Failure Analysis of Hybrid FRP Composites Laminated Bonded Tubular Lap Joints

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Abstract: Fibre-reinforced polymer composites have found extensive applications in the oil, gas industries. The use of interlayer Hybrid composite pipes are used in several engineering applications is increasing due to their superior properties such as high specific strength, high chemical resistance and resistance to UV rays .Hybrid composite adherends lap joints need to be explored to develop a cost-effective combination of materials to address the certain complex behavior due to hybridization . It is essential to understand the mechanical behavior of Hybrid Tubular Lap Joints (HTLJ) to provide design guidelines for safe performance of joint. In the present work Failure analysis of the adhesively bonded HTLJ is performed. Stress distributions within the joint region are estimated under tensile load. Failure indices at critical interfaces are evaluated by using Quadratic Failure Criterion (QFC).The failure index values of HTLJ were obtained for different overlap lengths. Effective overlap length for suitable performance of the joint is determined based on the Tsai-Wu failure criterion.

Key words: Hybrid FRP Laminated tubular lap joint , QFC, Failure analysis

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] analyzed 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] Analyzed 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 behavior 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 by Y.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 behavior 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].The Purpose of the present research is to develop a numerical model hybrid FRP laminated tubular lap joint using FEM consisting of layered brick elements for the adhesive and adherends. This can properly predict the three-dimensional stress distributions along with failure prone regions in adhesively bonded tubular joints individually subjected to tensile loading.

2. Numerical Model and Validation:

The geometry, loading, and boundary conditions for the bonded HTLJ specimen considered in the present analyses are shown in Figure 1. The ply orientations for the HTLJ of laminated FRP composite made pipes (adherends) have been considered to be $[0/90]_s$ Because plies oriented in the direction of applied tensile load are found to be the best orientation for resisting interfacial failures which was referred from Das and pradan [10].The laminated FRP composite tubular adherends with interlayer hybridization using two plies of T300/934 graphite/epoxy and two plies of E-Glass/epoxy of layup configuration of sequence [GL/C/GL/C] was used as a Tubular adherends which are similar with respect to length, thickness. The material properties along with their strength values for the orthotropic FRP composite made tubular adherends (pipes) and isotropic epoxy adhesive are given in Table 1. The inside radius of the inner tube (r_1=18.9 mm), thickness of both the adherends (t = 1mm) and length of each adherend (l=80 mm) have been kept constant throughout the analysis. The adhesive layer thickness was chosen to be 0.15 mm, for all overlap lengths.

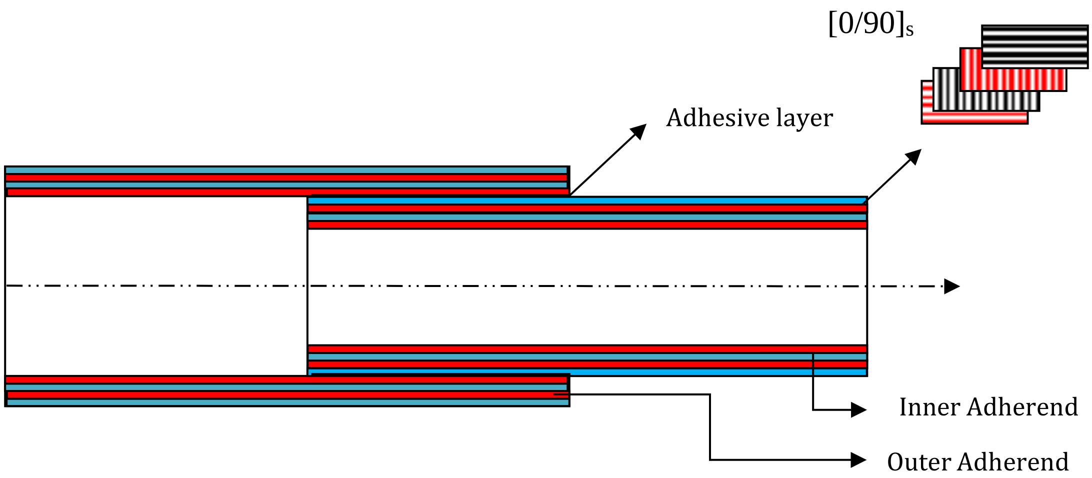

Fig 1: Sectional view of Hybrid Tubular lap joint

Table 1: Material properties and strength of composite adherends and adhesive.

