EFFECT OF THROUGH-THE-WIDTH EMBEDDED DELAMINATION ON DAMAGE PREDICTION OF SINGLE LAP FRP COMPOSITE JOINTS

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Keywords: Adhesive bonding, Delamination, FEA, Sublaminate technique, SLJ.

Abstract

Three-dimensional non-linear finite element analyses have been carried out to study the effects of through-the-width delaminations on damage prediction of adhesively bonded single lap laminated FRP composite joints. The delaminations have been presumed either to pre-exist or 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 and on the delamination fronts are responsible for initiation of different types of failures. Failure initiations due to adhesion, cohesion and delamination damages have been predicted in terms of failure index e_a, e_c and e_d, respectively for the FRP composite SLJ. Initiations of adhesion and cohesion failures have been predicted over the interfaces of adherends and adhesive layer, respectively, whereas, the delamination damage initiation have been predicted on the delamination front. It is observed that the positions of the delaminations pre-embedded in both the adherends have significant effect on initiation of damages. Also it is found that, the delamination damage initiation indices 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 damage initiation 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 due to its well known advantages over other joining methods such as mechanical fastening, welding, brazing and soldering etc. Among the commonly used joint geometries, the single lap joint (SLJ) is known to be the most sensitive to change in geometrical parameters. The loading eccentricity path makes these simple joints complex and the joint becomes weak. When the adherends are made of laminated FRP composites, the problem becomes still more complex and is quite involved due to its low interlaminar transverse strength and hence it is prone to have many defects or flaws like delamination. From the stress and strength analyses for a SLJ, it is reported by many research workers [1,2] that the free edges of the overlap ends are sensitive for the damage initiation. The present work emphasizes on studying the effects of through-the-width delaminations when embedded in both the adherends with varied locations on initiation of adhesion, cohesion and delamination failures.

The experimental, analytical and numerical solutions reveal that the stress state is three-dimensional in nature due to the material heterogeneity, load path eccentricity and geometrical discontinuities etc. Because of these factors, the analytical and experimental solutions are limited. Thus, Hart-Smith [3], Panigrahi and Pradhan [4], Kairouz and Matthews [5] and Carpenter [6] emphasized on Finite Element Method (FEM) as a tool among the various numerical techniques available due to its versatility to cover all types of problems with every complexity of bonded joints without compromising on the solutions.

The adhesion and cohesion failures are assumed to occur at the interfaces and in the adhesive layer, respectively, while delamination induced damages initiate from the delamination fronts and considered to be responsible for the joint failure. Many works have been done for cohesion failure study of SLJ. Moreover, at each point on the boundary between two dissimilar materials, there is an abrupt change in slope giving rise to a sharp corner, and this necessitates the study of failure along the bondline interfaces of the SLJ. The available methodology used for the prediction of location of initiation of adhesion (occurs along the bondline surfaces) failure, cohesion (occurs in the adhesive layer) failure and delamination failures are limited. As mentioned earlier, for the laminated FRP composite adherends, the existence of defects like delaminations are inevitable. Thus, the effects of the delamination position when embedded in both the adherends on location of damage initiation (along the interfacial surfaces, adhesive layer and along the delamination fronts) have not yet been studied.

The present work deals with an accurate 3D analysis for understanding the joint stress fields and the damage initiation in practical applications. The effect of through-the-width delamination position when embedded in both the adherends on location of failure initiation at the different surfaces of overlap region and on the delamination fronts of the SLJ have been studied. Geometrically non-linear contact analysis has been carried out to prevent the interpenetration between the delaminated surfaces.

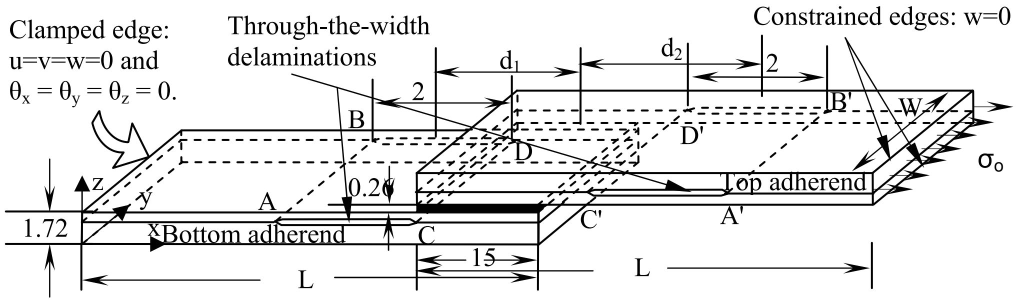
2 Joint specimen geometry, material constants and FE analyses

The laminated FRP composite SLJ specimen is shown in Fig. 1 and has length L = 95mm, width W =20mm, overlap length c = 15mm and adhesive layer thickness = 0.26mm. The top and bottom adherends are of $[0_8]$ graphite/epoxy FRP composite laminates whose material constants are given in Table 1. Each ply thickness is taken to be 0.125mm.

