



FEM based delamination damage analysis of bonded FRP composite pipe joints

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Abstract

Delamination damage is one of the major type of fractures encountered by laminated FRP structures, greatly effecting their structural stability. Development of finite element method (FEM) based modelling and simulation technique in order to analyze delamination growth in laminated FRP composite made single lap pipe joints, is the prime concern of the present research. Layered solid 185 elements of ANSYS 18.0 has been used for modelling the FRP composite tubes. Ansys Parametric Design Language (APDL) codes have been developed to simulate delaminations and study their effect on interlaminar stresses. Delamination damages have been considered in the ply-interfaces of the composite tubes in the close vicinity of the adhesive layer and their effect on the adhesive mid-layer stresses has been studied. Comparison of delamination damages in the outer and inner tubes on adhesive stresses revealed that damages in the inner tube are more critical as compared to the delaminated outer adherend.

Keywords Bonded joint · Delamination · FEM · FRP composite

Introduction

Laminated fibre reinforced polymer (FRP) composite made bonded pipe joints have tremendous applications in many industries such as aerospace, civil infrastructure, marine, oil-and-gas and land transport. Common failure modes in composite pipes are delaminations, transverse matrix cracks, holes or fibre fracture etc. Delaminations are matrix defects, where in-plane matrix cracks propagate between plies of a laminate, and run parallel to the fibre direction. Delamination in composite pipes can significantly influence the stress distribution within adhesive layers in the bonded region (overlap region). Overlap length is the region over which the two tubes have been coupled together through application of a layer of adhesive in-between. Hence, analysis of adhesively bonded pipe joints in

presence of delamination is of more importance, thus forms the prime objective of the present analysis.

Analytical and computational models have been predominantly used for analyzing tubular bonded joints. da Silva et al. (2009) have carried out a comprehensive literature survey, highlighting the analytical models used for characterization of behavior of bonded joints. They mentioned most of the notable analytical works carried out to assess the behavior of adhesively bonded joints composed of metallic and composite constituents, with linear and nonlinear adhesive layer properties. Onset and growth of delamination damages in FRP composite single lap joints have been thoroughly studied through a finite element method (FEM) based simulation technique developed by Das and Pradhan (2014). Tubular lap joints mating steel and composite pipe adherends and subjected to torsion were studied by Hipol (1984) using a computational procedure. He proposed an optimization scheme to minimize the peak stresses induced in the adhesive layer. Zou and Taheri (2006) performed a comprehensive investigation on the shear stress distribution in the adhesive layer of bonded sandwich pipe joints subjected to torsional moments. They have carried out analytical and computational analysis using FEM. Both single lap and socket joint configurations

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with different adherend materials have been considered by them. Tong and et al. (1998) used Goland and Reissner's solution to calculate the energy release rate at both the crack tips in terms of the membrane force, transverse shear forces and bending moments. They found that total energy release rate at crack tip decreases with the enlargement of the crack inside the overlap length. Esmael and Taheri (2009) have also studied the effect of an embedded delamination in the composite adherends of a single lap adhesively bonded tubular joint subjected to torsional loading. A parametric study has been performed by them to assess the effect of the delamination growth on adhesive layer peel and shear stresses. Recently Das and Pradhan (2010) introduced a FEM based model to study the adhesion failure propagation in adhesively bonded tubular single lap joints. Strain energy release rate (SERR) based on the virtual crack closure technique (VCCT) have been calculated by them and a failure index has been proposed based on the cohesion failure criterion. The delamination damage has been introduced as an interfacial de-bond between the adhesive layer and the adherends. They also drew valuable conclusions, emphasizing the importance of using 3D models instead of 2D models for accurately modeling such problems, since the free edges of the adhesive–adherend overlap region undergo a 3D state of stresses. Xu and Li (2010) have modelled the adhesive layer separately as 3D elastic body having non-uniform stress distribution and applied torsional load. They used finite difference method to solve the equilibrium equations. Effect of fiber orientation, laminate stacking sequence, overlap length, adhesive layer thickness and adhesive stiffness on Shear and peel stress distribution is analysed. 3D non-linear FEA have been carried out by Panigrahi and Pradhan (2007) to find the out-of-plane stresses at adhesive layer, inter-laminar stresses and modes of energy release rate in the delamination zones of Lap shear joint. They conclude that propagation of delamination front due to inter-laminar stresses and ERRs are not in same rate. Hosseinzadeh and Taheri (2009) performed a coupled experimental–Finite Element investigation for assessing the effect of the overlap length on the torsional capacity of adhesively bonded tubular pie joints. They concluded that the static torsional capacity of the composite-aluminium tubular joint can be increased by increasing bonding length. One of the few notable studies in this topic is the work of Qin and Dzenis (2003) who effectively analyzed a single lap adhesive joint with flat composite adherends that hosted a delamination. Analytical model developed by them has been dedicated for measuring the SERR at the delamination tips. It has been concluded by them that SERR decreased as the crack length increased. Das and Pradhan (2011) have also introduced FEM based simulation techniques for the analysis of adhesively bonded joints in

