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# FINITE ELEMENT ANALYSIS OF AN ADHESIVE BONDED TAPER-TAPER JOINT FOR A LAMINATED COMPOSITE PLATE

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**ABSTRACT**
*Design of joints is of paramount importance in all industries, wherever applicable. It even becomes more challenging when composites are joined to another composite or other material. More often these types of joints are designed based on experience and experimental data. They are more prone to failure and are expensive to repair. The absence of clearly defined steps for designing joints is due to the lack of understanding the mechanics. The taper-taper adhesive bonded joint, used in this research, is an attempt to understand its behavior under different mechanical loading condition. The research work is aimed to develop a model to predict the stress-strain distributions within a taper-taper joint between two laminated flat plates under mechanical loading using finite element method. Composites and adhesive peel stress were computed and compared with an analytical model for cross ply laminated plate. The results of analytical model agree well with the results of finite element model. Various taper angles ranging from 30º to 90º are chosen to demonstrate the variation in peel stresses with taper angle.*
**Keywords:** Taper-taper joint, adhesively-bonded joints, finite element analysis

## 1. INTRODUCTION

The potential use of composites for high stiffness and strengths, weight savings, directional properties and high corrosion resistance is widely recognized. Composites are extensively used in petroleum, petrochemical, transportation, sports and consumer industries. However, these characteristics are quite different from those ordinary materials to which we generally want to fasten composites. Often, the full strength and stiffness characteristics of the composites cannot be transferred through the joint without a weight penalty. In many applications adhesive bonded joints have replaced bolted joints because of the laminate damage inherent to the drilling process, the stress concentration developed at holes, the weight penalty of the bolting, and susceptibility of the bolting to corrosion. In industry, joint design is often based on experience and experimental data rather than analytical models. There is thus a need for further research in the field of adhesive bonded joint design and analysis.

The present research is motivated by the visit to the Fahud oil field in the north west of Oman. Currently, Petroleum Development Oman (PDO) is using composite pipes in various oil fields for varying tasks. These composite pipes are joined to carbon steels (near suction and injection pumps) and to composites using couplings, adhesive and bolts. However, as mentioned earlier, these joint types experience stress concentration, excessive vibration and corrosion in bolts. An adhesive bonded joint is a better alternative for such cases. The challenge in adhesive bonded joints is to transmit the load such that the resultant joint is damage tolerant. In addition the failure in bonded joints is matrix dominated, which is not yet fully understood. One possible way to eliminate these problems is to use taper-taper adhesive bonded joints. Taper-taper joints can be used in composite piping system to join composites to composites or composites to other materials. This will reduce the cost of the piping system by eliminating the material and labor cost of installing couplings. Consequently, it is essential to accurately predict the stress-strain distributions within a taper-taper joint for an improved design.

Adhesively bonded joints in composites have been investigated by many researchers using various methods [1] over the last fifty years. Single and double lap joints were the focus of attention for decades. However, due to layered nature of composite adherends and relative weakness in the through-the-thickness direction, interlaminar delamination is a typical failure mode [2]. In addition, in these joints the peel and shear stresses are not uniform along the overlap length and their gradients are very high near the ends of joint overlap. A series of studies on single lap, double lap, stepped lap and scarf joints were conducted by Hart-Smith [3-6] using continuum mechanics approach. The transverse shear deformation and edge effects were neglected and adhesive stresses were assumed constant through the thickness in most of the analyses found in literature. Erdogan and Ratwani [7] developed a plane stress model to predict stress-strain distribution in stepped-lap joint. Yang and Pang [8-9] investigated the stress-strain distribution in a single-lap joint under cylindrical bending and tension. The analytical work on isotropic adherends prior to 1961 was reviewed by Kutscha and Hofer [10]. Mathews et al. [11] reviewed classical and finite element analyses related to all aspects of adhesive bonded joints in composite materials. Tong et al [12] published a study on effects of adherend alignment on the behavior of double lap joints. The effect of end mismatch on peel and shear stresses was also studied.

