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Failure Analysis of Functionally Graded Adhesively Bonded Tubular Joint under Combination of Axial and Torsional Load

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Abstract: **-- This research deals with finite element based simulation of a functionally graded adhesively bonded tubular joint under combined axial and torsional loading. The tubes are made of Gr/E (T300/934) laminated FRP composites. The research carried out in past indicate high-stress concentration at both ends of overlap. By employing a modulus graded adhesive along the bond line the stress concentration at the ends of overlap can be reduced. This will result in significant increase in strength and lifespan of the adhesively bonded joint. The material gradation of the adhesive along the bond line is achieved by suitable smooth and continuous function profiles with varied modulus ratios. The out-of-plane shear stress and peel stress values have been calculated along the interfacial surfaces of the bond line of the tubular joint. Failure indices have been calculated by using Tsai-Wu coupled stress criterion to predict the failures onset location the critical location has been identified to be between the outer tube and adhesive layer near the loaded end. Results show the significant reduction in the value of failure index at the critical location thus increasing the joint strength and delayed failure onset location with functionally graded adhesive.**

Index Terms**: Functionally Graded Adhesive, FRP Composite Tubes, Failure Analysis, Combined Loading.**

I. INTRODUCTION

Fibre-reinforced polymer (FRP) composite materials possess many appealing qualities, e.g. high strength to weight ratio and good corrosion resistance, which single them out for use in the aerospace, offshore oil and gas, and chemical and petrochemical industries. Composite piping systems have been rigorously investigated for their potential development as next-generation infrastructures for those industries. Joint introduction is inevitable in most composite piping systems. No matter what forms of connections are used in any structure, the joints are potentially be considered as the weakest points. By the use of FRP composite materials, these weakest points increase, which may lead to the loss of structure.

An analysis of adhesive stresses of bonded joints which included the effects of load eccentricity was first performed by Goland and Reissner [1] with the assumptions: (i) adhesive flexibility is negligible, and the joint is homogeneous (i.e. ignore the presence of adhesive), and (ii) no axial stress exists, and other stresses do not vary through-the-thickness of the adhesive layer. The approach of Goland and Reissner was improved by Hart-Smith [2] by considering a third free body diagram for the adherend outside the joint in addition to the two free body diagrams for each of the upper and lower halves of the joint. The existence of stress gradients through-the-thickness of the adhesive layer close to the joint edges was observed by Adams and Peppiat [3] and studied the adhesive yielding using an iterative elasto-plastic FE programme. The same authors also indicated the effect of adhesive fillet and partial tapering of adherends on stress distributions in the adhesive layer under the axial load. Chon [5] analyzed tubular lap joint of FRP composites under torsion by developing a closed form solution. Effects of different parameters, such as wrap angles, overlap length, and thickness of adhesive layer stress concentration at and near the end of the joint were studied. Many studies have been proposed to reduce the stress concentrations, especially in case of lap joints, such as effects of spew and chamfer size, influence of slots etc. More recently, there are limited investigations to improve the joint strength by employing functionally graded materials, and functionally graded adhesive layer. Apalak [6, 7] performed three-dimensional stress analyses of adhesively bonded tubular lap joint with functionally graded adherends under tensile load and pressure loadings. Tubes

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were made of functionally gradient layer between a ceramic layer and metal layer. It was noticed that continuous variation of material composition across the tube thickness plays a significant role on the peak values of tube and adhesive stresses. The same author recommended a linear material function profile across the tube thickness in order to reduce the through thickness stress levels. Kumar [8] made efforts to improve the strength of adhesively bonded tubular joints under axial load by reducing stress concentrations at the ends of overlap and distributing stresses uniformly over the bond layer. This strength improvement was achieved by employing functionally graded adhesive layer in the joint. Research was carried out by conducting axis-symmetric elastic analysis and results showed that peel and shear stress peaks were much smaller than those of mono-modulus (R=1) adhesively bonded tubular joint. Kumar and Scanlan [9] also provided an analytical framework study for stress analysis of a shaft-tube bonded joint using a variational technique. Functionally modulus graded bond line (FMGB) adhesives were employed in order to reduce peak peel and shear stress levels. Those investigators found that there was a significant decrease in peak peel and shear stress levels in FMGB compared to those of mono-modulus adhesive materials.