Table 1. Layer wise material properties of adherends ($[0_8]$ Graphite/Epoxy laminate) and adhesive (Epoxy) [8]

Adherend:	Material constants
	$E_x = 181$ 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
	Strengths
	$Z_T = 94$ MPa, $Z_C = 290$ MPa,
	$S_{YZ} = 30$ MPa, $S_{XZ} = 98$ MPa.
Adhesive:	Material constants
	$E = 2.8$ GPa and $\nu = 0.4$
	Strengths
	$Y_T = 65$ MPa, $Y_C = 84.5$ MPa

The through-the-width delaminations of length 2mm each have been presumed to be pre-embedded as shown in Fig. 1. 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. $d_1 = d_2 = 0.4c$, (ii) when the mid point of the delamination is exactly aligned with the overlap end, i.e. $d_1 = d_2 = 0.5c$ and (iii) when the delamination is completely outside the overlap region of the SLJ, i.e. $d_1 = d_2 = 0.6c$. One end of the SLJ is clamped and the other end is uniformly loaded as shown in Fig. 1. A total of 20kN load has been uniformly distributed to be applied through this end. Stresses have been evaluated in the adhesive layer and on the delamination fronts using finite element software ANSYS 10.0 in a high speed IBM platform. The failure initiation indices e_a, e_c and e_d due to adhesion, cohesion and delamination damages respectively have been computed using different coupled stress failure criteria in respect to varied positions of the embedded delaminations.



d_1 and d_2 = Distance between the center of overlap length and delamination of bottom and top adherend, respectively

Fig. 1. Single lap laminated FRP composite joint showing through-the-width delaminations embedded in both the adherends near the overlap ends beneath the surface ply adjacent to the overlap region.

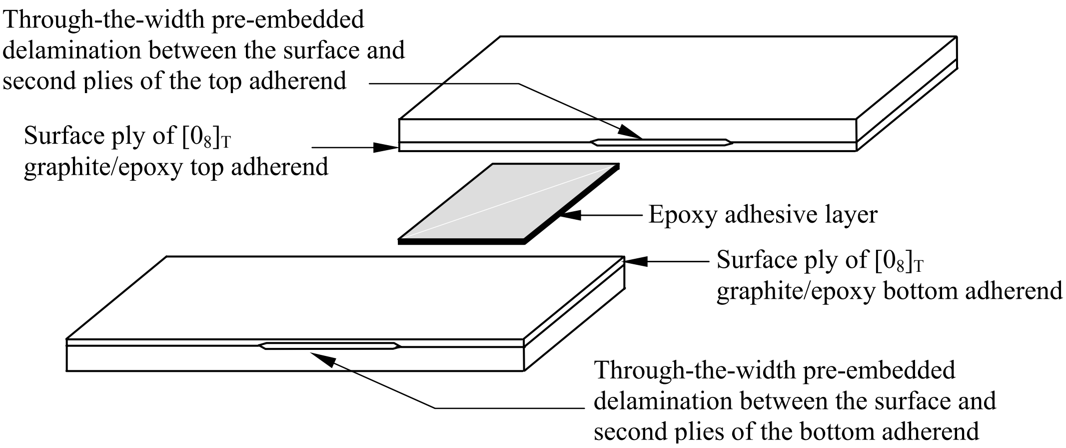


Fig. 2. Sublaminates of single lap FRP composite joint embedded with through-the-width delaminations.

