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Composite toughness enhancement with interlaminar reinforcement

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ABSTRACT

An experimental investigation of a newly proposed through-thickness reinforcement approach aimed to increase interlaminar toughness of laminated composites is presented. The approach alters conventional methods of creating three-dimensional fiber-reinforced polymer composites in that the reinforcing element is embedded into the host laminate after it has been cured. The resulting composite is shown to possess the benefits of a uniform surface quality and consolidation of the original unreinforced laminate. This technique was found to be highly effective in suppressing the damage propagation in delamination double-cantilever beam (DCB) test samples under mode I loading conditions. Pullout testing of a single reinforcing element was carried out to understand the bridging mechanics responsible for the improved interlaminar strength of reinforced laminate and stabilization and/or arrest of delamination crack propagation. The mode I interlaminar fracture of reinforced DCB samples was modeled using two-dimensional cohesive finite-element scheme to support interpretation of the experiments.

1. Introduction

Delamination in laminated composite structures can be a serious threat to their safety and performance, since the separation of individual plies (interlaminar fracture) can lead to significant loss of mechanical toughness properties. There can be many causes for the onset and development of delamination defects including the matrix cracks from monotonic or cyclic stresses from through-thickness tensile loads or in-plane shear, compressive loading accompanied by buckling, low energy impacts, or from the three dimensional interlaminar stresses that develop at stress-free edges of discontinuities. Those defects are found in aerospace, automobile, naval and civil engineering applications and may occur either during manufacturing or may be operationally induced. During operational use, the delaminations in composite parts can be found with different non-destructive methods (e.g. thermography, tap testing or ultrasonic testing) and when detected these defects generally make it necessary to replace the damaged part that comes at a cost.

The need to enhance interlaminar toughness of traditional carbon fiber composite laminates is a consequence of no fibers positioned through the material thickness in multi-axial laminates. For this reason, delamination is one of the most important failure modes in laminated composites. Several different techniques of through-thickness reinforcing have been developed to enhance interlaminar toughness. Today there are two commonly used commercial approaches to interlaminar reinforcement: (1) using a dry fabric preform which contains the through-thickness reinforcement prior to resin infusion (e.g. 3D weaving, stitching, or braiding [1] for textile laminates) and (2) reinforcing uncured pre-preg laminates in the through-thickness direction, called Z-pinning™ technique [2–6]. Both approaches have been shown to increase the delamination propagation resistance and compression after impact performance. The fabrication of z-pinned composites is similar to the manufacture of stitched composites in that the translaminar reinforcement is inserted as a separate processing step to create a 3D composite material. In this way these two reinforcement techniques differ from the textile technologies of weaving and braiding that create an integrated 3D fiber preform within a single stage process. In general, both reinforcing approaches share one common feature: they produce a 3D composite structure before the host laminate is cured and introduce extra-strength in the thickness direction after the host laminate is cured.

In this paper we propose and examine a new alternative technique to enhance the delamination resistance capability of polymer composite laminates, wherein through-thickness reinforcement is applied by embedding small diameter carbon fiber composite rod elements oriented orthogonally to the plane of the post-cured laminate (instead of driving the pins through the uncured laminate as in the case of Z-pinning™ method). This is achieved by drilling small holes in the cured (consolidated)

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laminate, filling the holes with liquid resin, insertion of reinforcing elements and curing the resin. The damage (fiber breakage) introduced by drilling the small hole in the parent laminate was considered. Experiments have shown [7,8] that the tensile and compressive strength of a composite laminate containing a hole or notch depends on hole or notch size. While the introduced hole diameter was quite small and the center-to-center distance was relatively large, the hole size effect revealed that the notched strength of parent laminate does not suffer significant degradation. Important benefits of installation of reinforcing elements into the cured laminate are (a) little surface perturbations in the resulting 3D composite and (b) consolidation of host laminate is not disturbed during its curing. There is evidence that these aspects may be significant in the case of z-pinned laminates. As it was reported in [9] for the specimens considered in their study, the increase in reinforced region thickness was of the order of 16–20% and this is because of a considerable effect of the presence of Z-pins on the resin flow during the consolidation and curing phase. The impact of Z-pinning on the material surface and consolidation quality can be seen in Fig. 1.

