrical parameters for tubular adherends of FRP and adhesive epoxy orthotropic and isotropic properties are given in Table 1 and Table 2. As illustrated in Figure 1, the loading & boundary conditions for the geometry of bonded HTLJ are taken into consideration in the current analysis. For laminated FRP [Fibre Reinforced Polymers] adherends as composite pipes, the ply orientations for the HTLJ have been determined to be [0/90]s. Because interfacial failures are found to be resisted by plies orientated in the direction of applied tensile force and are appropriate orientation this is refered from Das and Pradan [10].

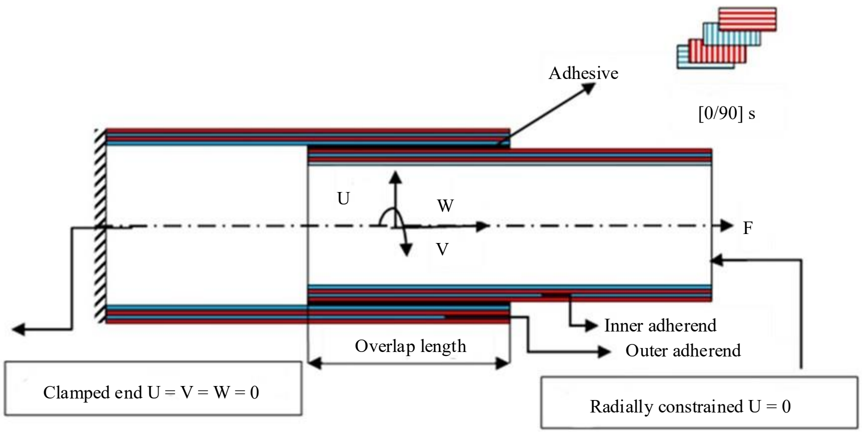

Figure 1. Sectional view of hybrid tubular lap joint.

Table 1. Material properties composite adherends and adhesive.

Joint materials	Material constants
1.T300/934graphite/epoxy	Ez 127.5GPa, Er 4.8 GPa E9GPa GG: 4.8GPa Ger 2.55GPa ϋθ 0.28 or 0.41
2. E-Glass/epoxy	E-41GPa, EE=10.4GPa GreGr=4.3GPa, Go 3.5GPa Dre Dre 0.2800 -0.50 E-80GPa Eo E-5.5GPa Gre= G=2.2GPa
3. Kevlar-49/epoxy	Go: 1.8GPa ϋθ= $ϋ_{r2}$ =0.34 ϋθ =0.40 E=2.8GPa
4.Epoxy adhesive(isotropic)	ϋ=0.4

Table 2. Geometric parameters of composite adherends.

Stacking sequence	[0/90]s
Adherend lengths	L = 80mm
Overlap length	I = 20mm
Adhesive thickness	ta = 0.15mm
Adherend thickness	$t_1 = t_2$ = 1mm
Inner radius of inner Adherend	18.9 mm
Inner radius of outer Adherend	20.05 mm

Two plies of T300/934 graphite/epoxy [Gr] and two plies of E-Glass/epoxy [G] and Kevlar/epoxy [K] with a layup configuration of sequence [G/Gr/G/Gr] and [G/K/G/K] and [G/G/Gr/Gr], [G/G/K/K], and [G/G/Gr/Gr], which are similar in length and thickness, were used as FRP laminated composite tubular adherends with interlayer hybridization. Hybrid tubular lap joint has been modeled by applying the finite element method. 8 node Brick elements are used for modeling the composite adherends & adhesive layer. The geometrical model of the bonded HTLJ & lay up sequence has been shown in Figure 2. (a) & (b). The research paper discusses the meshing pattern and boundary conditions for simulating pure axial loading in a hybrid tubular lap joint (HTLJ) using finite element analysis. It highlights that a finer meshing pattern is utilized around the joint region and coarser mesh is employed towards the free and fixed edges, as depicted in Figures 3(a) and 3(b). The boundary conditions are specified: at the clamped end of the outer tube, all displacement components (U=V=W=0) are constrained for all nodes, while at the loaded inner tube end, axial displacement is constrained (U=0) for all nodes. The significance of accuracy and clarity in these descriptions is emphasised in the summary. The chosen mesh density effectively produces stress values in the middle layer of the adhesive that align closely to findings from existing literature.

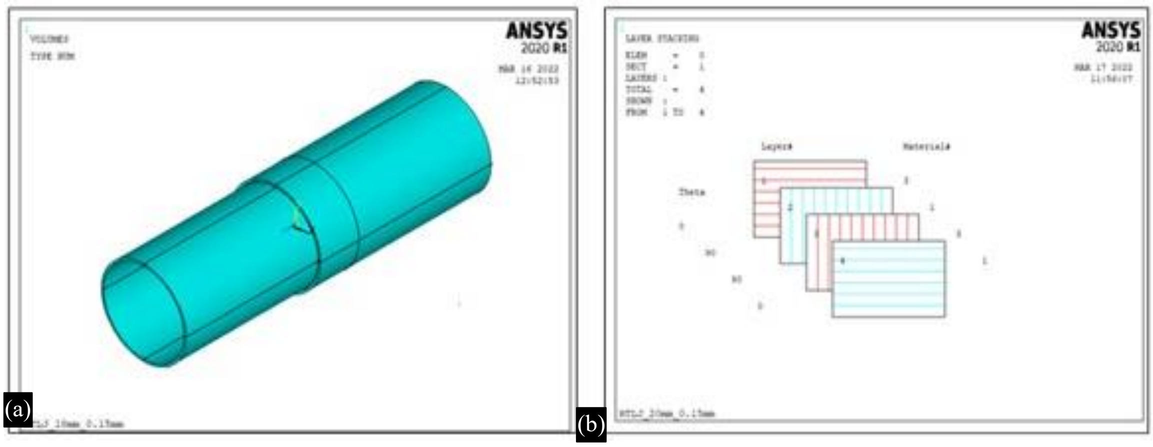

Figure 2. (a) Geometrical model of HTLJ (b) Lay-up sequence of HTLJ.