2.1 Finite element analyses of SLJ embedded with through-the-width delaminations

Out-of-plane stresses are responsible for the initiation and further propagation of delamination. Since the stress state is inherently three-dimensional [7], this aspect necessitates for a full three-dimensional damage analysis. The 3D brick element models are known to be more accurate for modelling and FE simulations of SLJ. Though, brick elements are more accurate for SERR computations, but by using many layers of brick elements through the thickness to model the individual plies, the modelling and computational effort may become prohibitively large [8-9]. Therefore, in the present analysis, three-dimensional eight-node layered volume elements (Solid 46) with layerwise material constants have been used to model the different sublaminates of laminated composite adherends and solid 45 elements have been used for the adhesive layer. The through-the-width delaminations are presumed to be embedded in either of the adherends between the surface and second plies and each has been modelled as a sublaminate as shown in Fig. 2. Figure 2 demonstrates the sublaminates of bottom and top adherends, respectively, to be used for finite element meshing. The zoomed views of 3D finite element meshes of the overlap region of the SLJ specimen embedded with through-the-width delaminations in both the adherends are shown in Figs. 3 (a-c).

In order to simulate the delamination damages, contact elements are used within the delaminated region to prevent mutual interpenetration of the top and bottom delaminated surfaces. This contact processor always maintains a positive value of displacement difference along the z-direction between the pair of nodes inside the delaminated zone of the top and bottom delaminated surfaces. Furthermore, it has been assumed that the delamination plane is the weakest and the delamination will propagate parallel to the xy plane. Thus, the possibility of out-of-plane propagation is ignored.

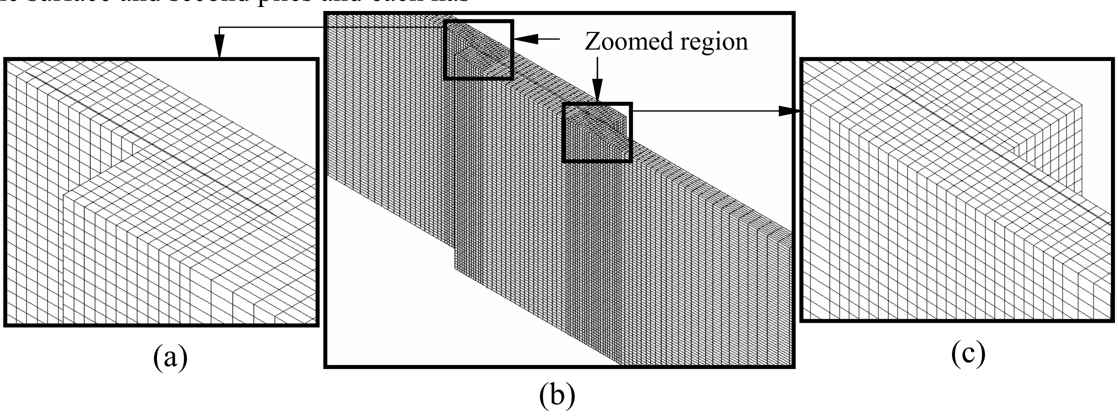


Fig. 3. Zoomed views of finite element meshes of the SLJ specimen embedded with through-the-width delaminations in both the adherends; (a) bottom adherend, (b) overlap region and (c) top adherend.

3 Prediction of damage initiation

It is customary for the joint designer to predict the failure initiation in an SLJ with known material properties, geometries and loading. Compared to the failure in metal joints a large number of failure modes can be identified for composites due to their anisotropic nature. The FRP composite laminates used for the adherends and the adhesive layer develop local failures or exhibit local damage such as adhesion failure, cohesion failure and delamination failure. The ability to predict initiation and growth of such damage is essential for assessing the performance of the joint.

Stress analyses are performed by most models using 2D linear or non-linear finite element analysis. However, in the case of SLJ, the stress states at the point of discontinuities are three-dimensional and depend on many complex parameters which can not be considered by 2D model. Thus, after the computation of stress from three-dimensional non-linear finite element analyses, stress based failure criteria [10,11]for laminated FRP composite may be used. Tsai-Wu's coupled stress failure criterion has been used to predict the failure initiation at (i) the interfacial surfaces of the overlap region of the joint and (ii) the delamination front and Raghava's cohesive failure criterion [12] is used to predict the cohesion failure in the adhesive layer. The failure criteria used for prediction of damage initiation pertaining to adhesion, cohesion and delamination induced damages in SLJ are as follows:

(i) The adhesion and delamination induced damage indices e_a and e_d, respectively are evaluated using Tsai-Wu [10,11] coupled stress failure criterion under the three dimensional stress states in the overlap region.