Joint materials	Material constants	Strengths
1. T300/934 graphite/epoxy FRP composite adherend	E_Z = 127.5GPa E_r = 4.8 GPa E_Θ = 9GPa $\upsilon_{zr} = \upsilon_{z\Theta}$= 0.28 $\upsilon_{\Theta r}$=0.41 G_{zr}= $G_{z\Theta}$ = 4.8GPa $G_{\Theta r}$=2.55GPa	Z_T = 1586 MPa Z_C = 1518 MPa $\Theta_T = \Theta_C$= 80MPa $R_T = R_C$ = 49 MPa $S_{\Theta r} = S_{zr}$ = 2.55MPa
2. E-Glass/epoxy	E_1=41GPa $E_2 = E_3$ =10.4GPa $G_{12} = G_{13}$ = 4.3GPa G_{23} = 3.5GPa	F_T = 39 MPa F_C= 89 MPa F_6= 4.3MPa
3. Epoxy adhesive(isotropic)	E=2.8 GPa υ= 0.4	Yield strengths: Y_T =65 MPa Y_C =84.5 MPa

The bonded HTLJ has been modeled using the FE codes of ANSYS 2020R1. Solid 8-node brick 185 elements have been used for modeling the adherends and adhesive layer. The geometrical model of the bonded HTLJ and lay up sequence has been shown in Fig.2 (a) and (b. A very fine mesh has been adopted to take care of high stress gradients at the free edges of the joint. The element size in the overlap region has been considered to be 1 parts × 80 parts × 100 parts for both the adherend and adhesive layer. 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.3(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 z=-(l-c); i.e. at the clamped end of the outer tube, and U=0, for all nodes along r=r1 and z= + (l-c); i.e. at the loaded end of the inner tube. In order to validate the FE modeling and simulation technique developed for the bonded HTLJ analytical results of thomsen [5] and pradan [10] have been considered in the present analysis.