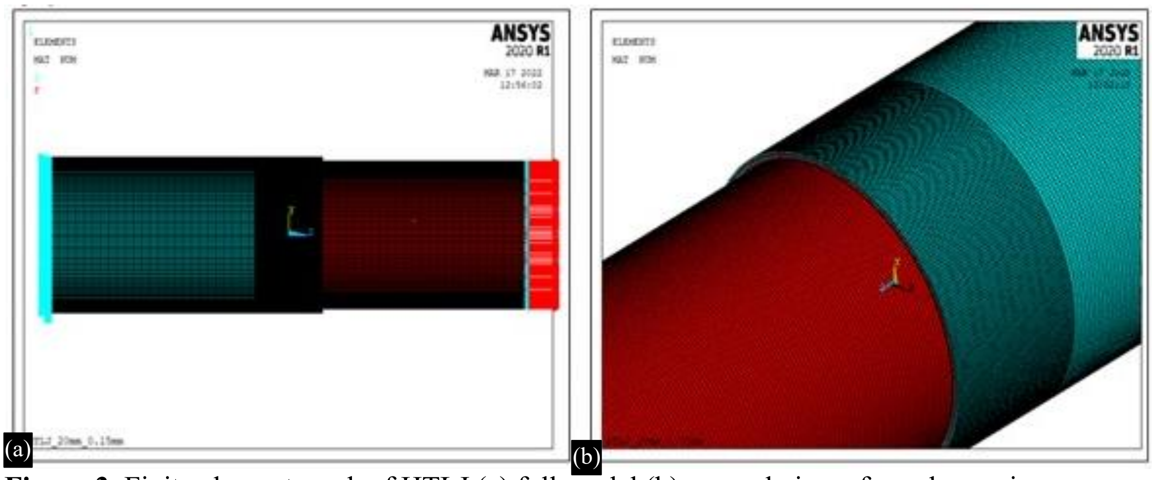

Figure 3. Finite element mesh of HTLJ (a) full model (b)zoomed view of overlap region.

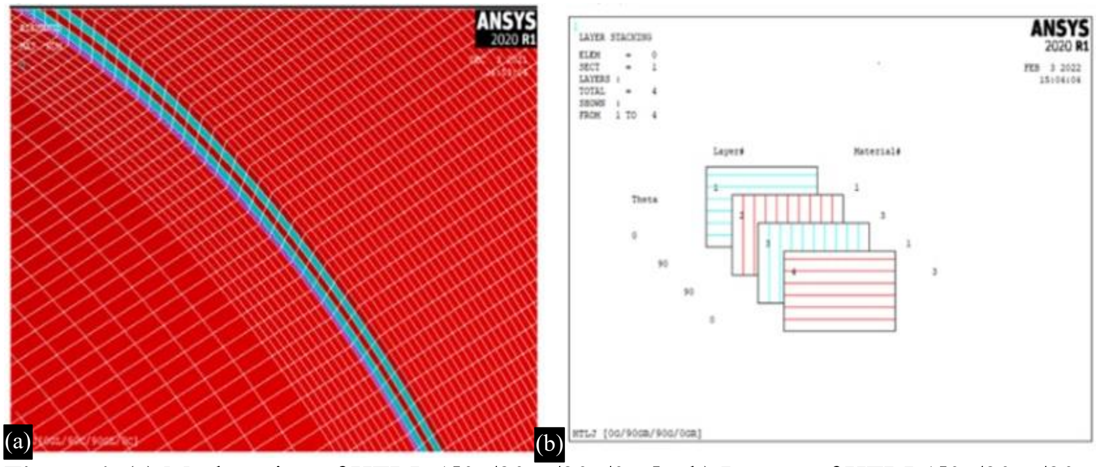

Figure 4. (a) Mesh region of HTLJ -1[$0_G/90_{GR}/90_G/0_{GR}$] $_T$ (b) Lay-up of HTLJ-1[$0_G/90_{GR}/90_G/0_{GR}$] $_T$

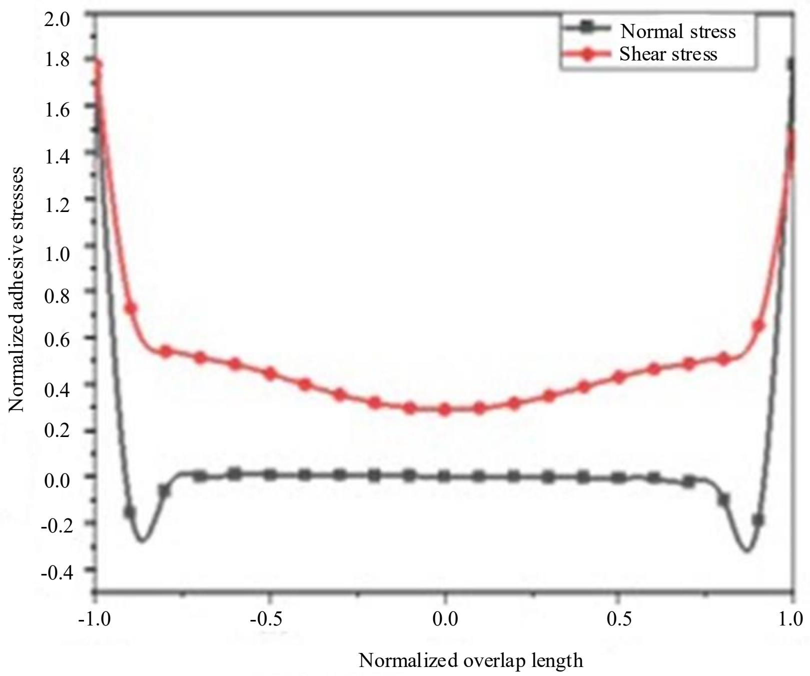

Figure 5. Normal stress and shear stress distribution in HTLJ-1 [$0_G/90_{GR}/90_G/0_{GR}$] T

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HTLJ -1

In HTLJ-1 the lay-up configuration in HTLJ-1 of two FRP laminated composite tubes used as adherends. (Glass/epoxy and Graphite/epoxy) with $[0/90]_s$ used as adherends. Mesh section & lay-up sequence of HTLJ-1$[0_G/90_{GR}/90_G/0_{GR}]_T$ as shown in Figure 4. (a) & (b). For HTLJ-1 Distribution of Normal stresses and shear stresses HTLJ-1 $[0_G/90_{GR}/90_G/0_{GR}]_T$ as shown in Figure.5