Other than single, double or stepped lap joints and scarf joints, taper-taper joints are also used in fine aircraft structures to join composites to composites or composites to other materials such as aluminum. In addition, these joints can also be successively used in composite piping system. Helms et al. [13] derived a mechanics of materials model of the taper-taper adhesive bonded joint under tension loading. The laminate strain was calculated and compared to a model published by Erdogan and Ratwani. A laminated plate model of the taper-taper adhesive bonded joint under tension and cylindrical bending was also developed by Helms et al. [14-15]. The objective of this present research is to develop a model to predict the stress-strain distributions within a taper-taper joint between two flat laminated plates under mechanical loading using finite element method. The results were obtained using ABAQUS, and compared with the analytical results obtained by Helms [15].

## 2. MODELING & ANALYSIS

Figure 1 shows the geometric configuration of taper-taper joint under mechanical loading. The joint is broken into three sections; $L_1$ and $L_2$ represent the length of sections to the left and right of the joint, while $L_3$ represents the length of the joint region. Based on first-order laminated plate theory, the displacement fields' $u(x)$ and $w(x)$ of laminated plate in x and z-directions, respectively, can be expressed as

$$u = u_o(x) + z\,\psi(x)\,, \quad \text{and} \quad w = w(x)\,,$$

where $u_o$ represents the mid-plane displacement along x-axis, $\psi$ is the corresponding bending slope and $x$ is the general length variable. The mathematical model describing the behavior of the adhesive in a taper-taper joint under cylindrical bending developed by Helms et al [15] depends on the above displacement field.

A finite element model of the joint under cylindrical bending was developed using ABAQUS, a commercial FEM package. The results were compared with analytical model results. The mesh was refined in $L_3$ (the joint region) to maintain the taper angle for all elements adjacent to the adhesive. Beyond the joint region, coarse mesh was used. Element widths in fine mesh region are equal to or less than the adhesive thickness. The final mesh consists of 2400, 8-node brick elements (C3D8R in ABAQUS). The elements were generated using reduced integration with hour-glass. These elements are capable of predicting the stresses in areas near the interface where there is a discontinuity of material properties. The boundary conditions correspond to those used in solving the analytical model.

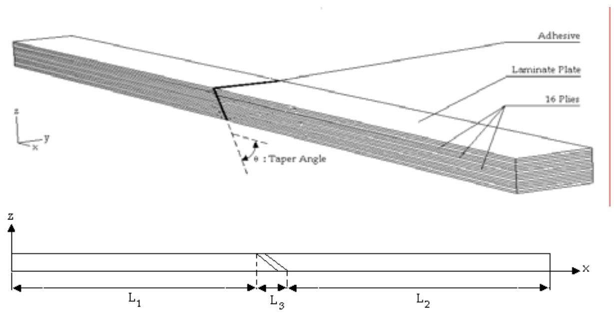


*Figure 1: Geometric Configuration of taper-taper joint for laminated*

**3. RESULTS & DISCUSSIONS**

A 16 ply laminate of T300/5208 (Graphite/Epoxy) with a ply thickness of 0.25 mm was used for both left and right adherends. The laminate lay-up sequence is $[90_4/0_4/90_4/0_4]$. The engineering constants are $E_x$ = 181 GPa, $E_y$ = 10.3 GPa, $G_{xy}$ = 7.17 GPa, and $\nu_{xy}$ = 0.28. The two adherends are joined together using a film of Metbond 408 with a thickness of 0.1 mm. The adhesive was assumed to be elastic isotropic with following material properties: $E$ = 0.96 GPa and $G$ = 0.34 GPa. Each laminate was of 50 mm long straight section on each side ($L_1$ and $L_2$) of the joint region ($L_3$). The length of the joint region is a function of the taper angle. A 20° taper angle was chosen for comparing finite element results with analytical results. Later, taper angles were varied between 30˚ to 90˚ to demonstrate the effect of taper angle on the joint strength. The applied bending moment is 2 Nm.