tubular composite structures. Influence of several parameters on the stress distribution within the adhesive in joints mating composite to composite and composite to aluminum adherends have been investigated by Esmael and Taheri (2011). The failure prediction of single lap joint of different stacking sequence subjected to uniaxial loading is carried out by Aydin (2008). Assumed geometric non-linearity at adhesive layer and calculated the failure indices by extended Drucker–Prager failure criterion. The stress distribution at the vicinity of the joint is extremely sensitive to out-of-plane stresses and bending-twisting coupling effects. More recently Baishya et al. (2017) analysed individual and combined effect of internal pressure and torsional loading on stress and failure characteristics in case of an adhesively bonded tubular single lap joints (TSLJ) made of laminated Fiber reinforced polymer (FRP) composite materials. Effect of changing torsional load magnitude on an internally pressurised adhesively bonded TSLJ on interlaminar stresses and onset of different joint fracture modes (adhesion and cohesion failures) has also been studied.

Bending is one of the most common load in piping system, Yang et al. (2002) and Yang (2000) applied first order laminated anisotropic plate theory to adhesive-bonded socket joint, butt-and-strap joint, and heat-activated coupling joint under bending and tensile load to calculate peel and shear stress distribution. Oh (2007) iteratively calculated the solution at joints by including nonlinear properties of adhesive. Compared the stress distribution of linear and nonlinear analysis, effect of bonding length on torsion. Nonlinear analysis relieves stress concentration at the edges of the joint.

Effect of delamination damages on the adhesive mid-layer stresses of a bonded tubular single lap joint (TSLJ) has been carefully studied in the present analysis under torsional loading conditions. Both locations and size of damages have been changed in order to visualize their individual and combined effect on the joint strength.

Methodology

Specimen geometry and boundary conditions

Geometry, configuration, loading and boundary conditions of the bonded TSLJ specimen analyzed in the present study have been considered from the work of Baishya et al. (2017). Two Gr/E [45/– 45]₈ laminated FRP composite tubes which are similar with respect to length, thickness, and properties have been used as adherends. The two tubes have been joined through a thin layer of adhesive (epoxy) as shown in the Fig. 1. The bonded TSLJ have been subjected to a torsional loading of 100 N-m at the free end of

