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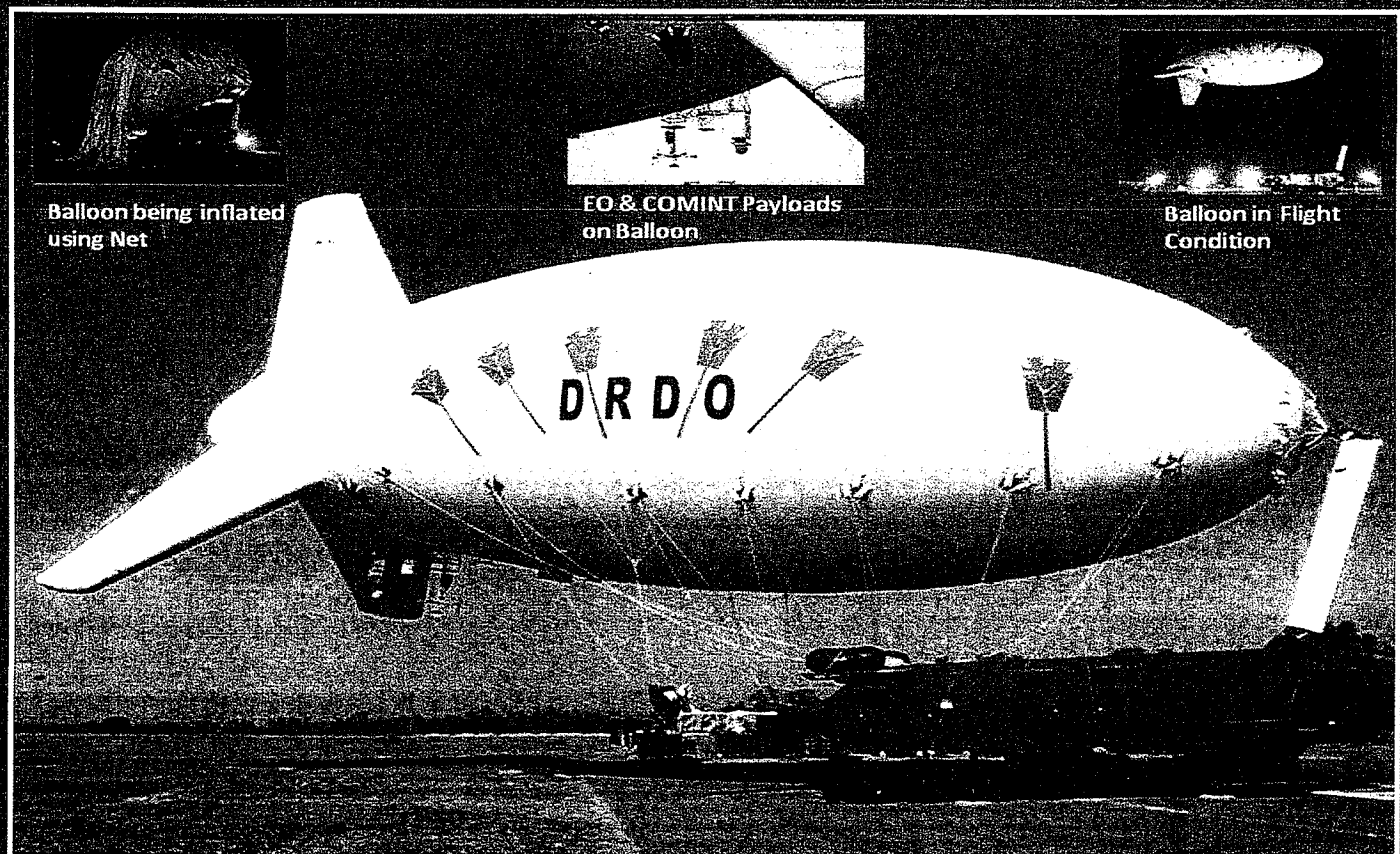
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TRANSLAMINAR REINFORCEMENTS IN FIBER COMPOSITES