II. FINITE ELEMENT ANALYSIS OF ADHESIVELY BONDED TUBULAR JOINT

Accurate analysis of tubular single lap joint can be performed by FEA and this is a tool that can provide physical insight and accurate results. In the present research, failure onset analyses of functionally graded adhesively bonded tubular lap joints of laminated FRP) composites under combination of axial and torsional load have been studied using three dimensional geometrically non-linear finite element (FE) analyses.

A. Modeling of tubular joint

Tubular lap joint, consisting of an adhesive layer and two composite tubes is considered for the present analysis. Tubes of the bonded tubular Joint are made of Gr/E (T300/934) laminated FRP composites with ply configuration [0/90]s, thickness of each ply is considered as 0.25 mm and epoxy has been used as adhesive. Here zero degree fiber orientation indicates circumferentially wound. The isometric view showing the geometry and configurations of tubular lap joint is shown in Figure 2. The main dimensions of the inner and outer tubes were taken as [11]: the inner radius of the inner tube R_1= 18.9 mm, the inner radius of outer tube R_2 = 20.05 mm, the wall thickness of both tubes t = 1 mm, the length of each tube l = 80 mm, the adhesive thickness h = 0.15 mm, the overlap length $2C$ = 22 mm, and total length of joint structure L = 138 mm. The Torsional load of 100 N-m at the free edge as well as the axial load is applied at the far end of the inner tube which is equivalent to uniform loading of intensity 10 MPa. The layer wise orthotropic material properties along with their strength values for FRP composite laminates and adhesive are shown in Table 1. Referring to Figure 2, the boundary conditions imposed in the present FE simulation for axial and torsional loadings are expressed as:

- $u = v = w = 0$, for all nodes along z = 0 , i.e., at the clamped end of the inner , and
- $u = 0$, for all nodes at inner radius of inner tube and z = L, i.e., near the loaded end of the inner tube

Table 1. Layer Wise Orthotropic Material Properties of Gr/E (T300/934) Composite and adhesive. [11]

Material	Material Constants	Strengths
Gr/E (T300/934)	E_z = 127.5 GPa E_θ = 4.8 GPa E_r = 9 GPa $G_{z\theta}$ = 4.8 GPa G_{zr} = 4.8 GPa $G_{\theta r}$ = 2.55 GPa $\nu_{zr} = \nu_{z\theta}$= 0.28 $\nu_{\theta r}$ = 0.41	R_T=R_C= 49 MPa $S_{r\theta}$= 2.55 MPa S_{rz}= 2.55 MPa
Epoxy adhesive	E = 2.8 GPa ν = 0.4	Y_T = 65 MPa Y_C = 84.5 MPa

B. Bond layer with functionally graded adhesive

Many researchers considered linear and exponential function profiles for functionally graded materials. It was clearly spelt out that the linear material gradation function profiles offer a better reduction in magnitude of peak values of peel stress based on 3D FE analysis [11]. The smooth variations of bond layer modulus have been implemented by applying a number of rings of adhesive of different moduli in the bond line which is expressed by following linear function profile [12]:

$$\begin{aligned} E &= E_1 + (E_2 - E_1)\times\frac{m}{C} \qquad \text{for bondlinelength0 to } C \\ E &= E_2 - (E_2 - E_1)\times\frac{m}{C} \qquad \text{for bondlinelength} C \text{ to } 2C \end{aligned} \tag{1}$$

Where 'm' is a variable, value varies from 0 to C. Material non-homogeneity of graded bond layer have been evaluated in terms of modulus ratio (R) which is expressed as follows

$$R = \frac{E_2}{E_1} \tag{2}$$

The detail distribution of gradation properties with varied modulus ratios along the bond layer of the tubular lap joint structure is shown in Figure 3. Based on stress distributions flexible adhesive having low values of elastic modulus (E_1) is used at both the overlap end zones. Whereas stiffest adhesive having the highest values of elastic modulus (E_2) is used at the central portion of the tubular joint structure. $E_2 = 2.8\ GPa$ and E_1 is varied according to modulus ratio (R).