$$\left(\frac{\sigma_z}{Z_T}\right)^2 + \left(\frac{\tau_{xz}}{S_{XZ}}\right)^2 + \left(\frac{\tau_{yz}}{S_{YZ}}\right)^2 \geq 1, \text{ for } (\sigma_z \geq 0) \qquad (1)$$

$$\left(\frac{\sigma_z}{Z_C}\right)^2 + \left(\frac{\tau_{xz}}{S_{XZ}}\right)^2 + \left(\frac{\tau_{yz}}{S_{YZ}}\right)^2 \geq 1, \text{ for } (\sigma_z < 0) \qquad (2)$$

(ii) 3D parabolic failure criterion proposed by Raghava [12] to determine the damage initiation index e_c due to cohesive failure which occurs in the adhesive layer is given by;

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 + 2(|Y_C| - Y_T)(\sigma_1 + \sigma_2 + \sigma_3) = 2|Y_C|Y_T \qquad (3)$$

The notations of the quantities appearing in the above failure criteria refer to local coordinate system. In this system, the x- and y- axes are parallel and transverse to the fibers, respectively, while, the z-axis coincides to the normal directions. The quantities in the denominators of Eqs. (1) and (2) are the strengths in the corresponding directions. σ_1, σ_2 and σ_3 are the principal stresses in the adhesive layer whose tensile and compressive strengths are Y_c and Y_T, respectively. Initiations of various types of damages in the SLJ are predicted using Eqs. (1) to (3) and material properties given in Table 1. The adhesion failure index (e_a), the cohesion failure index (e_c) and delamination damage index (e_d) have been computed using the above mentioned equations. Thus, based on the magnitudes of e_a, e_c and e_d, the critical location for damage initiation in the SLJ has been identified.

4 Results and discussions

4.1 Adhesion and cohesive failure prediction

The magnitudes of out-of-plane stresses at the interfaces of overlap region and in the adhesive is always an important factor of the bonded joint analysis. The out-of-plane stresses (σ_z, τ_{xz} and τ_{yz}) and the principal stresses in the adhesive layer of the considered SLJ are evaluated from three-dimensional FE analysis with varied delamination positions, when through-the-width delaminations are embedded in both the adherends. Using Eqs. (1) and (3), the adhesion and cohesion failure indices, e_a and e_c in the appropriate surfaces have been evaluated and are represented in Figs. (4) to (7), when delaminations are embedded at varied locations in both the adherends. The variations of e_a and e_c over the interfaces and the mid-surface of adhesive layer of SLJ have been shown in Fig. 4 for d_1=d_2=0 (i.e. no delamination). Similarly, for d_1=d_2=0.4c (i.e. embedded delaminations are completely inside the overlap region), d_1=d_2=0.5c (i.e. embedded delamination centres are exactly aligned with the overlap ends) and d_1=d_2=0.6c (i.e. embedded delaminations are completely outside the overlap region), e_a and e_c variations have been illustrated in Figs. 5-7.

As expected, e_a values are low along the free edges of the bottom and the top adherend interfaces compared to the other ends in the overlap region with and without delaminations. Thus it may be emphasized that the initiation of adhesion failures are from the edges of stress singularity points (where there is an abrupt change in slopes in case of SLJ). But, e_c values are almost same at the free edges for

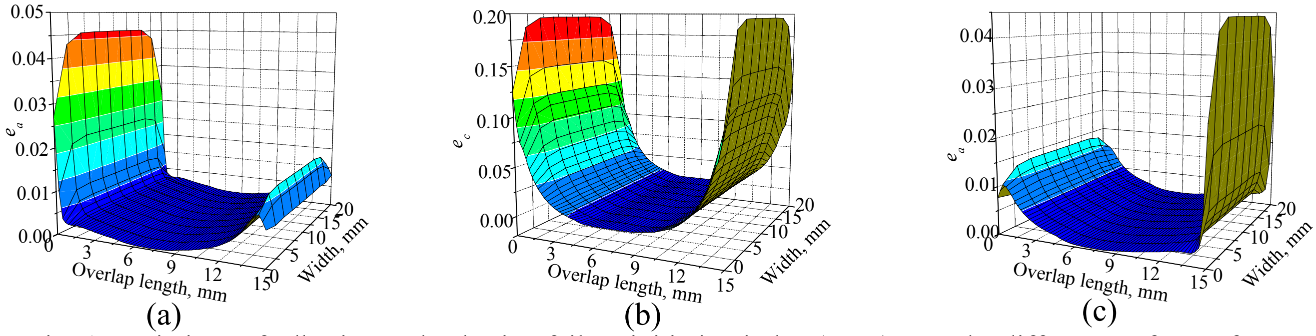


Fig. 4. Variations of adhesion and cohesion failure initiation index (e_a, e_c) over the different surfaces of SLJ: (a) bottom interface, (b) adhesive layer and (c) top interface, for $d_1 = d_2 = 0$ (i.e. no delamination).