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Abstract

Translaminar reinforcements (TLR) are effective means of improving the interlaminar fracture toughness of laminated fiber composites. The three methods to provide such reinforcements are: stitching, z-pinning and three-dimensional weaving. Although TLR are effective in improving the interlaminar fracture toughness, there is an optimum amount of reinforcement that can be provided to a given laminated structure. Excessive reinforcement may weaken the laminate. On the other hand weak reinforcements could be detrimental as they could lead to lowering the stiffness of the structure as the crack propagates. In this paper we review some of the analytical, numerical and experimental methods used to understand the effectiveness of TLR.

Keywords: Composite laminates, delamination, interlaminar fracture, stitching, z-pinning

Introduction

Laminated fiber composites such as graphite/epoxy have very high strength-to-weight and stiffness-to-weight ratios. They have tremendous advantages over the conventional materials in many applications, such as aerospace and automotive structures, in which the aforementioned properties are critical. Also, fiber-reinforced composite materials can easily be tailored to obtain desired properties in different directions and can be optimized to meet specific performance requirements. However, these materials suffer a big deficiency - lack of through-the-thickness reinforcement. Fracture toughness of these materials is so low that as crack is initiated between the layers, the delamination can propagate easily. Through-the-thickness stitching, z-pinning and three-dimensional weaving are some of the methods to reinforce the laminated composites and prevent delamination crack propagation. Sharma and Sankar conducted a study on the effects of stitching on interlaminar fracture toughness of uniweave textile composites [1-4]. They used the double cantilever beam setup to test low density stitched specimens and the University of Florida Compression-After-Impact (UFCAI) test fixture to investigate effects of stitching on sublaminar buckling behavior. Their study showed that stitching had a profound effect on Mode I fracture toughness and CAI strength. They also found that stitching does not increase the impact load at which delamination begins to propagate, but greatly reduces the extent of delamination growth at

the end of the impact event. Chen et al. [5-8] developed specialized fixtures and methods to test composites with very high stitch density. Conventional methods failed for these specimens because the specimens failed before the stitch broke and delaminations could propagate. The mixed mode fracture of stitched specimens was investigated by Rys et al. [9].

Analytical methods to study stitched composites under Mode I delamination were developed by Sankar and Dharmapuri [10]. Sankar and Zhu [11] simulated low velocity impact of composite laminates and used Mode II model to study delamination propagation under impact. Recently Song et al. [12, 13] developed an analytical model for z-pinned composites. They verified their models using finite element analysis. Analytical model for mixed mode loading has been developed by Jang and Sankar [14]. Wallace et al. [15] studied the effect of z-pinning on delamination suppression in sandwich composite beams under axial compression. The high-strain rate effects on stitched composites were studied using split Hopkinson pressure bar by Dee et al. [16]. Recently attention has been paid to three-dimensionally woven composites to understand the effects of translaminar reinforcements under very high impact loading [17-19].

In this paper we briefly describe the various tools, analytical, numerical and experimental tools used to un-

understand the effectiveness of TLR in laminated composite structures.

Analytical Approach

Analytical approach for Mode I delamination of composites with translaminar reinforcements is based on the idea that the bridging zone developed during delamination can be mathematically represented as distributed traction acting on a beam or plate-like structure as shown in Fig. 1. Distributed traction is actually the smeared force exerted by the reinforcements. The bridging force during delamination depends on type of translaminar reinforcement since failure mechanisms are different in different types of reinforcements. Fiber breakage after stretching is the main mechanism in stitching while pull-out is the predominant mechanism in z-pinned composites. The mechanisms are much more complicated in woven composites and also when the laminate is subjected to mixed-mode fracture. Usually cohesive elements are used to represent the translaminar reinforcements. For example, the load-displacement behavior of the reinforcements in stitched and z-pinned composites is depicted in Fig. 2. In the case of stitching (Fig. 2a) the force-displacement relation is assumed as linear and the failure is assumed to be of brittle type. In the case of z-pins, the force is maximum (f_m) in the beginning, and gradually reduces as the pin pulls out of the composite.