**3.1 Stress Distribution in Adhesive**

The peel stress is defined as the adhesive stress component which is perpendicular to the taper surface. Figures 2 and 3 show the peel and shear stress distributions along the taper for both the finite element and analytical models, respectively. These stresses correspond to a taper angle of 20 deg. As can be seen from figures that there is a good correlation between the stress distributions obtained using the analytical model and the finite element model. The close agreement in stress distribution results validates both models. As expected, the peak stresses are carried by the zone adjacent to the 0˚ angle plies. The peel stress reaches a value of 100 MPa (tensile) at the beginning of the first longitudinally oriented ply and decreases with x, and in last ply it reaches a magnitude of 150 MPa (compressive). Similar behavior was obtained for shear stresses: it reaches a maximum value of 220 MPa (tensile) and reverses to 300 MPa (compressive). In the laterally oriented plies (90 deg), the stresses are almost zero. The variation of peel and shear stresses (deduced from stress contours) with respect to the taper angle (20°), plotted in Figure 4, shows that the peel and shear stresses peak at 45˚ taper angle.

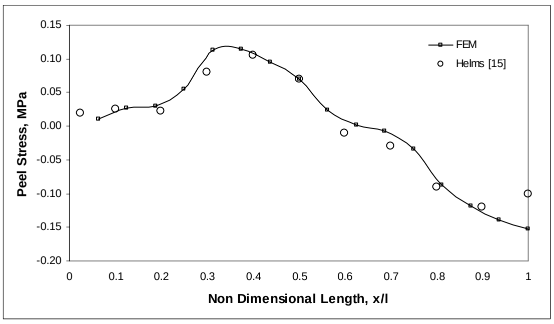


*Figure 2: Adhesive peel stress*

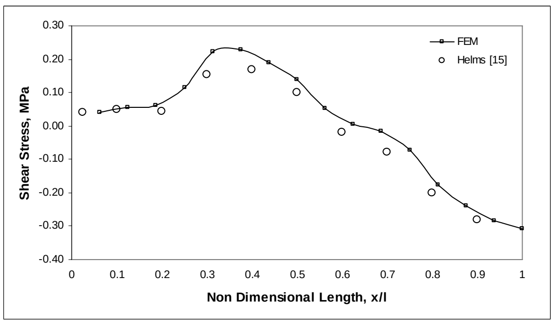


*Figure 3: Adhesive shear stress*

**3.2 Stress Distribution in Laminate Plate**

A reasonable correlation is noticed between the stress distributions obtained by the finite element model and analytical model, as shown in Figure 5. It can be deduced that far from the neighborhood of the adhesive, the classical theory of laminated plate remains useful. However, in the near vicinity, the transverse shear deformation effect can not be neglected. Contour plots show that the magnitude of peel and shear stresses are higher in adherends as compared to those in the adhesive. It is important to mention that the magnitudes of transverse stresses are less then 5 % of the longitudinal stress, away from the joint region.

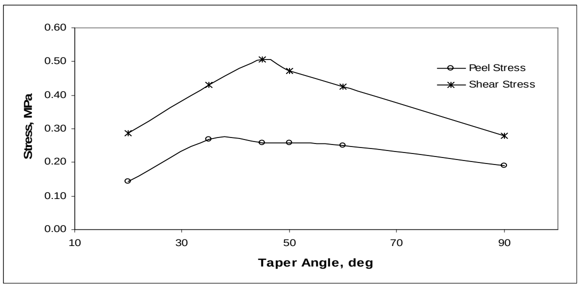


*Figure 4: Peel and shear stress vs. taper angl*

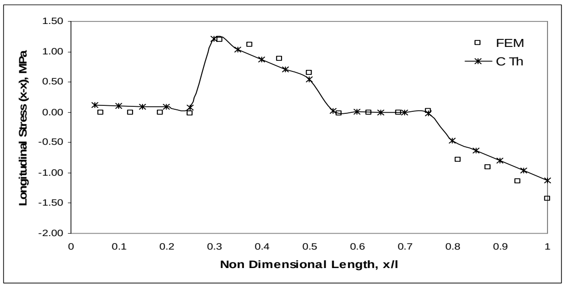


*Figure 5: Longitudinal stress distribution in adherends*

## 4. CONCLUSIONS

A finite element model of the stress-strain distribution in an adhesively-bonded taper-taper joint under cylindrical bending has been developed using laminated plate theory. The finite element model results were compared with analytical model results of Helms et. al and were found in good agreement. The model accurately computes the peak peel and shear stresses in adherends and adhesives. The model can be used to analyze joints for safe and efficient design.

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## 6. ACKNOWLEDGEMENT

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