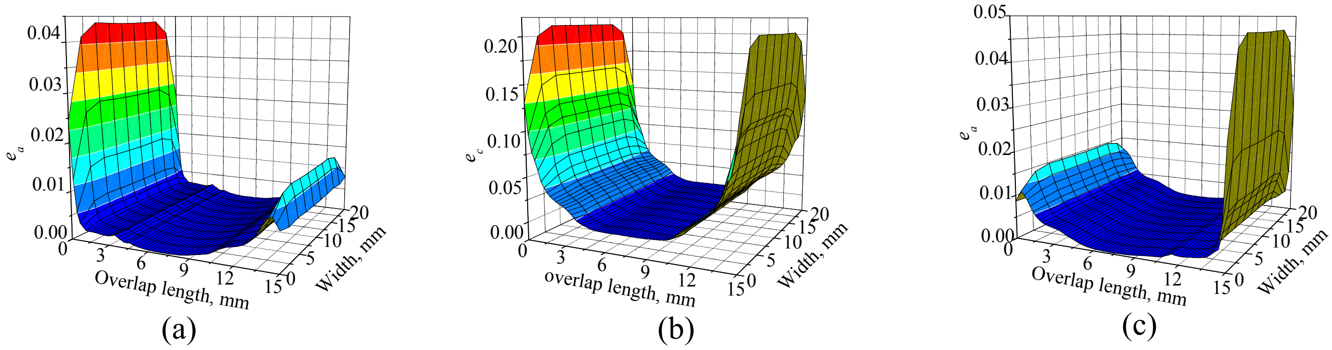


Fig. 5. Variations of adhesion and cohesion failure initiation index (e_a, e_c) over the different surfaces of SLJ: (a) bottom interface, (b) adhesive layer and (c) top interface for $d_1 = d_2 = 0.4c$ (i.e. embedded delaminations are completely inside the overlap region)

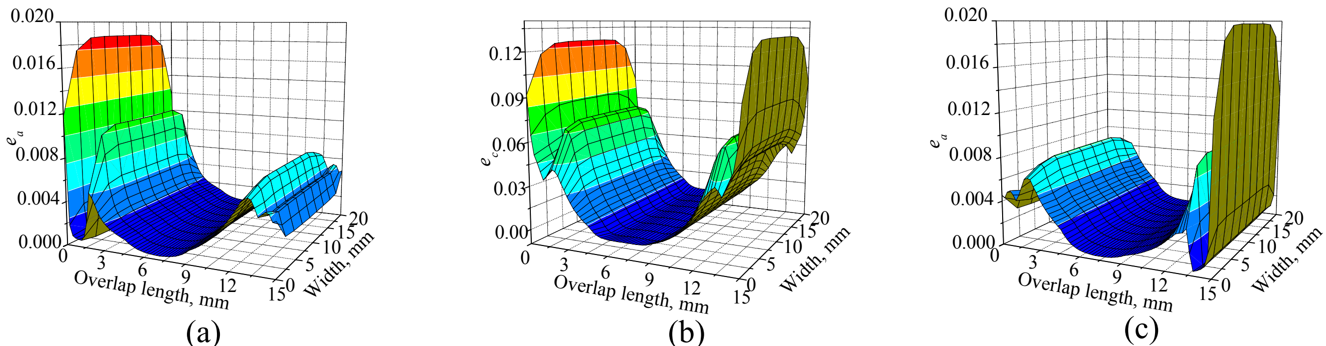


Fig. 6. Variations of adhesion and cohesion failure initiation index (e_a, e_c) over the different surfaces of SLJ: (a) bottom interface, (b) adhesive layer and (c) top interface for $d_1 = d_2 = 0.5c$ (i.e. embedded delamination centres are exactly aligned with overlap ends)