C. Meshing scheme

The isotropic adhesive layer has been modeled using SOLID186 Homogeneous Structural Solid Element. And layer Structural Solid elements designated as SOLID 186 have been used to model the composite tube. A very fine mesh has been adopted to take care of high stress gradients at the free edges of the joint as shown in figure 1. However, a comparatively coarse mesh has been adopted for the tubular portion lying outside the overlap region. The meshing pattern has been made comparatively finer towards the joint and course towards the free and fixed edges for better simulation and accurate results.

Figure 1. Zoomed View of FE Model of Tubular Lap Joint

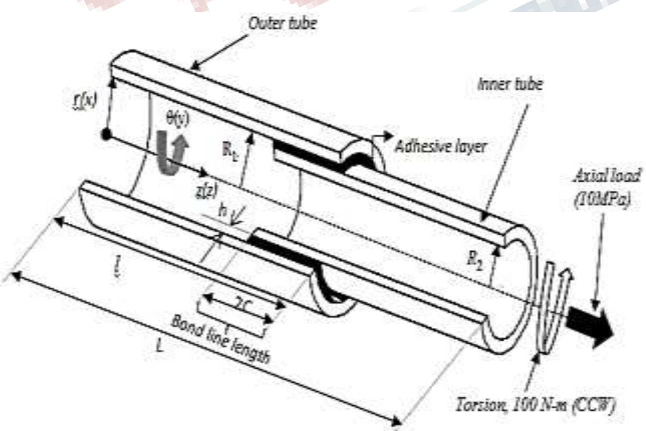

Figure 2. Geometry and configuration of the adhesively bonded tubular lap joint

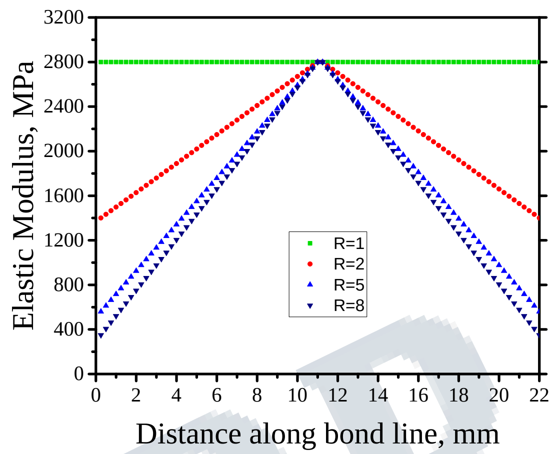

Figure 3. Gradation of elastic modulus along bond length.

D. Failure Onset in Tubular Joint

The adhesively bonded joint experiences two important modes of mechanical failure: (i) Interfacial failure also known as the adhesion failure which occurs between the adhesive and the tube, and (ii) Cohesive failure within the adhesive apart from the failure or damage due to delamination in the composites tube. The initiation of interfacial failure along the critical surfaces of bond layer has been identified by the Tsai-Wü coupled stress criterion [4]

$$\frac{\sigma_{rr}^2}{R_T^2}+\frac{\sigma_\theta^2}{\theta_T^2}+\frac{\sigma_z^2}{Z_T^2}+\frac{\tau_{r\theta}^2}{S_{r\theta}^2}+\frac{\tau_{rz}^2}{S_{rz}^2}+\frac{\tau_{z\theta}^2}{S_{z\theta}^2}$$
$$+\sigma_r\left(\frac{1}{R_T}-\frac{1}{R_C}\right)+\sigma_\theta\left(\frac{1}{\theta_T}-\frac{1}{\theta_C}\right)+\sigma_z\left(\frac{1}{Z_T}-\frac{1}{Z_C}\right) \tag{3}$$
$$+f_{r\theta}\sigma_\theta\sigma_r+f_{rz}\sigma_z\sigma_r+f_{\theta z}\sigma_z\sigma_\theta=e^2$$