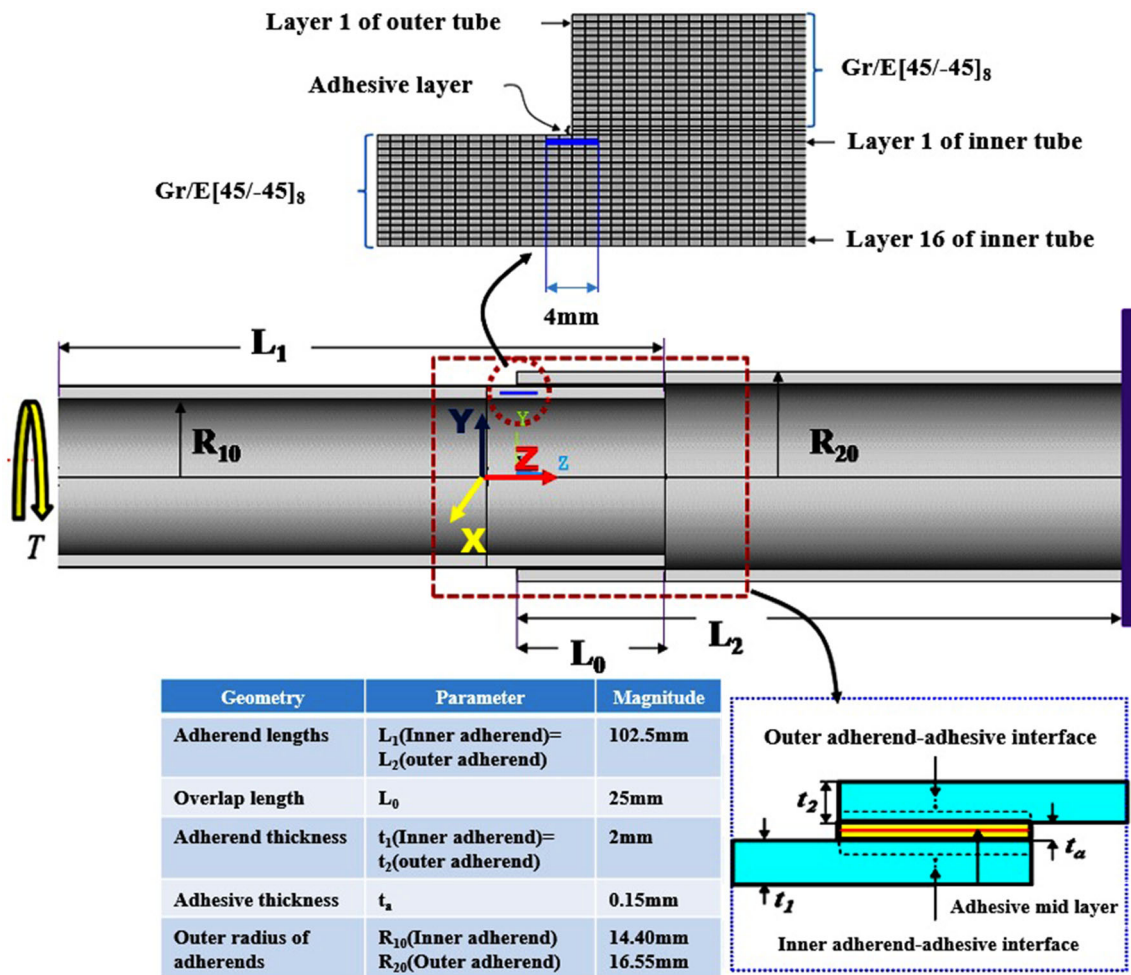


Fig. 1 Orthographic view of the bonded TSLJ specimen with delaminated inner adherend subjected to torsional loading

the bonded TSLJ structure. The material properties along with strength values for adhesive and adherends have been adopted from the work of Das and Pradhan. (2010), has been enlisted in Table 1. The boundary conditions adopted in this problem has been mentioned below:

- at $z = 102.5$ mm (clamped end of the bonded TSLJ), all the nodes have been restrained with respect to all the degrees of freedom, i.e., $U_r = U_\theta = U_z = 0$.
- at $z = -77.5$ mm (free end of the bonded TSLJ), all the nodes have been restricted in radial and axial

directions, i.e., $U_r = U_z = 0$ but allowed to move along circumferential (U_θ) directions.

- at $z = -77.5$ mm, all the nodes have been subjected to a torque (CW when viewed from the free edge) of 100 N-m.