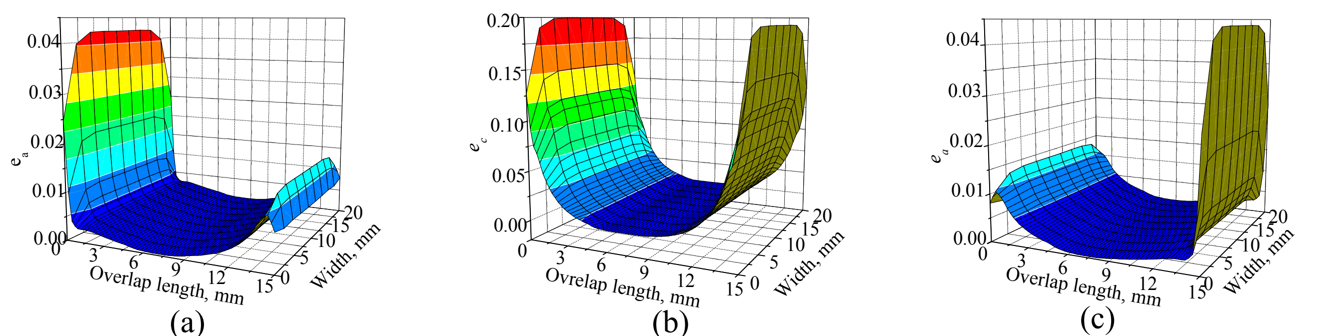


Fig. 7. Variations of adhesion and cohesion failure initiation index (e_a, e_c) over the different surfaces of SLJ: (a) bottom interface, (b) adhesive layer and (c) top interface for $d_1 = d_2 = 0.6c$ (i.e. embedded delaminations are completely outside the overlap region).

the adhesive layer. However, e_c values are significantly higher compared to e_a values, indicating the cohesion failure initiation in the adhesive layer is ahead of adhesion failure. It is interesting to note that, e_a and e_c variations are nearly same as seen in Figs. 4 and 7. Thus it may be concluded that the presence of delamination outside the overlap region seldom affects the initiation of adhesion or cohesion failure. However, referring to Figs. 5 and 6, the e_a and e_c values are affected significantly, when delaminations are located (partially or completely) inside the overlap region. In such situations, secondary peak values of e_a and e_c appear at the location near to the delamination front and the magnitudes of peak values are higher when the mid point of the delamination is exactly aligned with the overlap end, i.e. $d_1 = d_2 = 0.5c$ (Fig. 6) compared to the case when the delamination is completely within the overlap region of the SLJ, i.e. $d_1 = d_2 = 0.4c$.

In general, e_a and e_c values in the overlap region remain more or less same along the width except at the free edges.

4.2 Delamination damage prediction

Interlaminar stresses (σ_z, τ_{xz} and τ_{yz}) along the delamination fronts AB, CD and A'B', C'D' are responsible for delamination growth and have been computed from non-linear finite element analyses. Generally, the delamination growth may be studied either by using energy principle based on fracture mechanics or stress based principle. Here, stress based method has been adopted by expressing delamination initiation in term of delamination damage initiation index e_d. Eqs. (1) and (2) have been used to evaluate e_d. The variations of e_d along the delamination fronts AB, A'B' and CD, C'D' have been illustrated in Figs. 8 and 9 for varied delamination positions. It is seen that e_d values