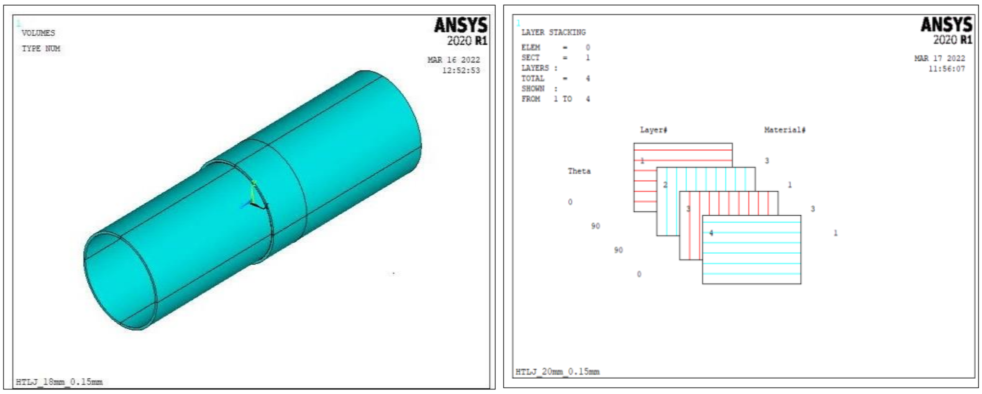

Fig 2: (a) Geometrical model of HTLJ (b) Lay-up sequence of HTLJ

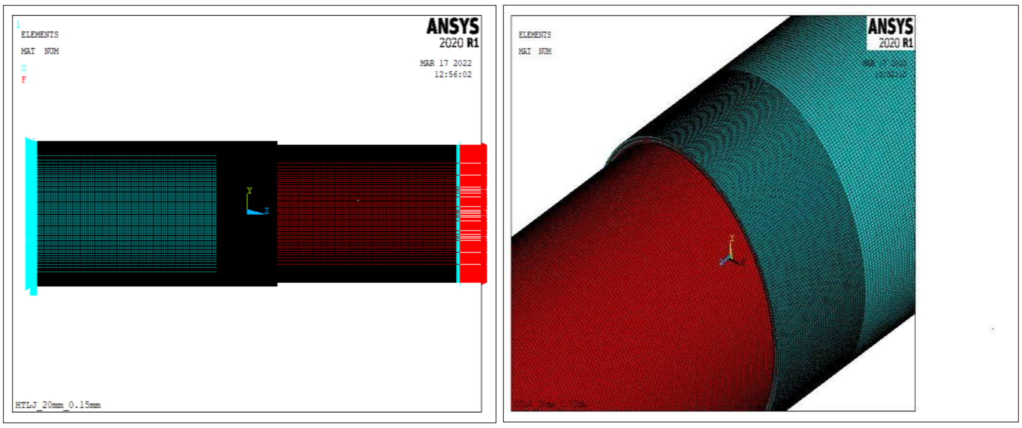

Fig 3: Finite element mesh of HTLJ (a) full model (b) zoomed view of overlap region

2.1 validation of F.E. model:

In order to verify the modeling procedure described in the present study. The FE results of HTLJ are compared with Thomsen [5] and pradan [10]. Validated results were shown in Fig 4(a) and 4(b). The peel and shear stress distribution of TSLJ and HTLJ are similar maximum at the joint edges

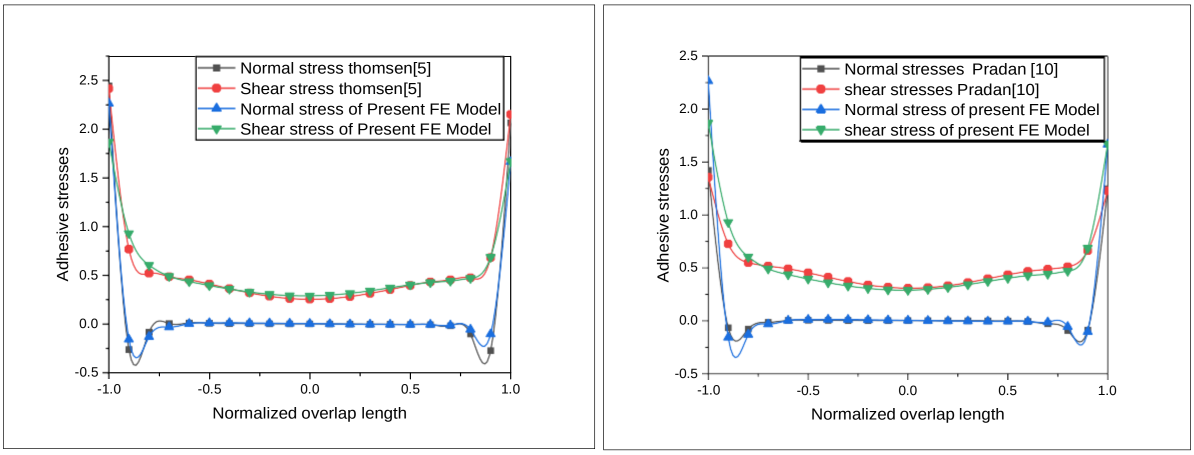

Fig 4(a): Adhesive stress distribution in thomsen [5] and HTLJ (b) Adhesive stress distribution in pradan [10] and HTLJ

3. Results and Discussion

In the present analysis Three different bond line interfaces have been identified to be the critical regions prone to stress concentration has been indicated (i) interface between the inner tube and adhesive, (ii) adhesive mid-layer, and (iii) interface between the outer tube and adhesive. The out-of-plane shear and normal stresses (σr, $\tau_{r\Theta}$ τ_{rz}) have been assumed to be playing a major role towards initiation of adhesion and cohesion failures Pradhan [10]. Hence during stress analysis within the joint region only these stresses have been considered in all the bond line interfaces of HTLJ. It was observed that middle and outer layers exhibited negligible failure index, while inner layer showed considerably higher values for the same adhesive thickness for different overlap lengths. This may be interpreted as increased chance of failure in the inner layer. Failure index of HTLJ with different overlap lengths at inner adherend and adhesive interface have been calculated and are represented as shown in Fig 4 and at two zones of joint region at interface of inner adherend adhesive interface and at outer adherend adhesive combined for all overlap lengths are shown in Fig 6. Compare to all lengths when for overlap length of 24 mm, the failure index was found to be minimum in all the cases. Hence, overlap length of 24mm considered for further studies.