A delamination damage of length 4 mm has been considered at the interface of the first and second plies of the inner composite tube as shown in Fig. 1. Delamination at interface between 1st and 2nd ply has taken because it is closer to the adhesive layer than other layer's interface so effect of delamination on adhesive mid layer stress is more

Table 1 Material properties of the FRP composite adherends and isotropic adhesive (Das and Pradhan 2010)

Joint materials	Material constants
T 300/934 Graphite/epoxy (Gr/E) FRP composite adherend	$E_z = 127.5$ GPa, $E_r = 4.8$ GPa, $E_\theta = 9.0$ GPa $\nu_{zr} = \nu_{z\theta} = 0.28$, $\nu_{\theta r} = 0.41$ $G_{zr} = G_{z\theta} = 4.8$ GPa $G_{\theta r} = 2.55$ GPa
Epoxy adhesive (isotropic)	$E = 2.8$ GPa, $\nu = 0.4$

as compared to other layers interface. It has been reported in the work of Esmaeel and Taheri (2011) that delaminations with its mid plane coinciding with the edge of the joint are expected to effect the joint strength to a large extent. Accordingly the delamination has been simulated so that its mid plane coincides with the edge of the joint as shown in Fig. 1.

The delamination has been considered over an angle of 45° ($\varphi = 45^\circ$) through the circumference of the inner adherend. In order to verify the effect of its growth in circumferential direction on the adhesive strength, the included angle of the delamination has been varied from 30° to 60° . In the second phase of the analysis, a delamination similar with respect to size and location has been considered in the outer adherend of the bonded TSLJ. Individual effects of the delaminations on the joint strength has been compared and pertinent conclusions have been drawn.

Finite element modelling

The bonded TSLJ has been modelled using the FE codes of ANSYS 18.0. The FE mesh of the bonded TSLJ specimen has been shown in Fig. 2.

SOLID BRICK 8-node 185 elements of ANSYS FE package have been used for modelling both the FRP composite adherends and the epoxy adhesive layer. These elements provide the advantage of simulating both structural and layered elements. 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 or 2 parts \times 120 parts \times 125 parts corresponding to the radial, circumferential, and axial directions, respectively for both the adherend and adhesive layer (Baishya et al. 2017). However for the portion of the

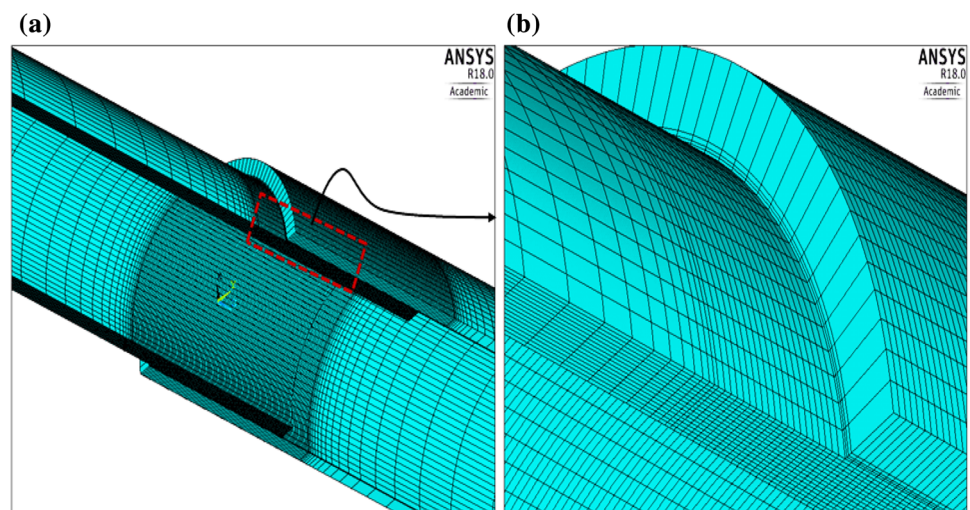
tubular adherends laying outside the overlap region a comparatively coarse mesh has been adopted. For better results the meshing pattern has been made comparatively finer towards the joint and course towards the free and fixed edges (Fig. 2). The delamination damage has been simulated through use of multiple nodes at the destined ply-interface where it is to be simulated. Finite element nodes corresponding to the delamination fronts have been merged into one whereas the nodes within the delamination region has been kept unmerged. The developed FEM based modelling for the bonded composite tubular joint has been validated with respect to the adhesive stress results obtained by Esameel and Taheri (2011) and found to be in good agreement (as shown in Figs. 3 and 4). The different normal stress components generated at the adhesive mid-layer in the joint region of a GI/E made bonded TSLJ considered by Esameel and Taheri (2011) have been shown in Fig. 3a which well agree with the literature (Esmaeel and Taheri 2011). Similarly, the different shear stress component obtained at the adhesive mid-layer of the GI/E composite made bonded TSLJ, through the present FEM model has been shown in Fig. 3b, and is in close agreement with each other. The delamination damage effect on adhesive are in good agreement to the damage effected adhesive stress results available in literature (Esmaeel and Taheri 2011) as shown in Fig. 4.