HTLJ-2

In HTLJ-2 the lay-up configuration in HTLJ-2 of two laminated FRP composite tubes used as adherends. (Glass/epoxy and kevlar/epoxy) with $[0/90]_s$ used as adherends Mesh region and Lay-up sequence of HTLJ -2$[0_G/90_K/90_G/0_K]_T$ as shown in Figure 6(a) and (b). For HTLJ-2 Normal stresses and shear stresses in HTLJ-2 $[0_G/90_K/90_G/0_K]_T$ as shown in Figure 7

HTLJ -3

In HTLJ-3 the lay-up configuration in HTLJ-3 of two FRP laminated composite tubes used as adherends. (Glass/epoxy and Graphite/epoxy) with $[0/90]_s$ used as adherends Mesh region and Lay-up sequence of HTLJ-3 $[0_G/90_G/90_{GR}/0_{GR}]_T$ as shown in Figure 8(a) and (b). For HTLJ -3 Normal stresses and shear stresses in HTLJ-3 $[0_G/90_G/90_{GR}/0_{GR}]_T$ as shown in Figure 9.

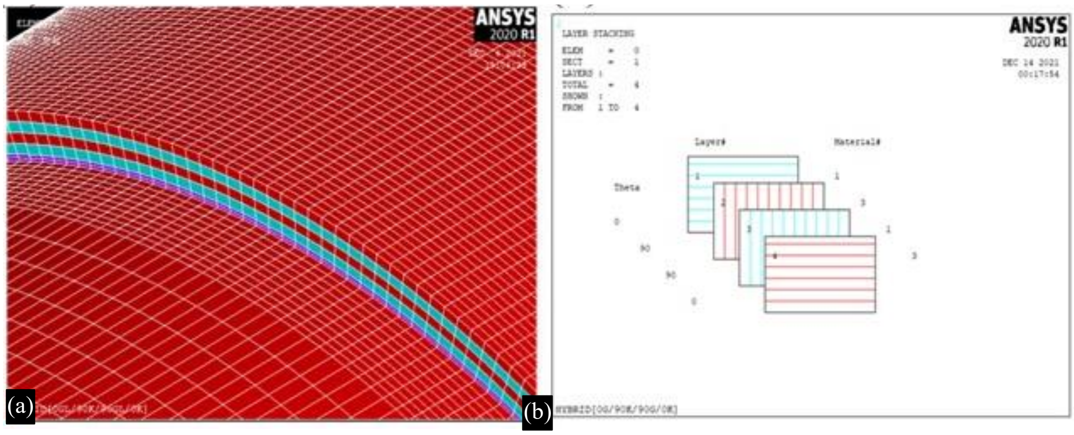

Figure 6. (a) Mesh region of HTLJ-2 $[0_G/90_K/90_G/0_K]_T$ (b) Lay-up of HTLJ-2 $[0_G/90_K/90_G/0_K]_T$.

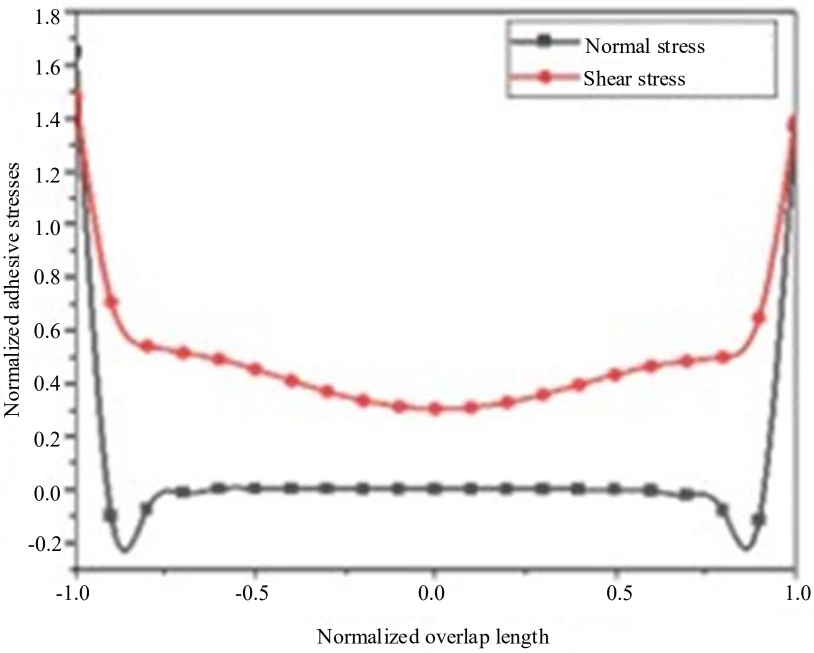

Figure 7. Normal stress and shear stress distribution in HTLJ-2 $[0_G/90_K/90_G/0_K]$ T