Stitch Model

For stitched laminated composites, shear deformable beam theory was employed by Sankar and Dharmapuri [10]. The laminate was modeled as a cantilever beam on elastic foundation with foundation constant k defined as:

$$k = N \frac{A_s E_s}{h} \quad (1)$$

In the above equation A_s is the area of cross section of the stitch yarn, E_s is Young's modulus of the stitch material and N is stitch density in number of stitches per unit area. Then the governing equations for the beam rotation $\psi(x)$ and transverse deflection $w(x)$ are:

$$EI \frac{d^2 \psi}{dx^2} - GA \psi - GA \frac{dw}{dx} = 0 \quad (2)$$

$$GA \frac{d\psi}{dx} + GA \frac{d^2 w}{dx^2} - kbw = 0 \quad (3)$$

where EI and GA are equivalent flexural rigidity and transverse shear rigidity of the laminate and b is the width of the laminate in the y -direction. Solutions for Eq. (2) and Eq. (3) can be assumed as

$$\psi(x) = \sum_{i=1}^4 a_i e^{\lambda_i x} \quad (4)$$

$$w(x) = \sum_{i=1}^4 b_i e^{\lambda_i x} \quad (5)$$

where the roots are

$$\lambda_{1,2,3,4} = \pm \sqrt{\frac{\frac{k}{GA} \pm \sqrt{\frac{k^2}{GA^2} - \frac{4k}{EA}}}{2}}$$

Coefficients for Eq. (4) and Eq. (5) can be obtained from four boundary conditions such that

$$\begin{aligned} \text{at } x = 0 & \quad \begin{cases} V = GA \left(\psi + \frac{dw}{dx} \right) = -F \\ M = EI \frac{d\psi}{dx} = -C \end{cases} \\ \text{at } x = c & \quad \begin{cases} w = 0 \\ \psi = 0 \end{cases} \end{aligned} \quad (6)$$

where c is the bridging zone length. Also, another criterion related to delamination onset should be considered to find appropriate bridging length c . According to Sankar et al. [20] the strain energy release rate at the physical crack tip is given by:

$$G_I = \frac{1}{b} \left(\frac{M^2}{EI} + \frac{V^2}{GA} \right) \quad (7)$$

Based on this solution, we can compute apparent fracture toughness and express it as

$$G_{Ic, app} = G_{Ic} + NA_s E_s h \epsilon_u^2 \quad (8)$$

As shown in Eq. (8), apparent fracture toughness increases with inherent fracture toughness and strength or

ultimate strain of ϵ_u of the stitch material. According to Sankar et al. [10] bridging length decreases when inherent fracture toughness increases and increased strength of the stitch yarn results in larger bridging length. In addition to apparent fracture toughness, the bridging length should also be considered in the design of translaminar reinforcements. The expression for bridging zone length c in stitched composites under Mode I loading is given by:

$$\bar{c} = c/h = 0.76 \frac{\sqrt{\epsilon_u}}{\bar{G}_{Ic}^{1/4}} \quad (9)$$

where ϵ_u is the ultimate tensile strain of the stitch material and the nondimensional Mode I fracture toughness of the composite \bar{G}_{Ic} is given by $\bar{G}_{Ic} = \bar{G}_{Ic} / E_b h$. The equivalent Young's modulus of the composite beam E_b is computed from the flexural stiffness EI of the beam as $EI = E_b bh^3/12$.