$\sigma_{rr}, \sigma_\theta, \sigma_z, \tau_{r\theta}, \tau_{rz}$, and $S_{z\theta}$ are the normal and shearing stresses in cylindrical coordinate system. R_T, θ_T, Z_T and R_T, θ_C, Z_C are the allowable tensile and compressive strengths in the three principal material directions, respectively; and $S_{r\theta}$, S_{rz}, and$S_{z\theta}$ are the shear strengths of the orthotropic layer in various coupling modes. The coupling coefficient reflecting the interaction between r, θ, and z directions are given by $f_{r\theta}$, f_{rz}, and $f_{\theta z}$, respectively. Failure index (e) is defined as the parameter to evaluate the condition whether the bonded tubular joint is likely to fail or not. If $e \geq 1$ failure occurs, else there is no failure. Generally, the stresses (σ_{rr}, $\tau_{r\theta}$, and τ_{rz}) are majorly responsible for the initiation of joint failures. Hence, only the inter laminar shear stresses

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($\tau_{r\theta}$ and τ_{rz}) and through-the-thickness normal or peel stress (σ_{rr}) are required to predict the joint fracture initiation. Therefore, the Tsai-Wu criterion given in Equation (3) reduces to the form

$$\left(\frac{\sigma_{rr}}{R_T}\right)^2 + \left(\frac{\tau_{r\theta}}{S_{r\theta}}\right)^2 + \left(\frac{\tau_{rz}}{S_{rz}}\right)^2 = e^2 \quad \begin{cases} e \geq 1, \text{failure} \\ e < 1, \text{no failure} \end{cases} \qquad (4)$$

Similarly, the failure index of tubular joint in the adhesive layer is formulated by a cohesive failure philosophy [10].

III. RESULT AND DISCUSIONS

A non-linear three-dimensional FE analyses have been carried out for tubular joint made of laminated FRP composites under torsional loading environment. Out-of plane stresses ($\sigma_{rr}, \tau_{r\theta}, \tau_{rz}$) responsible for failure initiation are evaluated on different interfacial surfaces i.e. (i) inner tube and adhesive, (ii) mid-surface of adhesive, (iii) outer tube and adhesive. Tsai-Wu coupled stress failure criterion [4] has been used to compute failure indices 'e' on the interfacial surfaces whereas, parabolic yield criterion [10] is used to evaluate the failure indices 'e' within adhesive layer. The details of failure initiation for tubular joint under combination of loading environment are discussed here. On the basis of observation of magnitudes of failure indices for all the bond layer surfaces, it is clearly noticed that mid-surface of adhesive is ignored for failure initiation as compared to interfacial failure at inner/outer tube-adhesive interfaces. Referring to Figure 4, it is observed that the magnitudes of failure index attains a peak value at the

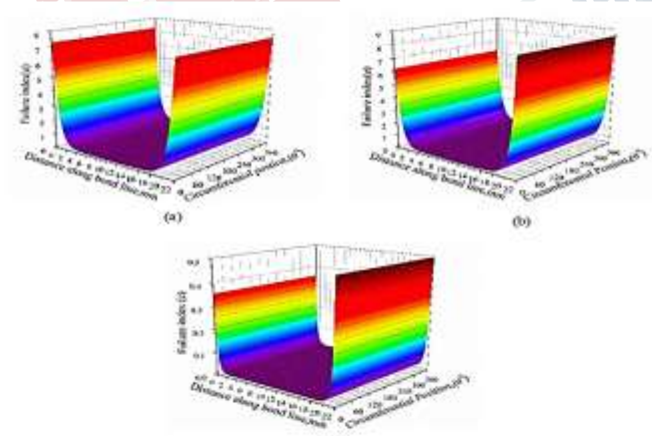

Figure 4. Distribution of failure index at the interface of (a) inner tube and adhesive, (b) outer tube and adhesive , and (c) mid surface of adhesive layer.

interface of outer tube and adhesive layer near the edge of bond layer closer to loaded end of joint structure. Hence, this