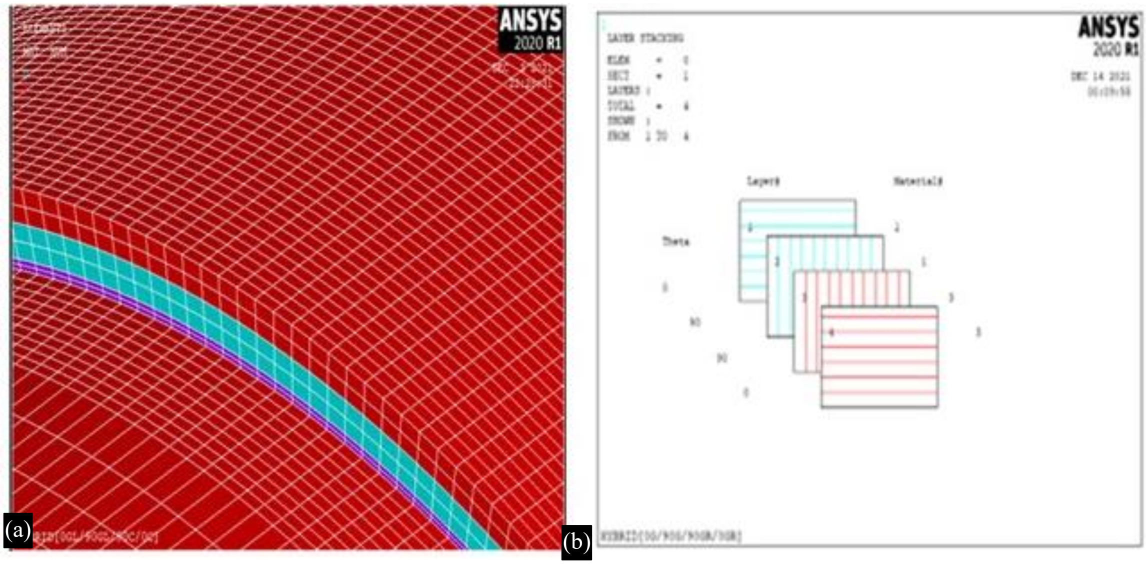

Figure 8. (a) Mesh region of HTLJ-3 $[0_G/90_G/90_{GR}/0_{GR}]_T$ (b) Lay-up of HTLJ-3 $[0_G/90_G/90_{GR}/0_{GR}]_T$

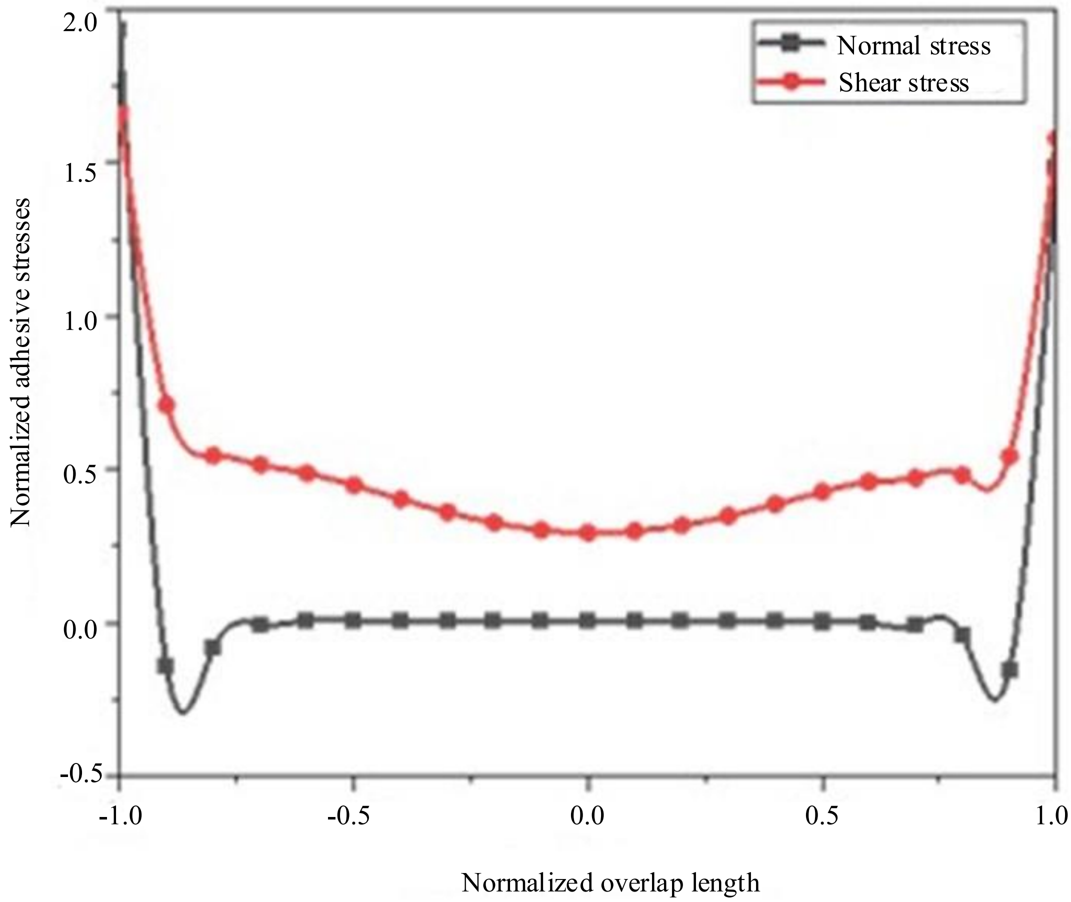

Figure 9. Normal stress and shear stress distribution in HTLJ -3$[0_G/90_G/90_{GR}/0_{GR}]_T$.

HTLJ -4

In the lay-up configuration in HTLJ-4 of two FRP laminated composite tubes used as adherends. (Glass/epoxy and kevlar/epoxy) with $[0/90]_s$ used as adherends Mesh region and Lay-up Sequence of HTLJ $[0_G/90_G/90_K/0_K]_T$ as shown in Figure 10(a) and 10(b). For HTLJ -4 Distribution of Normal stresses and shear stresses HTLJ $[0_G/90_G/90_K/0_K]_T$as shown in Figure 11.