2. Experimental work and results

2.1. Materials, samples and test methods

Crack propagation resistance in Mode I loading conditions is studied with the double cantilever beam (DCB) delamination test

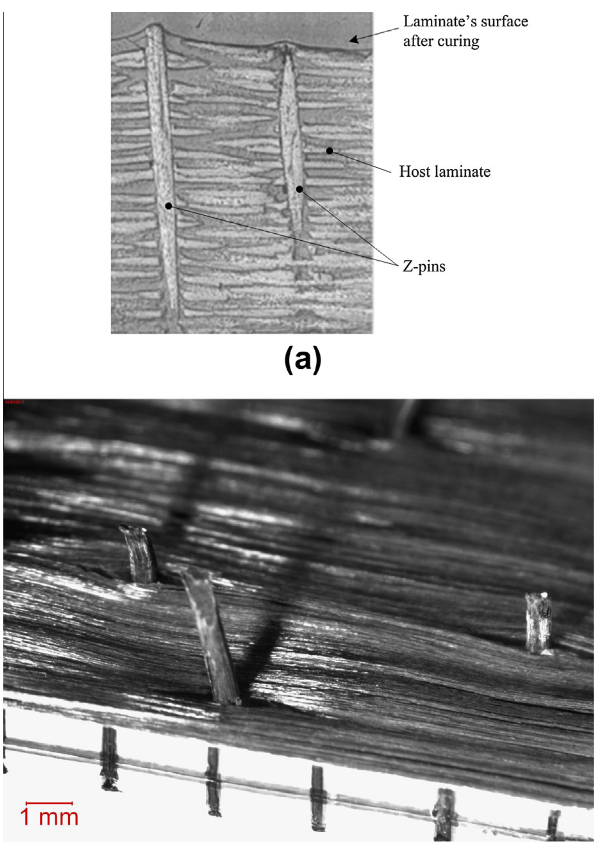

Fig. 1. (a) Illustration of the damage to the cured laminated composite's surface caused by the insertion of Z-fibers in prepreg (photograph is adapted from [10]); (b) Detail on the post-mortem fracture surface of a Z-pined sample (the sample is the courtesy of Dr. Weinong Chen and Dr. Andrew Schlueter). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

specimens. The tests were carried out with both through-thickness reinforced (TTR) and unreinforced (control) specimens. The DCB specimens were tested in an MTS test machine in a displacement-controlled loading with a crosshead rate of 1 mm/min.

The laminates were made of unidirectional prepreg tape of carbon fiber-reinforced epoxy, NCT321 34-700 G150 supplied by Newport Adhesives and Composites, Inc. This prepreg contains G150 graphite fibers with a fiber volume fraction of 64%. The thermoset matrix material was NCT321, a high temperature curing epoxy resin (350 °F). To manufacture unidirectional DCB samples of average thickness of 6.1 mm, 40 plies were laid up and cured in autoclave following the conventional procedures. A thin Teflon film (0.03 mm thick) was inserted between the upper and lower laminate surfaces to form the initial crack between them. The through-thickness reinforcing elements were segments of the 0.51 mm diameter pultruded (i.e. containing only axial fibers) and postcured rods made from carbon fiber and vinyl ester resin system with a fiber volume fraction of 62%. The rods used as through-thickness reinforcement were supplied by Graphtek LLC. The holes in specimens were drilled with a 0.75 mm diameter diamond impregnated drill bit and filled by infusion with a toughened, low viscosity epoxy resin system, CPD 4505A Resin/CPD 4507B Hardener supplied by Endurance Technologies, Inc. of St. Paul, MN, to bond host laminate and reinforcing rods after the resin cured. The above mentioned drilled oversized hole and rod diameters provide the "rod filling fraction" of 68% relative to the surrounding bonding resin which is found to be acceptable. Only one row of 6 reinforcing rods per TTR specimen is considered in the current research. The pin-to-pin distance (center-to-center) was 2.77 mm.

Three types of samples were tested: (1) control group without reinforcement; (2) TTR type I DCB specimens with initial delamination crack length, a_0, of 50 mm and carbon rods placed 5 mm ahead of a crack tip in the undamaged zone; (3) TTR type II DCB specimens with advanced delamination crack length, a_0^*, of 60 mm and carbon rods located 5 mm ahead of the crack tip in the delamination zone (shown in Fig. 2). All specimens were 165 mm in length and 19.4 mm in width. Five specimens in each group of samples were tested to enhance the consistency of experimentally obtained data. Fig. 3 shows the optical photo micrographs illustrating the surface quality and plies consolidation of TTR laminate where the superior quality, compared to the z-pinned sample surfaces, can be seen.

2.2. Experimental findings, discussions of failure mechanism and delamination behavior

The observations from the experiments are presented through the plotted data of opening displacement between the loading points of the two DCB arms, 2δ, reaction force at the displacement application point, P, and delamination crack length, a (see Fig. 2 for the notations).

The data collected from the control (unreinforced) DCB samples which are used as a reference data for the sake of estimation of efficiency of the through-thickness reinforcing method proposed, is represented in Figs. 4 and 5.

Fig. 4 shows the load (P) and crack length (a) versus opening displacement (2δ) traces of the mode I delamination fracture tests on the TTR type I DCB samples. Fig. 5 provides the data of how the crack length (a) advances with load (P).

Ultimate fracture load of these samples compared with the unreinforced samples was increased by a factor of 2 and the structural response of TTR sample is more complex comparing with the unreinforced case. Close consideration of Figs. 4 and 5 curves points out the distinct phases of mode I failure behavior for this type of sample. The first phase prior to crack propagation is shown