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Through-the-width delamination damage propagation characteristics in single-lap laminated FRP composite joints

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ABSTRACT

Three-dimensional non-linear finite element analyses have been carried out to study the effects of through-the-width delaminations on delamination damage propagation characteristics in adhesively bonded single-lap laminated FRP composite joints. The delaminations have been presumed either to pre-exist or to get evolved due to coupled stress failure criteria in the laminated FRP composite adherends near the overlap ends beneath the ply adjacent to the overlap region. The out-of-plane stresses in the adhesive layer, the interlaminar stress distributions along the delamination fronts and the strain energy release rates (SERRs) corresponding to the three individual modes have been evaluated for varying positions of the delaminations pre-embedded in either of the adherends. A good matching between the present 3D results and experimental and analytical solution of the literature has been established for the undamaged and a damaged model. A significant difference in the interlaminar stresses and the SERR values has been observed and is largely dependent on the adherends (bottom or top) possessing the through-the-width delamination damages. Also, the interlaminar stresses and SERR values along the two corresponding delamination fronts are different. Accordingly, it can be concluded that the positions of the through-the-width delaminations significantly influence the delamination damage propagation behaviour vis-a-vis the performance of the composite joint.

1. Introduction

Adhesive bonding in laminated FRP composites is being increasingly used in many applications, especially in space, aircraft and automobile industries, because of its well-known advantages over the other joining methods such as mechanical fastening, welding, brazing and soldering, etc. A good number of research investigations relating to adhesively bonded joints in FRP composites have included the single-lap joint configurations amongst the wide variety of geometries being analyzed. Notably among them, Volkersen [1], Goland and Reissner [2], Hart-Smith [3] and Adams et al. [4–7] provided considerable elucidations of qualitative behaviour of loaded adhesively bonded single-lap joints. Their analyses are based on certain simplified assumptions as highlighted by Carpenter [8] in order to achieve tractable results and the consequent quantitative agreement with experiments has hitherto been less than adequate to form a basis for the designer without empirical modifications. The factors considered for these analyses include adhesive plasticity, adherend stiffness imbalance, nature of loadings and other influencing parameters like spew geometry, thickness of the adherends and the adhesive layer, overlap lengths, etc. With optimized values of those influencing parameters along with valid assumptions, extensive research efforts have been put forward by Tong [9–12], Adams et al. [4–7], Renton and Vinson [13] and Jena [14] etc. for laminated FRP composite adherends using analytical, experimental and numerical techniques. The potential problems of coupled anisotropy and material heterogeneity associated with the use of laminated composite adherends always require a relook for further research. In addition to the existing complexities due to the material heterogeneity and discontinuities of loading and geometry giving rise to stress concentration effect, the various modes of failures such as delaminations, fiber breakage and interlaminar cracking make the joint analyses more complex and involved.

Interlaminar or interply delamination is a major failure mode in the adherends of a FRP composite bonded joint [7,15–16]. As a result of this, the structures having bonded joints reduce their strengths and stiffnesses and thus the lives of the structures are limited. Due to the low transverse tensile strength, the adherends of the SLJ are likely to fail in transverse tension (peel stresses) before the adhesive layer fails. Like the shear stresses, the values

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of the peel stresses are the highest at the overlap ends and hence can induce adherend failures due to the low tensile strength in the transverse direction (through-the-thickness). Also, the severity of joint failure would be enhanced due to loading eccentricity in case of SLJ. In such cases, even though the remote loading is of inplane type, the local loading effect near the discontinuities prevailing around the overlap portions of the joint may be out-of-plane type. Although a lot of work has been done to understand and predict the failure behaviour of laminated FRP SLJ [17–22], limited effort has been devoted to understand the effect of the presence of through-the-width delamination when embedded in the adherends on delamination propagation parameters such as interlaminar stresses (σ_z, τ_{yz} and τ_{xz}) and the three individual modes of strain energy release rates (SERR).

The present work deals with the study of the effect of embedded delamination positions on stress distributions in the adhesive layer, interlaminar stress distributions and SERR variations on delamination fronts, when they are present in either of the laminated adherends for the considered SLJ as shown in Fig. 1. The analytical solutions [2,3,6,23,24] indicate that the peel stress and shear stress distributions in the adhesive layer are maximum at the overlap ends. Thus, it necessitates to study the effects of through-the-width embedded delamination, located beneath the surface ply of either adherends adjacent to the adhesive layer and closer to the overlap ends of the joint, on stress distributions in the adhesive layer, interlaminar stress variations and different modes of SERR (G_{I}, G_{II} and G_{III}). Fig. 1(a) represents the geometry and configuration of the laminated FRP composite SLJ when through-the-width delamination is embedded in the bottom adherend, and similarly Fig. 1(b) shows the delamination damage location in the top adherend. Non-linear finite element analyses have been carried out for varying delamination locations by embedding them at a distance of either d_1 or d_2 equal to 0.4c, 0.5c and 0.6c in either of the adherends. Here, d_1 or d_2 is the distance between the center of the embedded delamination and the midpoint of the overlap length c of the bottom or the top adherend of the joint, respectively. The stress states are much different at the two overlap ends because of the loading eccentricity prevailing in the joint and the different boundary conditions, and hence analyses have been performed separately for the two cases corresponding to Fig. 1(a) and (b).