Results and discussion

Effect of delamination damages on adhesive stresses

In the first phase of the analysis, a delamination damage of length 4 mm and spread over a circumferential angle,

Fig. 2 **a** Finite element mesh for the bonded TSLJ. **b** FE mesh in the joint region



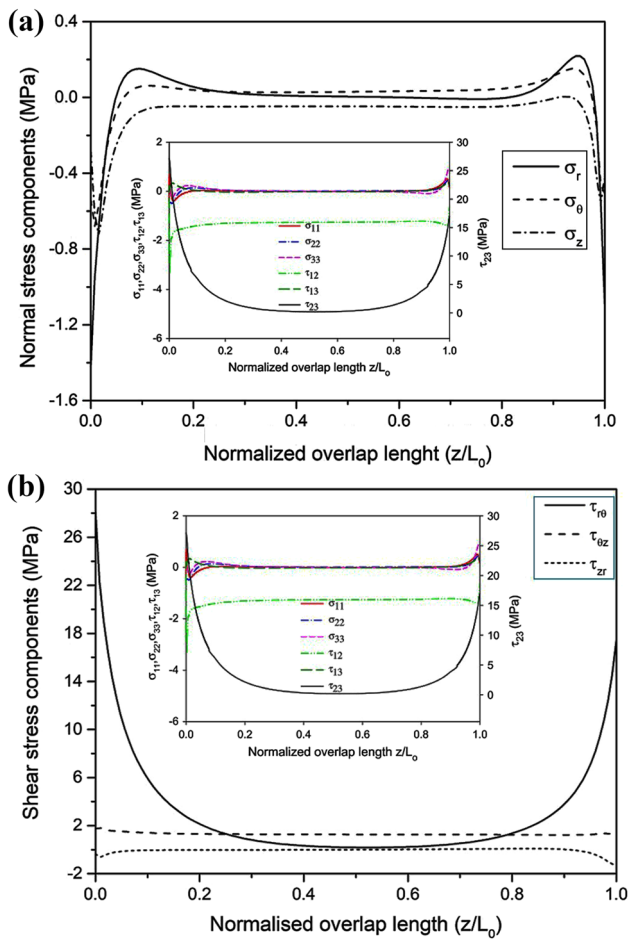


Fig. 3 Finite element model validation for bonded TSLJ specimen with respect to the adhesive stress results obtained by Esameel and Taheri (2011). **a** Normal stress components. **b** shear stress components