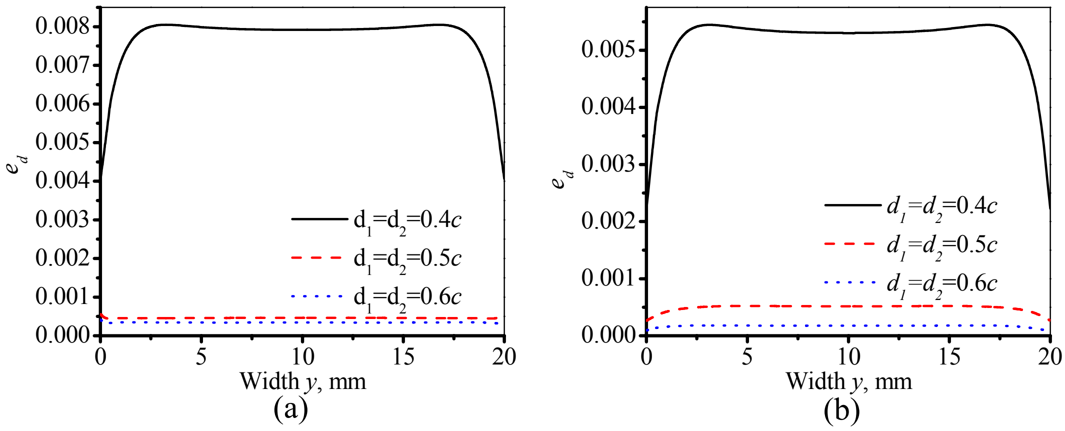


Fig. 8. Variations of delamination damage initiation index (e_d) over the delamination fronts (a) AB and (b) A'B' for varying delamination positions.

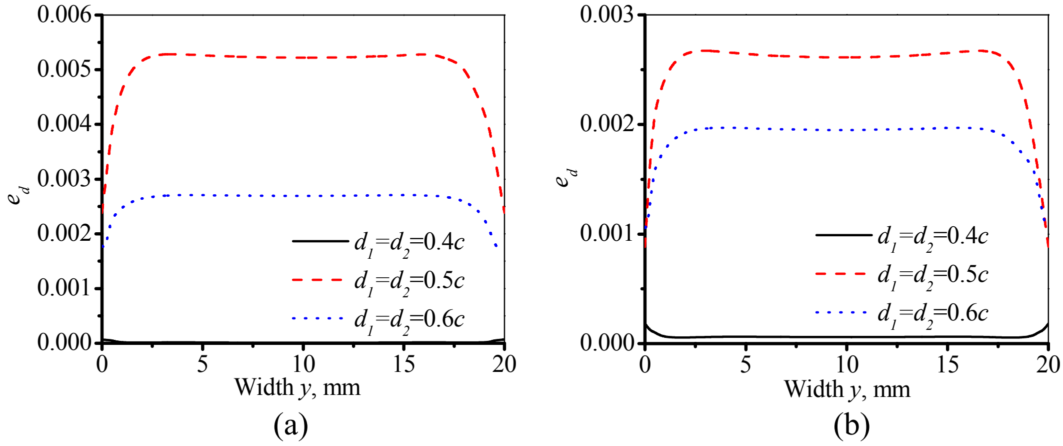


Fig. 9. Variations of delamination damage initiation index (e_d) over the delamination fronts (a) CD and (b) C'D' for varying delamination positions.

remain constant and are of higher magnitude along the delamination fronts i.e along the width of the joint in the central region compared to the free edges for all embedded delamination lengths.

Figures 8 and 9 show that, e_d values along the delamination front AB or CD are high compared to the front A'B' or C'D', indicating the delamination front AB or CD are more vulnerable for delamination growth. More precisely, the delamination when embedded in the bottom adherend is more detrimental compared to that when embedded in the top adherend.

In regard to the delamination growth with varied delamination positions, it is seen from Fig. 8 that, e_d values along the delamination front AB for $d_1 = d_2 = 0.4c$ (when the delamination is completely within the overlap region) is higher compared to the other locations of delamination when present in both the adherends. It indicates that the delamination front nearer to the free edge of the overlap end irrespective of its presence in any adherends is vulnerable for the growth of delamination damages. On the contrary, the delamination front CD for $d_1 = d_2 = 0.5c$ (when the mid point of the delamination is exactly aligned with the overlap end) will grow due to higher values of e_d compared to other locations of delamination as shown in Fig. 9.

5 Conclusions

Three-dimensional non-linear finite element analyses have been carried out to study the effects of through-the-width delaminations pre-embedded in laminated FRP composite adherends on prediction of different damage initiations in adhesively bonded single lap joints. It is seen that the locations of through-the-width delaminations play significant role on the damage initiations due to adhesion, cohesion and delamination damages. Based on the above, the following conclusions are derived.

- The initiation of adhesion failures are from the edges of stress singularity points for an SLJ.
- Under in-plane loading, the cohesion failure initiation in the adhesive layer occurs ahead of the adhesion failure.
- The presence of delamination outside the overlap region seldom affects the initiation of adhesion or cohesion failures.
- The delamination when embedded in the bottom adherend is more detrimental for the failure of SLJ due to delamination growth compared to that when embedded in the top adherend.
- Delamination front nearer to the free edge of the overlap end irrespective of its presence in any adherend of an SLJ is vulnerable for the growth of delamination damages.

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