Z-Pin Model

For z-pinned composites even more simple method was chosen, e.g., [12, 13]. The governing equation for a z-pinned one-dimensional laminate based on Euler-Bernoulli beam theory is given as:

$$EI \frac{d^4 w}{dx^4} - 2bp_m \frac{w}{h} = -bp_m \quad (10)$$

The maximum value of the traction p_m due to the z-pins is given by $p_m = Nf_m$ where N is the z-pin density, number of pins per unit area. For simplicity, Eq. (10) can be written in a non-dimensional form as:

$$\frac{d^4 \bar{w}}{d\bar{x}^4} - 2\bar{p}_m \bar{w} = -\bar{p}_m \quad (11)$$

where

$$\bar{x} = \frac{x}{h}, \bar{a}_p = \frac{a_p}{h}, \bar{c} = \frac{c}{h}, \bar{w} = \frac{w}{h} \text{ and } \bar{p}_m = \frac{12 p_m}{E}$$

Solutions for Eq.(11) is

$$\bar{w}(\bar{x}) = C_1 \cos \bar{\lambda} \bar{x} + C_2 \sin \bar{\lambda} \bar{x} + C_3 \cosh \bar{\lambda} \bar{x} + C_4 \sinh \bar{\lambda} \bar{x} + \frac{1}{2} \quad (12)$$

where $\bar{\lambda} = 4\sqrt{2\bar{p}_m}$. coefficients in the solution for Eq.(11) can be obtained with boundary conditions as follows :

$$\bar{w}(0) = \bar{w}_o, (0 < w_o \leq 1/2)$$

$$\frac{d^2 \bar{w}}{d\bar{x}^2}(\bar{c}) = \bar{a}_p \frac{d^3 \bar{w}}{d\bar{x}^3}(\bar{c})$$

$$\bar{w}(\bar{c}) = 0$$

$$\frac{d\bar{w}}{d\bar{x}}(\bar{c}) = 0 \quad (13)$$

Also the bridging length \bar{c} can be determined from

$$\left(\frac{d^2 \bar{w}(\bar{c})}{d\bar{x}^2} \right) = \bar{G}_{Ic} = \frac{12 G_{Ic}}{Eh} \quad (14)$$

In general, solutions of above equations can be obtained through iterative procedure. According to results apparent fracture toughness has linear relationship with inherent fracture toughness and maximum frictional force of Z-pin.

$$\bar{G}_{Ic-app} = \bar{G}_{Ic} + \frac{1}{2} \bar{p}_m \quad (15)$$

where

$$\bar{G}_{Ic} = \frac{12 G_{Ic}}{Eh}, \bar{G}_{Ic-app} = \frac{12 G_{Ic-app}}{Eh} \text{ and } \bar{p}_m = \frac{12 p_m}{E}$$

Based on the above results apparent fracture toughness is the sum of inherent fracture toughness of the composite and the maximum frictional force of the z-pin as shown in Fig.3.

On the other hand, steady state bridging length exponentially reduces with inherent fracture toughness and maximum frictional force of Z-pin as shown in Fig.4.

In order to enhance apparent fracture toughness with translaminar reinforcements inherent material should be strong enough to resist the subjected loading. For the composite materials with ultimate strain ϵ_u , a limiting value of the apparent fracture toughness exists [12, 13].

$$\bar{G}_{Ic-app} = \bar{G}_{Ic} + \frac{1}{2} \bar{p}_m < 4 \epsilon_u^2 \quad (16)$$

Numerical and Experimental Approaches

In reality, translamina reinforcements are discrete reinforcements. As a verification tool of our analytical solution or direct comparison with experimental result, finite element simulations are widely used. Two-dimensional analysis using plane beam element [21-22] and 3D analysis using solid or shell element [23] were performed by previous researches. Most FEM analyses were focused on modeling of crack propagation and damage of translamina reinforcement. Virtual Crack Closure Technique (VCCT) and J-integral based on fracture mechanics and cohesive zone model based on damage mechanics are adapted for crack propagation whereas nonlinear spring elements were implemented for translamina reinforcement.