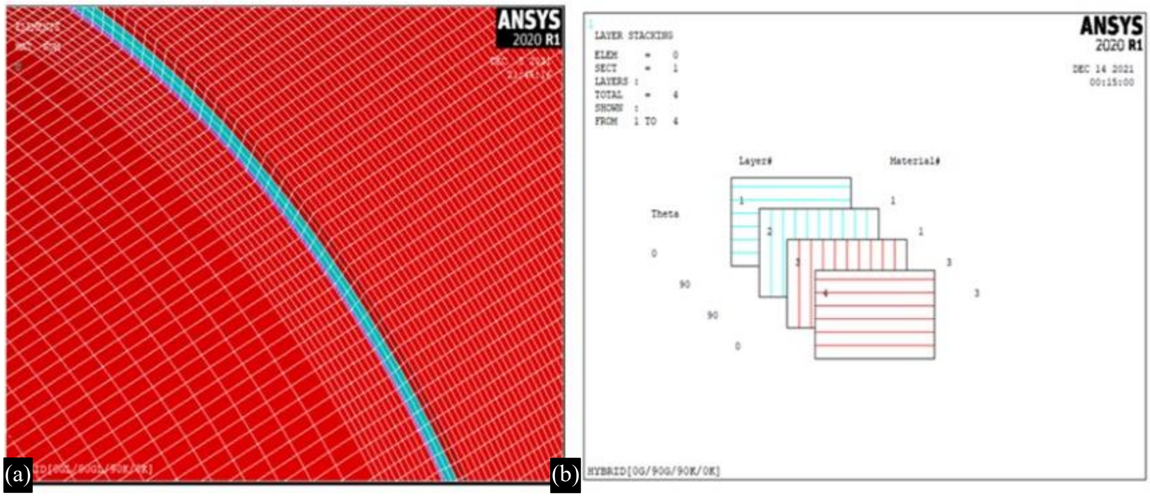

Figure 10. (a) Mesh region of HTLJ-4 $[0_G/90_G/90_K/0_K]_T$ (b) Lay-up of HTLJ-4 $[0_G/90_G/90_K/0_K]_T$..

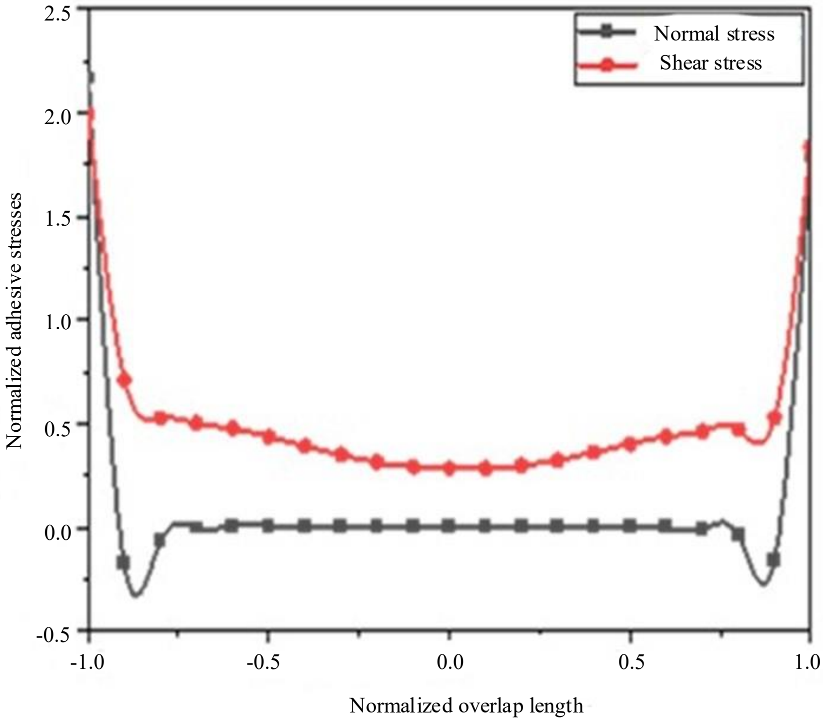

Figure 11. Normal stress and shear stress distribution in HTLJ-4 $[0_G/90_G/90_K/90_K]_T$.

FAILUREANALYSIS OF HTLJ

The adhesive bonded joints are experiences two types of failures a) failure in adherends due to adhesion which occurs between the adhesive and the adherend b) cohesion failure is within the adhesive. A part from these inter laminar delamination is occur in the composite adherends. Delamination damage analyses were performed by many authors by presumed delamination and damages at the adhesive-adherend and ply interfaces at various locations in composite adherends the damage initiation due to delamination at ply interfaces of composite tubular adherends of failure index value has been evaluated by the Tsai-Wu quadratic failure criterion which takes into account of six stress components given by.

$$\frac{\sigma_r^2}{R_T^2}+\frac{\sigma_\theta^2}{\theta_T^2}+\frac{\sigma_Z^2}{Z_T^2}+\frac{\tau_{\theta r}^2}{S_{\theta r}^2}+\frac{\tau_{zr}^2}{S_{zr}^2}+\frac{\tau_{z\theta}^2}{S_{z\theta}^2}+\sigma_r\left(\frac{1}{R_T}-\frac{1}{R_C}\right)+\sigma_\theta\left(\frac{1}{\theta_T}-\frac{1}{\theta_C}\right)+\sigma_Z\left(\frac{1}{Z_T}-\frac{1}{Z_C}\right)+f_{\theta r}\sigma_\theta\sigma_r+ f_{zr}\sigma_z\sigma_r+f_{z\theta}\sigma_z\sigma_\theta=e^2\begin{cases}e\geq 1, & failure\\ e<1, nofailure\end{cases} \quad (1)$$

Where, the three principal material directions of R_T, Θ_T, Z_T are the allowable tensile strengths and R_C, Θ_C, Z_C are the allowable compressive strengths respectively. The orthotropic layer's $S_{\theta r}$, S_{zr} & $S_{z\theta}$ shear strengths in different coupling modes. $f_{\theta r}$, $f_{zr}$and $f_{z\theta}$ respectively are the coupling coefficients that represent the interaction between r, ɵ and z directions. To assess the state of the structure and determine its likelihood of failure. Failure index (e) is the measure that failure happens if $e \geq 1$; else, failure does not occur. To predict the damage intitation Generally, the interlaminar or out-of-plane stresses are responsible for the initiation of adhesion and delamination failures and hence only the interlaminar shear stresses ($\tau_{\theta r}$, τ_{zr}) and the through-the-thickness normal stress or peel stress (σ_r). Therefore, the Tsai-Wu criterion given in Eq. (1) reduces to the form as

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

Where interlaminar normal strength R_T & interlaminar shear strengths of $S_{\theta r}$ and S_{zr} with the two orthogonal shear coupling directions.