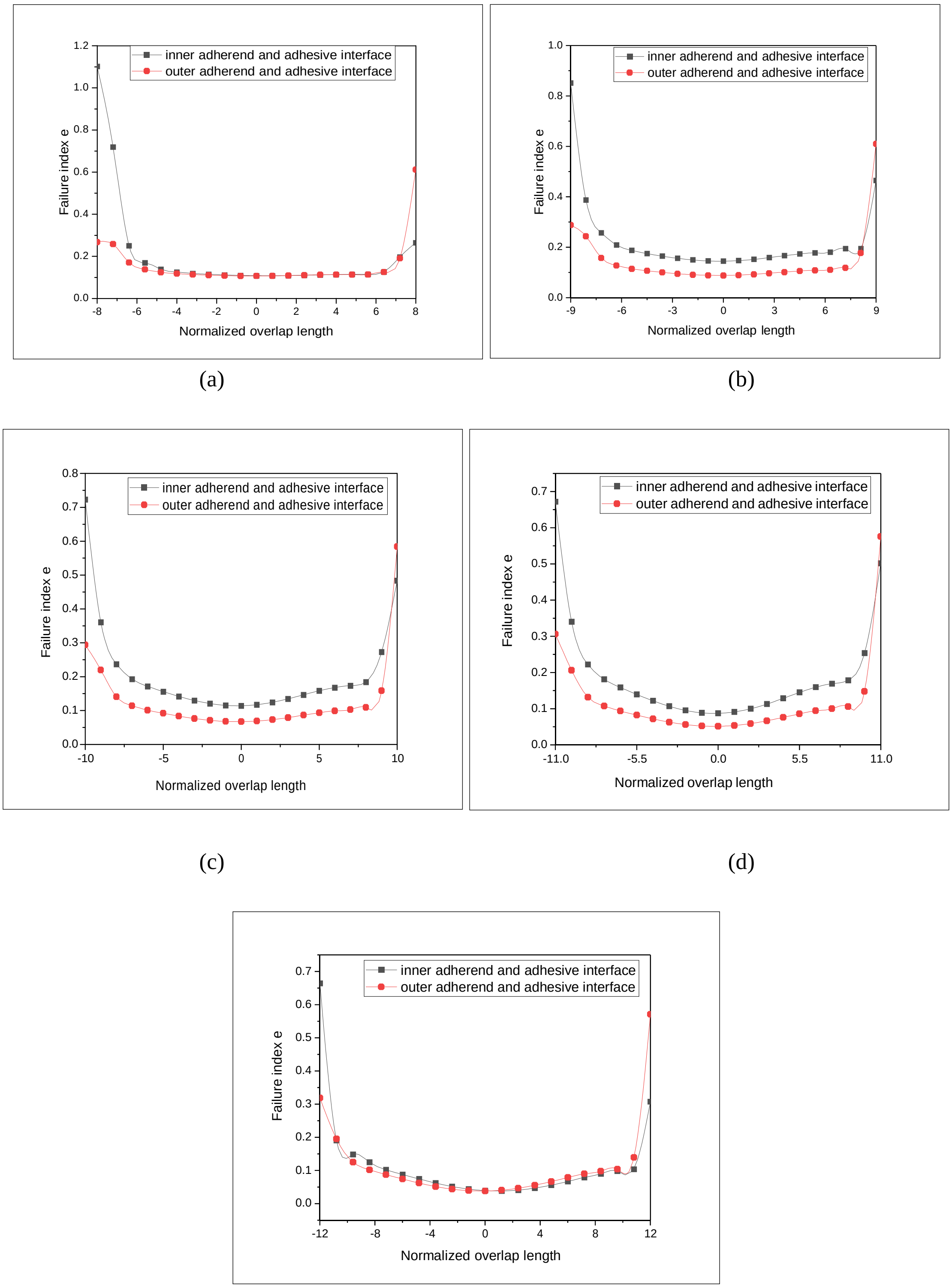

Fig 5: Failure index values of (a) 16mm (b) 18mm(c) 20mm (d) 22mm (e)24mm

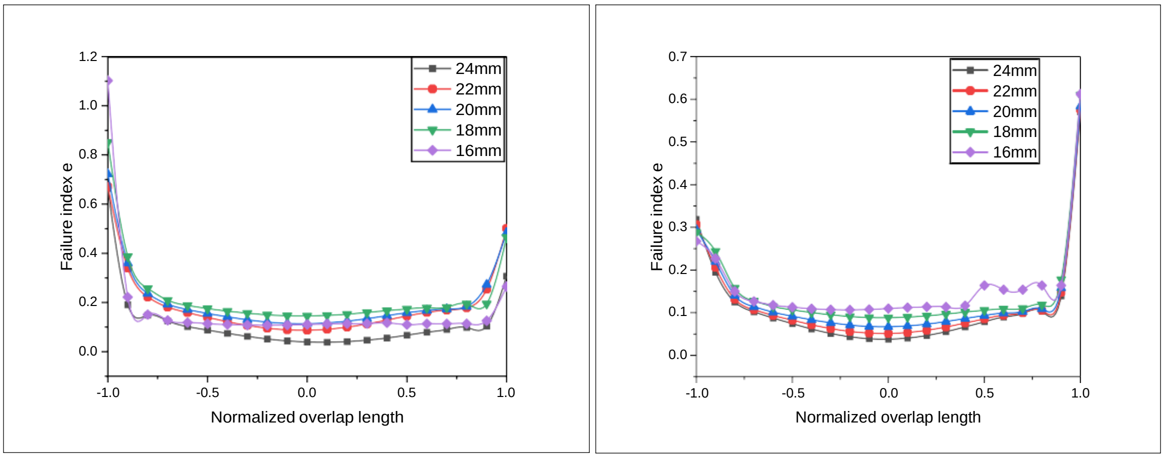

Fig 6: Failure index values at inner adherend and adhesive interface and outer adherend and adhesive interface for all overlap lengths.

Based on maximum magnitude of stress concentration effects and failure index magnitudes at different overlap lengths and the critical bondline interface has been identified. Normal and shear stress distributions of 24 mm overlap length of HTLJ was shown minimum values as shown in Fig 7 (a) inner adherend and adhesive interface (b) adhesive mid layer (c) outer adherend and adhesive interface .