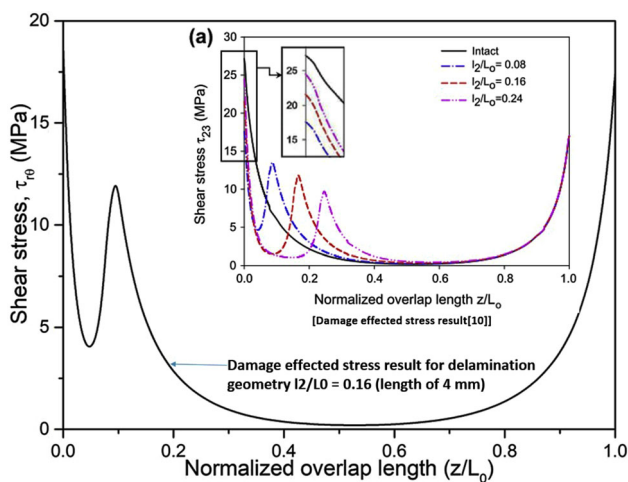


Fig. 4 Finite element model validation for delamination damage simulation with respect to the damage effected adhesive stress results obtained by Esameel and Taheri (2011)

$\varphi = 45^\circ$ has been simulated at the interface of 1st and 2nd plies of the inner composite tube as shown in Fig. 1. It may be observed from the adhesive stress results shown in Fig. 3 that the radial-circumferential shear stress ($\tau_{r\theta}$) is the most critical stress within the adhesive layer. Hence, effect of the delamination damage on this stress component has been studied in the present analysis and has been shown in Fig. 5. It may be observed from the plot that due to presence of the delamination damage in the inner composite tube, the joint edges of the bonded TSLJ become flexible leading to a minimization of stress concentration effects at both the joint edges. However, a secondary peak may be observed which indicates stress concentration effects in the adhesive mid-layer corresponds to the region in close proximity of the delamination front (Fig. 5).

In the second phase of the analysis, the delamination damage has again been considered in the outer composite tube in the similar location. Its effect on the adhesive mid-layer critical shear stress component ($\tau_{r\theta}$) has been represented in Fig. 6. The effects are similar to the delaminated inner tube case. Individual effect of both of these delamination damages on adhesive stresses have been shown in Fig. 7. Based on the magnitude of shear stress concentrations it may be concluded that the delaminated inner adherend is more critical as compared to the delaminated outer adherend in case of a bonded TSLJ structure subjected to torsional loading conditions. It may clearly be observed from Fig. 7 that, peak shear stress value for the left side delamination case (LSD) is about 11.2 MPa whereas, the peak shear stress value for the right side delamination (RSD) in the outer composite tube is 6.8 MPa. Hence, delamination damages in the inner adherend must be avoided for a better structural stability of

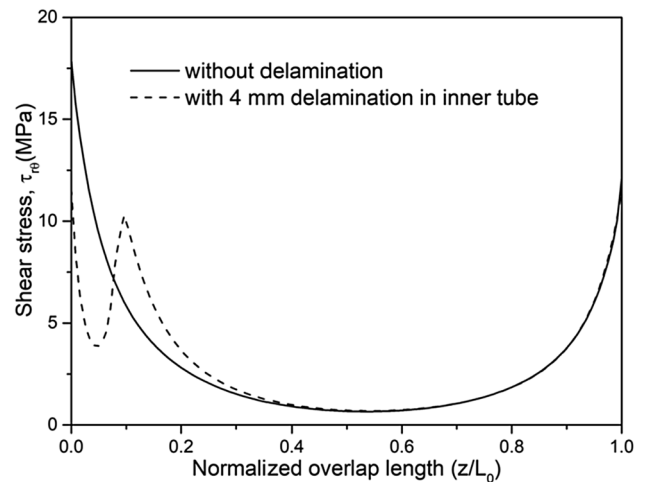


Fig. 5 Effect of delamination damage (length 4 mm, $\varphi = 45^\circ$) present in the inner composite tube on adhesive mid-layer shear stress component ($\tau_{r\theta}$)