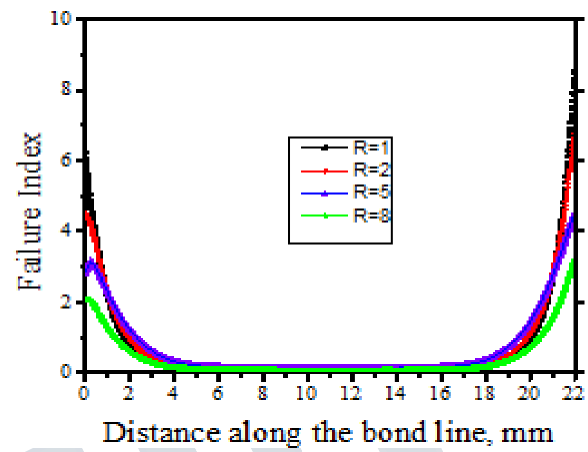

Figure 5. Effect of functionally graded adhesive with different modulus ratios 'R' on variations of failure index at the interface of outer tube and adhesive.

location is more prone for the failure onset. Further, efforts have been made to reduce intensity of stress concentration and failure index at the ends of overlap for tubular joint using functionally graded adhesive material. Bond line has been graded by linear function profile. The variations of failure indices along the above predicted critical interfacial surface of tubular joint of functionally graded adhesive with modulus ratios (R) varying from 1 to 8 are shown in Figure 5. Results are compared between mono-modulus and graded adhesive. Results indicate that when there is increase in modulus ratio, peak values of failure index decreases significantly by 20-65% at both the free ends. This situation leads to an increase in strength and will delay the failure.

IV. CONCLUSION

Detailed three dimensional FE analyses have been used to predict onset of failure in tubular joint under axial and torsion loading. The critical location have been identified to be between the outer tube and adhesive layer near the loaded end. Tubular joint made with functionally graded adhesive reduces the peak values of failure index at the overlap end, thus reducing the possibility of failure. It would be appropriate to conclude that for strategic designing of an effective and durable adhesively bonded FRP composite joint, it is a pre-requisite to develop a balanced adhesive material to provide better load carrying capabilities. Therefore, recommendation can be made for utilization of functionally graded bond layer as compared to mono-modulus adhesive in tubular joint.

REFERENCE

[1] M Goland, E Reissner, "The stresses in cemented joints," ASME Trans, Journal of applied MechanicS, vol. 11, 17–27, 1944.

[2] L. J. Hart-Smith, "Adhesive-bonded double lap joints." NASA-CR–112235, 1973.

[3] R. D. Adams RD and N. A. Peppiatt, "Stress analysis of adhesive bonded tubular lap joints," Journal of Adhesion, vol. 9, pp. 1-18, 1977.

[4] S. W. Tsai, E. M. Wu, "A general theory of strength for anisotropic materials, "Journal of Composite Materials, vol.5, p.p. 58-80, 1971.

[5] Chon CT, "Analysis of tubular joint in torsion." The Journal of composite Material, vol. 16, 268-311, 1986.

[6] M. K. Apalak, "Elastic stresses in an adhesively bonded functionally graded tubular single-lap joint in tension," Journal of Adhesion Science and Technology, vol. 20, pp.1019-1046, 2006.

[7] M. K. Apalak, "Stress analysis of an adhesively bonded functionally graded tubular single lap joint subjected to an internal pressure," Science and Engineering of Composite Materials, vol. 13, pp. 183-211,2006.

[8] S. Kumar, "Analysis of Tubular Adhesive Joints with a functionally modulus graded bond line subjected to axial loads," International Journal of Adhesion and Adhesives,vol. 29, pp. 785-795, 2009.

[9] S. Kumar and J. P. Scanlan: Stress analysis of shaft-tube bonded joints using a variational method, Journal of Adhesion, vol. 86, pp. 369-394, 2010.

[10] R. Raghava, R. M. Caddel, "The macroscopic yield behavior of polymers, "Journal of Materials Science, vol. 8, p.p. 225-232,1973.

[11] S.V. Nimje, S.K. Panigrahi. "Effects of functionally graded adhesive on failures of socket joint of laminated FRP composite tubes," International Journal of Adhesion and Adhesives, vol. 48, 139–149, 2014.

[12] K.S. Ravi Chandran, I. Barsoum, "Determination of stress intensity factor solutions for cracks in finite-width functionally graded materials, "International Journal of Fracture, vol.121, 183–203, 2003.