The cohesion failure which is occurs within the adhesive layer. Finding the location of cohesion failure in the adhesively bonded tubular lap joint can be determined using a failure index within the joint region. However, thereby using the parabolic yield criterion for isotropic materials. The failure of the adhesively bonded tubular lap joint (TSLJ) within the adhesive layer has been calculated by the value of failure index to identify the location of cohesion failure initiation in the joint region. The criterion used for this evaluation is given by:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 2(|Y_C| - Y_T)(\sigma_1 + \sigma_2 + \sigma_3) = 2|Y_C|Y_{Te} \quad (3)$$

The failure index value in adhesive for adhesive bonded tubular joints by knowing principle stresses of σ_1, σ_2 and σ_3 from the analysis in the adhesive yield strengths of tensile and compressive causing yield in isotropic material. The earlier yield criterion is thought to decrease to the most well-known Von-Mises yield criterion when YC and YT are equal. From the parabolic yield criteria equation (3) is used to find the failure index value in adhesive layer for TSLJ and HTLJ of various models Hybrid-1, Hybrid-2, Hybrid-3. Hybrid-4 compared to TSLJ as shown in Figure 12 (a) and (b).

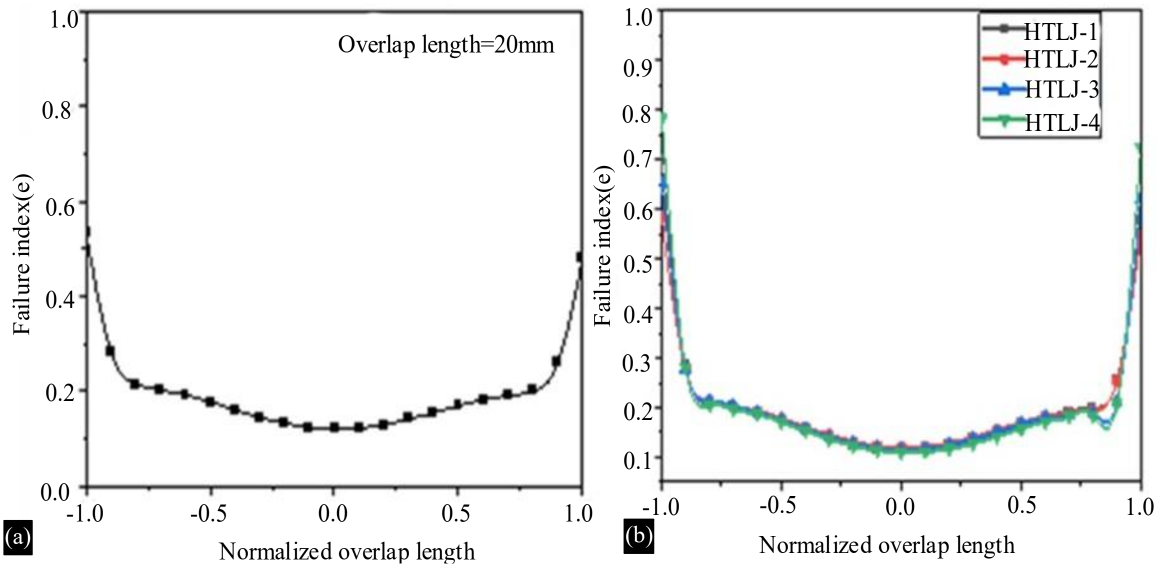

Figure 12. (a) Failure index value for TSLJ(b) failure index value for HTLJ-1,2,3,4.

RESULT AND DISCUSSIONS

Validation of FE Model: To validate the Finite Element (FE) modeling and simulation technique developed for the bonded Hybrid Tubular Lap Joint (HTLJ), the analytical results of Thomsen [5] and Pradhan [12] have been compared in the present analysis. This process ensures that the FE model accurately predicts the stress distribution, failure modes, and other critical parameters involved in the adhesive joint's behavior. The maximum peel stresses are occurred at the overlap length edges, and after reduce drastically and remain consistent over a greater portion of the overlap region for isotropic adherend's and composite adherends as shown in Figure 13(a) and (b). The maximum shear stress (τ_{zr}) occur at overlap length edges the edges. (like peel stress), thereafter decrease acutely and become the minimum at the mid-span of the overlap length as shown in Figure 14(a), (b). This behavior demonstrates qualitative agreement with the findings documented in the literature that is currently available. The analysis of Tubular Single Lap Joints (TSLJs) reveals important insights into stress distribution in adherend-adhesive interfaces. Peak peel stresses at the inner interface are highest near the clamped end due to concentrated stresses, while at the outer interface, peak stresses occur near the loaded end, reflecting different stress patterns influenced by external loads. This variation underscores the complexity of adhesive joints, highlighting the critical interplay between load application and geometric constraints. Understanding these stress distributions is essential for optimizing TSLJ design and enhancing joint reliability; targeted reinforcement in stress-critical areas can improve performance. Further research into adhesive properties and load responses may help address failure mechanisms related to stress concentrations.

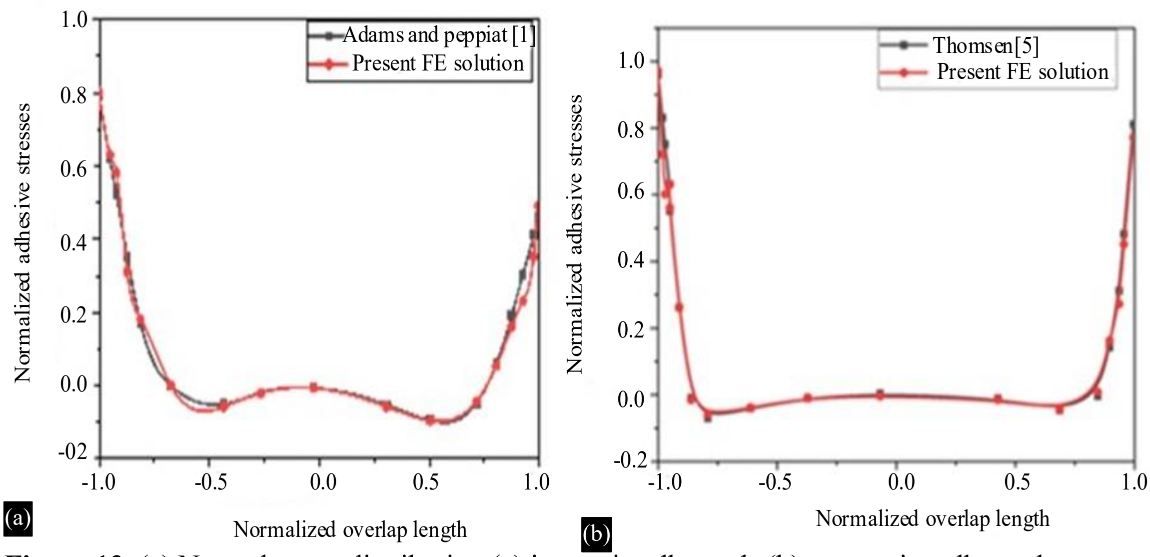

Figure 13. (a) Normal stress distribution (a) isotropic adherends (b) composite adherends.