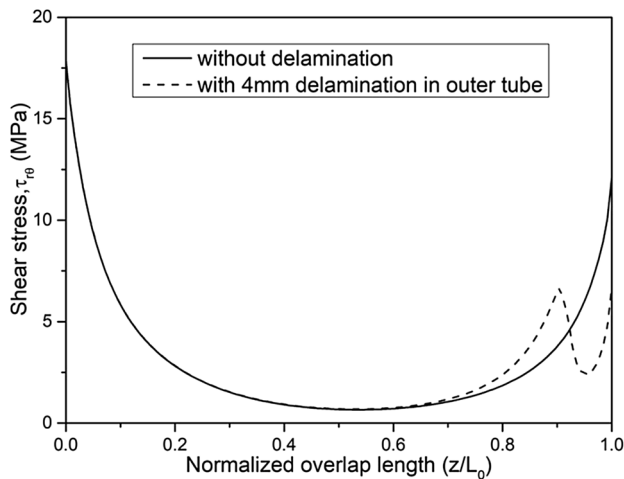


Fig. 6 Effect of delamination damage (length 4 mm, $\varphi = 45^\circ$) present in the outer composite tube on adhesive mid-layer shear stress component (τ_{r0})

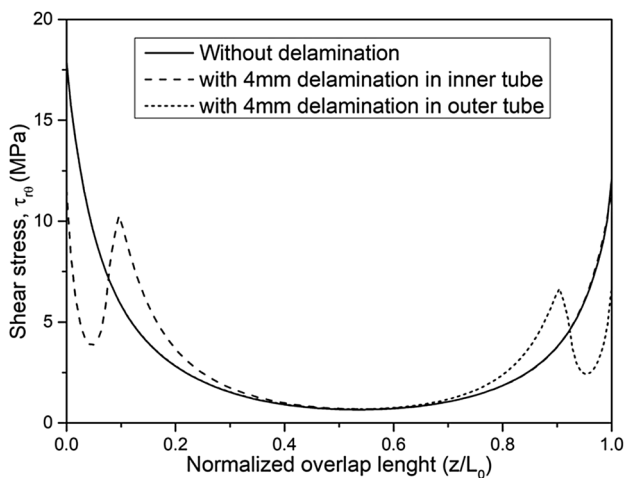


Fig. 7 Effect of delamination damage (length 4 mm, $\varphi = 45^\circ$) present in the inner and outer composite tubes on adhesive mid-layer shear stress component (τ_{r0})

the bonded TSLJ. It is important to note that delamination in outer tube has almost same value for primary and secondary peak.

Effect of axial growth of delamination damage on adhesive stresses

In the third phase of the analysis, the axial length of delamination damage is varied whereas circumferential length is kept constant ($\varphi = 45^\circ$) at same location in inner tube. Effect on adhesive mid-layer critical shear stress component (τ_{r0}) has been represented in Fig. 8. It can be clearly seen in Fig. 8 that, as the axial length of delamination is increasing the secondary peak values goes on

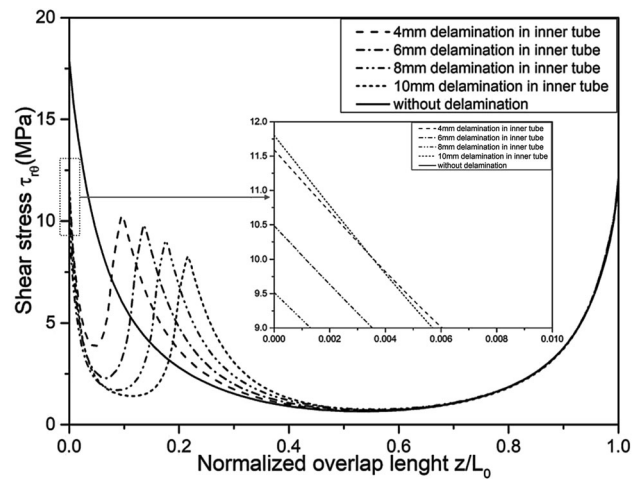


Fig. 8 Effect of axial growth of delamination damage ($\varphi = 45^\circ$) present in the inner composite tube on adhesive mid-layer shear stress component (τ_{r0})