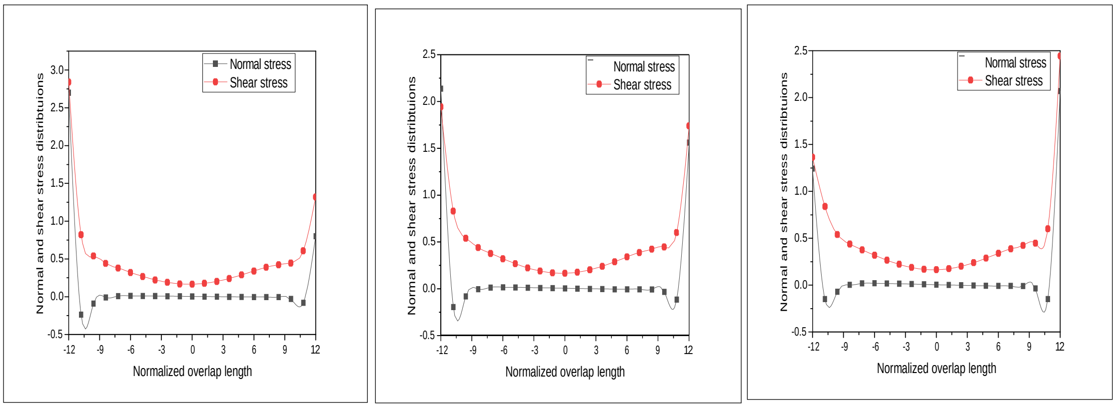

Fig 7(a): Inner adherend and adhesive interface (b) adhesive mid layer(c) outer adherend and adhesive interface

4. Conclusion

The overlap length of the HTLJ have been optimized using ANSYS 2020R1. The Numerical model used in the study has been validated. Failure index of the considered interlayer hybridization of tubes using epoxy as adhesive was found minimum in case of adhesive thickness of 0.15 mm and overlap length of 24 cm.

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