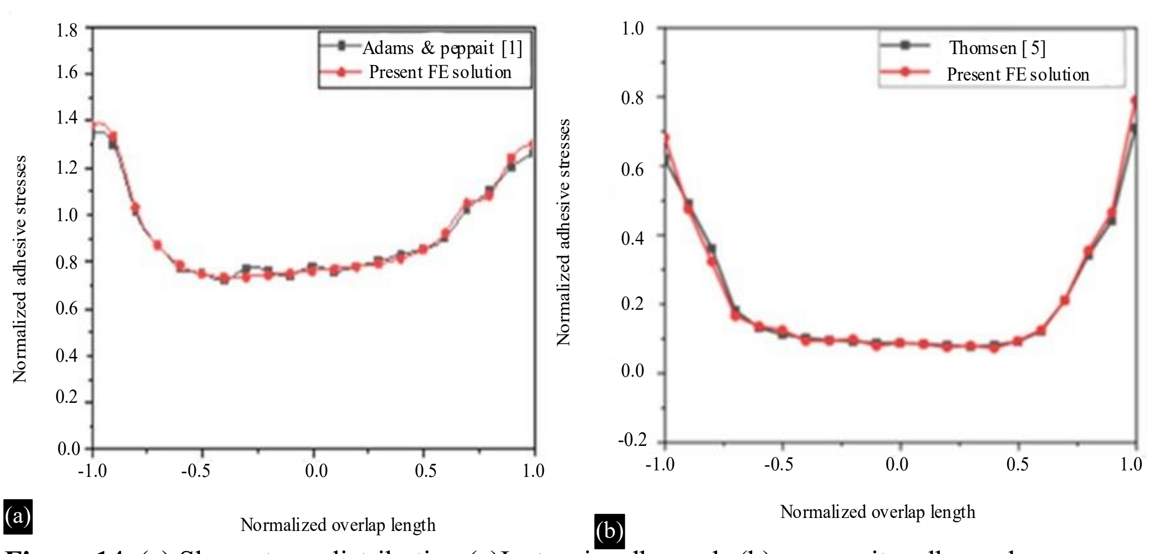

Figure 14. (a) Shear stress distribution (a)Isotropic adherends (b) composite adherends.

Comparison of TSLJ and HTLJ

The stress distributions of different configurations of HTLJ are compared with conventional TSLJ. By observing the Model-1 and Model-2 of HTLJ $[0_G/90_{GR}/90_G/0_{GR}]_T$ and HTLJ $[0_G/90_K/90_G/0_K]_T$ as shown in Figure 5 and 7 the Normal and shear stress values are higher for HTLJ $[0_G/90_{GR}/90_G/0_{GR}]_T$ compare to HTLJ $[0_G/90_K/90_G/0_K]_T$ and from Model-3 and Model-4 of HTLJ $[0_G/90_G/90_{GR}/0_{GR}]_T$ HTLJ$[0_G/90_G/90_K/0_K]_T$ as shown in Fig .9 and Figure 11The normal and shear stress values are higher for HTLJ$[0_G/90_G/90_K/0_K]_T$ compared HTLJ $[0_G/90_G/90_{GR}/0_{GR}]_T$ .The maximum peel stresses occur at the edges of the overlap length. After reaching this peak, the peel stress decreases significantly and then remain constant over a larger portion of the overlap region. This indicates that the adhesive joint is subjected to the highest peel stress near the edges, but the stress levels stabilize as you move inward from the edges. Alike peel stresses, shear stresses also reach their extreme values at the edges of the overlap. The shear stress profile follows a similar trend , it peaks at the overlap boundaries and then decreases as you move towards the center of the overlap region, there after reduce drastically and become the minimum at the mid-span of the overlap length as shown in Figure 15(a) and (b) It is evident from the stress analysis that there are large tensile peel stresses near end of the overlap length near the clamped end of HTLJ was observed similar to TSLJ.Where failure index value was compared with HTLJ and TSLJ as shown in Figure 15(a) and Figure 15(b). It is observed that the failure index value is less than 1(e≥1) for both HTLJ and TSLJ. Distribution of Normal stresses and shear stresses HTLJ $[0_G/90_{GR}/90_G/0_{GR}]_T$ and $[0_G/90_K/90_G/0_K]_T$ Compared to TSLJ Distribution of Normal stresses and shear stresses HTLJ $[0_G/90_G/90_{GR}/0_{GR}]_T$ and $[0_G/90_G/90_K/0_K]_T$ compared to TSLJ.