Progressive Delamination Using Cohesive Element

In order to simulate progressive delamination in transversely reinforced composites cohesive element of which the area of damage curve is same as inherent fracture toughness is broadly used since it is not necessary to check out criterion for crack initiation. For z-pinned DCB specimen as shown Fig.5, FEM analysis was conducted [12, 13]. Cohesive elements defined by bi-linear traction-separation law (see Fig.6) given by [24] were implemented between shell elements representing top and bottom beam. The traction law is given by

$$\sigma = (1 - D_c) Kd$$

$$D_c = \begin{cases} 0, & d < d_o \\ \frac{d_f(d - d_o)}{d(d_f - d_o)}, & d_o < d < d_f \\ 1, & d_f < d \end{cases} \quad (17)$$

where σ is traction, K is the stiffness, D is the damage variable, d is displacement, d_o is the displacement at damage initiation and d_f is the final displacement. In addition, nonlinear spring elements to represent translamina reinforcement were located in same manner. From the displacement input condition at the free end of DCB specimen, load-deflection plot was obtained. This plot was considerably comparable to analytical and experimental results [19].

Experimental Methods

Traditionally DCB and ENF specimens have been used to measure the Mode I and Mode II fracture toughness of translamina reinforced specimens. Reeder and Crews [25] developed a fixture to measure fracture toughness under mixed-mode conditions. The key feature of this fixture is that the mode mixity remains constant as the crack propagates. Recently Davidson et al. [26] presented a shear-torsion-bending test for Mixed Mode I-II-III delamination toughness determination. Most of the tests developed so far are for either unstitched composites or moderately reinforced in the z-direction. Most of these fixtures fail when testing heavily reinforced composite laminates. The specimen ligaments fail before the delamination could propagate and break the z-reinforcements. Chen et al. [5] solved this problem by developing a novel test fixture. In this method a uniform tensile force is applied to the DCB specimen. This force being same in the two legs of the DCB, it does not contribute to the strain energy release rate. This tensile stress mitigates the high compressive stresses that form as the DCB specimen is bent and thus delays the specimen failure. The fixture is depicted in Fig.7. It was able to test stitched specimens with G_{Ic} as high as 20kJ/m^2 .

Summary

Translamina reinforcements considerably improve the interlamina fracture toughness of laminated composites. While stitching and z-pinning are proven methods, three-dimensional weaving also provides considerable through-the-thickness reinforcements. More studies need to be performed in understanding the failure mechanisms, especially delamination, in 3-D composites. The current methods need to be extended to other complicated structures such as skin-stiffener assembly and also to fatigue loading of stitched composite structures.

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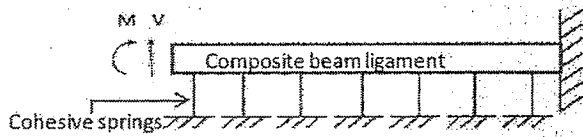


Fig.1 Beam Model to Represent Bridging Zone in a Laminate with Translaminar Reinforcements

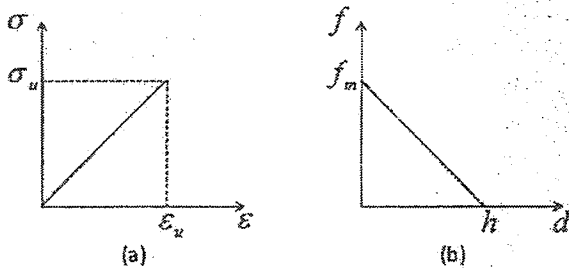


Fig.2 Simplified Load-deflection Behavior of Translaminar Reinforcements (a) Stitching (b) Z-pinning