2. Joint specimen geometry and material constants

The laminated FRP composite SLJ specimen is shown in Fig. 1 and has length $L = 5$ mm, width $W = 20$ mm, overlap length $c = 15$ mm and adhesive layer thickness $t_a = 0.26$ mm. The top and bottom adherends are of [8] graphite/epoxy FRP composite laminates, whose material constants are given in Table 1. Each ply thickness is taken to be 0.125 mm. The through-the-width delaminations of length 2 mm each have been presumed to be pre-embedded as shown in Fig. 1(a) and (b), respectively. Non-linear finite element analyses have been carried out for the SLJ with embedded delaminations at three specified locations; (i) when the delamination is completely within the overlap region of the SLJ, i.e. d_1 or $d_2 = 0.4c$, (ii) when the midpoint of the delamination is exactly aligned with the overlap end, i.e. d_1 or $d_2 = 0.5c$ and (iii) when the delamination is completely outside the overlap region of the SLJ, i.e. d_1 or $d_2 = 0.6c$. One end of the SLJ

Table 1
Material constants [33]

Adherend	(0_8) Graphite/epoxy laminate Layer properties: $E_x = 181$ GPa, $E_y = E_z = 10.3$ GPa $\nu_{xy} = \nu_{xz} = 0.28$, $\nu_{yz} = 0.3$ $G_{xy} = G_{xz} = 7.17$ GPa, $G_{yz} = 4$ GPa
Adhesive	Epoxy $E = 2.8$ GPa and $\nu = 0.4$

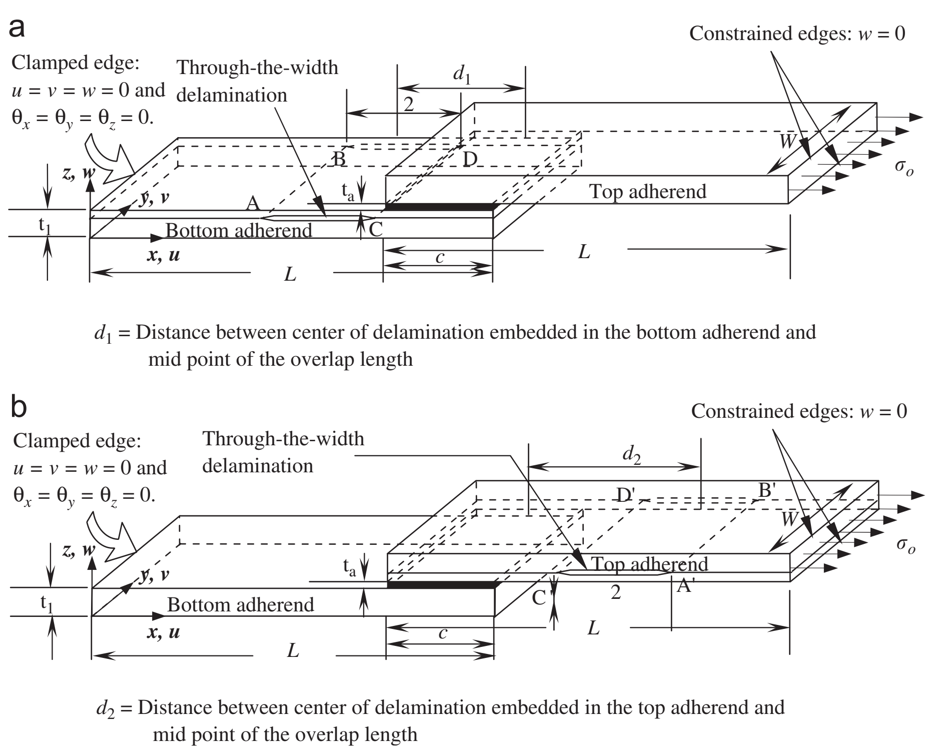

Fig. 1. Single-lap laminated FRP composite joint showing through-the-width delaminations embedded in either of the adherends near the overlap ends beneath the surface ply adjacent to the overlap region: (a) bottom adherend showing two delamination fronts AB and CD and (b) top adherend showing two delamination fronts A′B′ and C′D′