Trans-Laminar-Reinforced (TLR) Composites

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Abstract

A Trans-Laminar-Reinforced (TLR) composite is defined as composite laminate with up to five percent volume of fibrous reinforcement oriented in a "trans-laminar" fashion in the through-thickness direction. The TLR can be continuous threads as in "stitched laminates," or it can be discontinuous rods or pins as in "Z-Fiber™" materials. It has been repeatedly documented in the literature that adding TLR to an otherwise two dimensional laminate results in the following advantages: substantially improved compression-after-impact response; considerably increased fracture toughness in mode I (double cantilever beam and mode II (end notch flexure); and severely restricted size and growth of impact damage and edge delamination. TLR has also been used to eliminate catastrophic stiffener disbonding in stiffened structures. TLR directly supports the "Achilles' heel" of laminated composites, that is delamination. As little as one percent volume of TLR significantly alters the mechanical response of laminates.

The objective of this work was to characterize the effects of TLR on the in-plane and inter-laminar mechanical response of undamaged composite laminates. Detailed finite element models of "unit cells," or representative volumes, were used to study the effects of adding TLR on the elastic constants; the in-plane strength; and the initiation of delamination. Parameters investigated included TLR material, TLR volume fraction, TLR diameter, TLR through-thickness angle, ply stacking sequence, and the microstructural features of pure resin regions and curved in-plane fibers. The work was limited to the linear response of undamaged material with at least on ply interface. An inter-laminar dominated problem of practical interest, a flanged skin in bending, was also modeled.

Adding a few percent TLR had a small negative effect on the in-plane extensional and shear moduli, E_x, E_y and G_{xy}, but had a large positive effect (up to 60 percent) on the thickness direction extensional modulus, E_z. The volume fraction and the axial modulus of the TLR were the controlling parameters affecting E_z. The out-of-plane shear moduli, G_{xz} and G_{yz}, were significantly affected only with the use of a TLR with a shear modulus an order of magnitude greater than that of the composite lamina. A simple stiffness averaging method for calculating the elastic constants was found to compare closely with the finite element results, with the greatest difference being found in the inter-laminar shear moduli, G_{xz} and G_{yz}. The unit cell analyses results were used to conclude that in-plane loads are concentrated next to the TLR inclusion and that the microstructural features of pure resin regions and curved in-plane fibers slightly lessen this stress concentration. Delamination initiation was studied with a strength of materials approach in the unit cell models and the flanged skin models. It was concluded that if the formation of a transverse crack is included as a source of delamination initiation, the addition of TLR will not be effective in preventing or delaying the onset of delamination. The many benefits of TLR may be accounted for by an increased resistance to delamination growth by crack bridging phenomenon, which is best studied with a fracture mechanics approach.