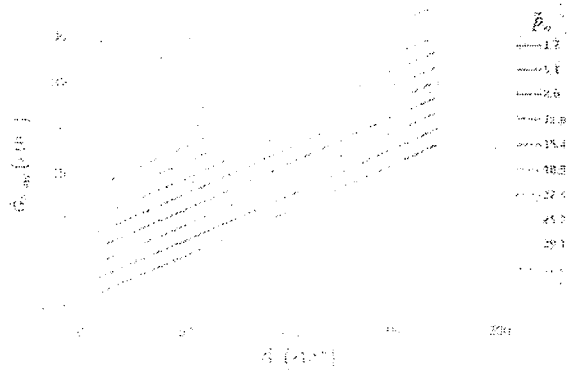


Fig.3 Apparent Fracture Toughness of Z-pinned Composites

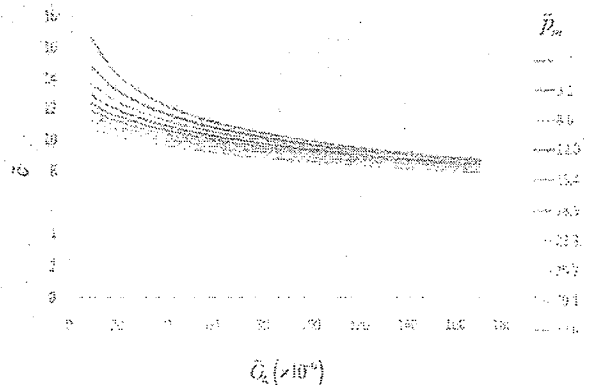


Fig.4 Bridging Length of Z-pinned Composites

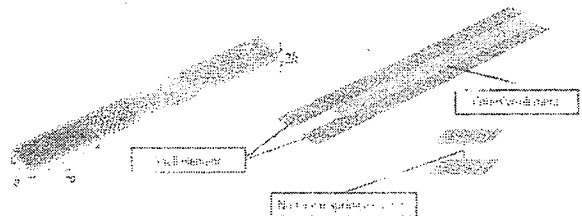


Fig.5 FE Model of the Z-pinned Composite

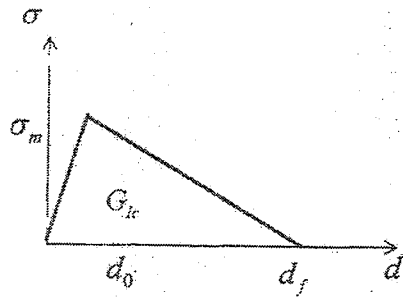


Fig.6 B-linear Traction-Separation Law for Cohesive Element

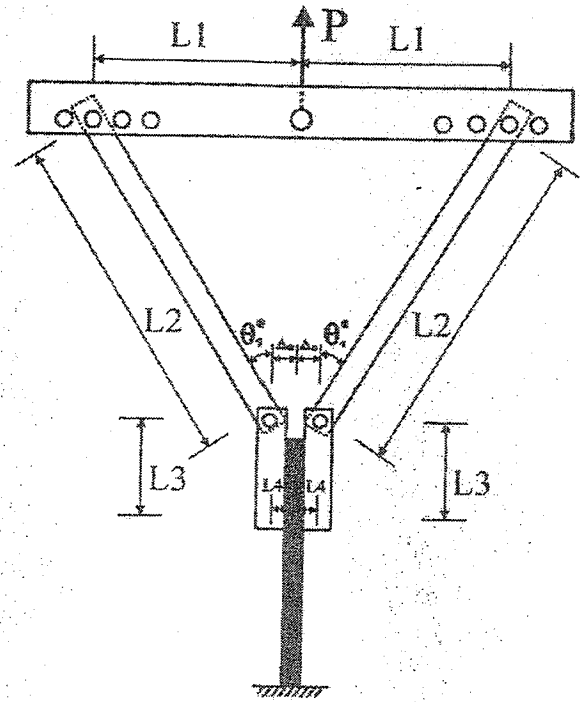


Fig.7 The DCB Test Fixture to Test Heavily Stitched Composite Laminates (Chen et al. [5])