decreasing and shifting of secondary peaks can be observed. With increasing the axial length of delamination the primary peak value goes on decreasing up to 8 mm delamination, for delamination of 10 mm axial length have higher value of radial circumferential stress. So it can be conclude that as we increase the axial length of delamination the primary and secondary peaks decreases for some values and after that particular axial length of delamination the primary peak increase whereas the secondary peak continuously goes on decreasing and shifting takes place.

Effect of circumferential growth of delamination damage on adhesive stresses

In the final phase of the analysis, the delamination damage of length 4 mm and spread over a circumferential angle, $\varphi = 45^\circ$ simulated at the interface of 1st and 2nd plies of the inner composite tube has been allowed to grow in circumferential direction by changing the included angle ' φ ' from 30° to 60° with an interval of 15° . In the work of Esmaeel and Taheri (2011) the delamination damage has been allowed to grow axially and its effect on the adhesive mid-layer shear stresses has been studied. They have not studied the circumferential growth of delamination and its effect on the joint strength which has been addressed in the present analysis. The results corresponding to this has been shown in Fig. 9. It may be observed that, as the delamination grows circumferentially, the primary peaks corresponding to the joint edges of the bonded TSLJ has been observed to be decreasing. However, it may be noted from Fig. 9 that, the secondary peaks corresponding to the delamination fronts have been observed to be increasing in magnitude, as the delamination grows circumferentially.

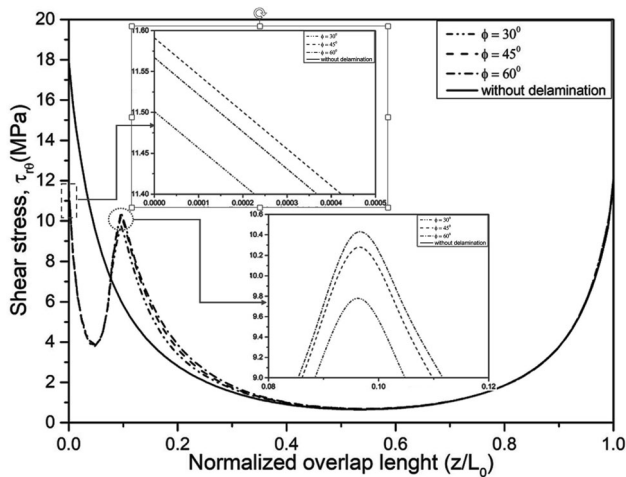


Fig. 9 Effect of circumferential growth of delamination damage (length 4 mm) present in the inner composite tube on adhesive mid-layer shear stress component ($\tau_{r\theta}$)

Conclusions

Three dimensional stress and fracture analysis of a bonded TSLJ made of laminated FRP composite tubes has been carried out in the present analysis. Effect of delamination damages simulated in inner and outer composite adherends on adhesive stresses has been studied. In addition to that, effect of circumferential growth of the delamination damage on adhesive shear stresses has also been verified in details. Salient conclusions of the present analysis are:

- Radial-circumferential shear stress ($\tau_{r\theta}$) is the most critical stress within the adhesive layer in the joint region of the bonded TSLJ subjected to torsion.
- Delamination damages in each of adherends cause reduction of stress concentration effects at the joint edges. However a secondary peak is introduced corresponding to the delamination front associated region of the adhesive layer.
- Delaminated inner adherend is more critical as compared to the delaminated outer adherend causing more stress concentration effects.
- Axial growth of the delamination damage reduces the secondary peaks and shifting of secondary peaks takes place.
- Circumferentially growth of delamination damage reduces the primary peaks corresponding to the joint edges of the bonded TSLJ, whereas the secondary peaks undergo an increase.

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