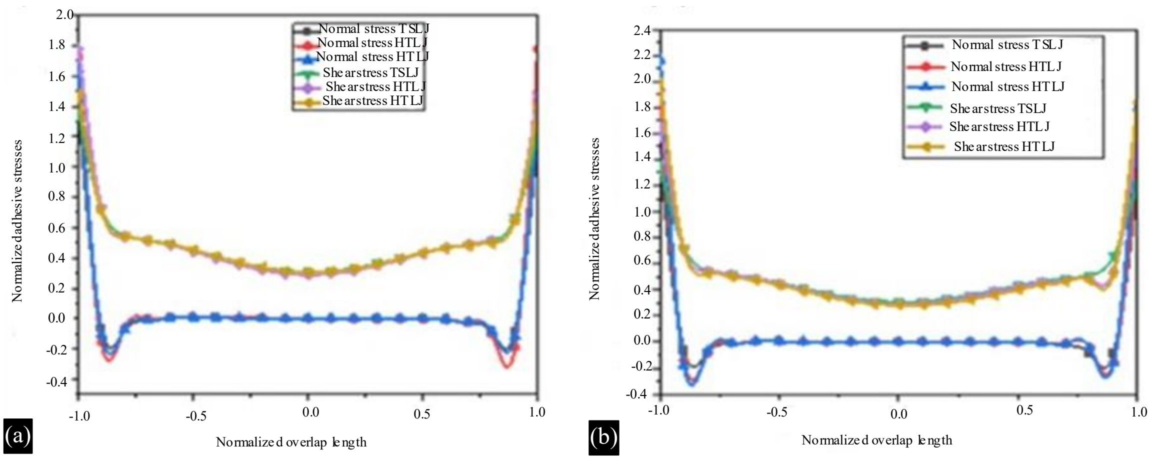

Figure 15. (a) Normal stresses and shear stresses HTLJ-1,2(b) Normal stresses and shear stresses HTLJ-3,4,compared to TSLJ

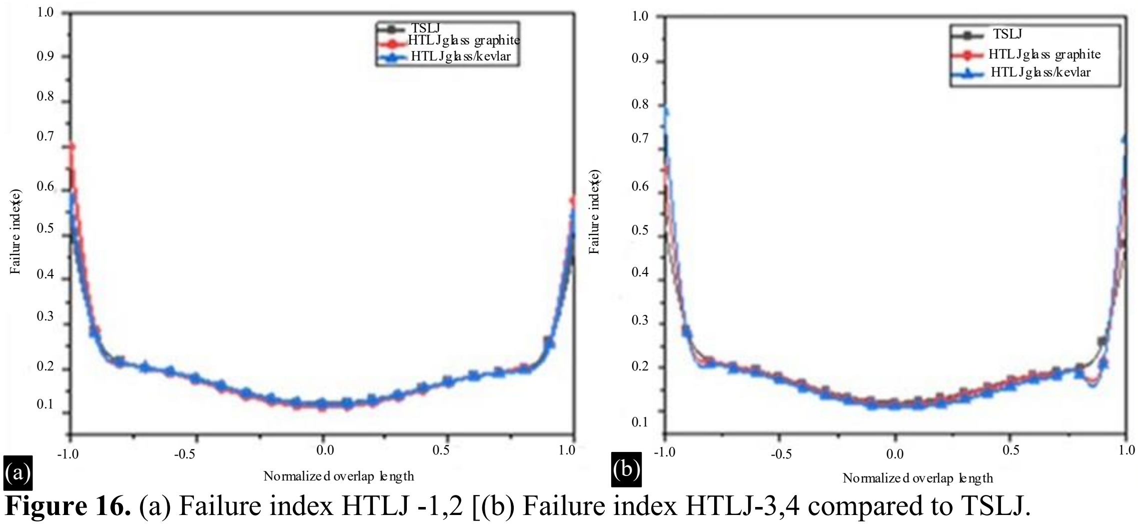

Figure 16. (a) Failure index HTLJ -1,2 [(b) Failure index HTLJ-3,4 compared to TSLJ.

CONCLUSIONS

A finite element analysis of the HTLJ has been performed for different hybrid models of HTLJ -1, HTLJ-2, HTLJ-3, HTLJ-4 of interlayer hybrid composite adherends. The study investigates the normal and shear stresses in the adhesive mid-layer of joints, comparing the results with existing literature. The key findings highlight the following failure modes adhesion failure and cohesion failure. The study employs the parabolic yield criterion to evaluate the failure index values in the adhesive layer for different hybrid models. These values are compared with the numerical results of a Tubular Single Lap Joint (TSLJ), showing good agreement with available literature.

The results suggest that interlayer hybrid adherends can significantly improve the performance of adhesive joints. These hybrid models can help enhance the structural integrity of the joint while reducing overall costs, making them a viable option for improving joint performance in structural applications.

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REFERENCES

1. Adams, R. D., & Peppiatt, N. A. Stress Analysis of Adhesive Bonded Tubular Lap Joints. The Journal of Adhesion, 1977; 9(1), 1-18. p.
2. Y. R. Nagaraja& R. S. Alwar. Nonlinear Stress Analysis of an Adhesive Tubular Lap Joint. The Journal of Adhesion, 1979; 10:2, 97-106 p.
3. Choon T. Chon. Analysis of Tubular Lap Joint in Torsion. Journal of Composite Materials, 1982; 16: 268
4. Philip J. Hipol. Analysis and Optimization of a Tubular Lap Joint Subjected to Torsion, Journal of Composite Materials, 1983; 18.
5. Thomsen OT. Elasto-static and elasto-plastic stress analysis of adhesive bonded tubular lap joints. Composite Structures, 1992; 21,249-59 p.
6. Chihdar Yang Design and Analysis of Composite Pipe Joints under Tensile Loading Journal of Composite Materials, 2000; 34.
7. Nemes, O. Lachaud, F., &Mojtabi, A. Contribution to the study of cylindrical adhesive joining. International Journal of Adhesion and Adhesives, 2006; 26(6), 474-480p.
8. Zuraida, A., Khalid, A. A., & Ismail, A. F. Performance of hybrid filament wound composite tubes subjected to quasi static indentation. Materials & Design, 2007; 28(1), 71
9. S. Kumar Analysis of tubular adhesive joints with a functionally modulus graded bond line subjected to axial loads. International Journal of Adhesion and Adhesives, 2009; 29:785-95p.
10. Das, R.R., & Pradhan, B. Adhesion failure analyses of bonded tubular single lap joints in laminated fibre reinforced plastic composites. International Journal of Adhesion and Adhesives, 2010; 30(6), 425-438p.
11. K.Chellamuthu Experimental and FE Simulation of Hybrid Composite Tubes Under Axial Compression Third Asian Conference on Mechanics of Functional Materials and Structures 2020;IIT Delhi.
12. Amar Maziz, Rechak, S., & Tarfaoui, M. Comparative study of tubular composite structure subjected to internal pressure loading: Analytical and numerical investigation. Journal of Composite Materials. 2020;1-17p.

