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Nonlinear Spring Finite Elements for Predicting Mode I-Dominated Delamination Growth in Laminated Structure with Through-Thickness reinforcement

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One particular concern of polymer matrix composite laminates is the relatively low resistance to delamination cracking, in particular when the dominant type of failure is mode I opening. One method proposed for alleviating this problem involves the insertion pultruded carbon pins through the laminate thickness. The pins, known as z-pins, are inserted into the prepreg laminate using an ultrasonic hammer prior to the curing process, resulting in a field of pins embedded normal to the laminate plane as illustrated in Figure. 1. Pin diameters range between 0.28-mm to 0.5-mm and standard areal densities range from 0.5% to 4%. The z-pins are provided by the manufacturer, Aztex®, in a low-density foam preform, which acts to stabilize orientation of the pins during the insertion process [1-3]. Typical pin materials include boron and carbon fibers embedded in a polymer matrix.

A number of methods have been developed for predicting delamination growth in laminates reinforced with z-pins. During a study on the effect of z-pin reinforcement on mode I delamination resistance, finite element analyses of z-pin reinforced double cantilever beam (DCB) specimens were performed by Cartie and Partridge [4]. The z-pin bridging stresses were modeled by applying equivalent forces at the pin locations. Single z-pin pull-out tests were performed to characterize the traction law of the pins under mode I loading conditions. Analytical solutions for delamination growth in z-pin reinforced DCB specimens were independently derived by Robinson and Das [5] and Ratcliffe and O'Brien [6]. In the former case, pin bridging stresses were modeled using a distributed load and in the latter example the bridging stresses were discretely modeled by way of grounded springs. Additionally, Robinson and Das developed a data reduction strategy for calculating mode I fracture toughness, G_{Ic}, from a z-pin reinforced DCB specimen test [5]. In both cases a traction law similar to that adopted by Cartie and Partridge was used to represent z-pin failure under mode I loading conditions.

In the current work spring elements available in most commercial finite element codes were used to model z-pins. The traction law used in previous analyses [4-6] was employed to represent z-pin damage. This method is intended for and is limited to simulating z-pins in composite laminate structure containing mode I-dominated delamination cracking. The current technique differs from previous analyses in that spring finite elements (available in commercial codes) are employed for simulating z-pins, reducing the complexity of the analysis construction process. Furthermore, the analysis method can be applied to general structure that experiences mode I-dominated delamination cracking, in contrast to existing analytical solutions that are only applicable to coupon DCB specimens.

This paper outlines the development of the analysis procedure. Two-node spring elements (type SPRINGA) in the commercial code ABAQUS ver 6.4 [7] were used to represent individual z-pins. An existing material option was used to assign the nonlinear traction law that emulates z-pin failure under mode I-dominated loading conditions. The traction law was amended to include energy dissipation associated with delamination of the parent laminate. Therefore, each spring element is essentially used to model z-pin failure and parent laminate delamination. Contact elements are used in the delamination region to prevent mesh interpenetration. Contact pressure data is used to approximate the delamination front location. The analysis technique was verified by modeling DCB specimens with various z-pin configurations and comparing the results with those obtained from an analytical solution [6]. A typical mesh of a DCB specimen containing spring elements is given in Fig. 2. Finally, the analysis approach was applied in a finite element analysis of a post-buckled skin/stringer panel containing a delamination located between a stringer foot and panel skin [8]. The delamination area was reinforced with z-pins by attaching spring elements representing the z-pin field. The analysis results indicated that the magnitude of strain energy release rate across the delamination front was reduced sufficiently to halt delamination growth for the displacement value prescribed in the analysis. An illustration of the skin/stringer panel mesh is given in Fig. 3.

[1] Freitas, G., Magee, C., Boyce, J., and Bott, R., "Service Tough Composite Structures Using the Z-Direction Reinforcement Process", Proceedings of the 9th DoD/NASA/FAA Conference on Fibrous Composites in Structural Design, Lake Tahoe, Nevada, USA, November 1991, NASA-CR-198718.

[2] Childress, J.J., and Freitas, G., "Z-direction Pinning of Composite Laminates for Increased Survivability", Proceedings of the AIAA Aerospace Design Conference, Irvine, California, USA, February 1992, paper 92-1099.

[3] Freitas, G., Magee, C., Dardsinski, P., and Fusco, T., "Fiber Insertion process for Improved Damage Tolerance in Aircraft Laminates", *Journal of Advanced Materials*, vol.24, July 1994, pp.36-43.

[4] Cartié, D.D.R., PhD Thesis. Cranfield College of Aeronautics, Cranfield University, UK, 2001. Advisor I. K. Partridge.

[5] Robinson, P., and Das, S., "Mode I DCB Testing of Z-Fiber Reinforced Laminates: A Simple Model for the Investigation of Data Reduction Strategies", *Engineering Fracture Mechanics*, vol.71, 2004, pp.345-364.

[6] Ratcliffe, J.G., and O'Brien, T.K., "Discrete Spring Model for Predicting Delamination Growth in Z-Fiber Reinforced DCB Specimens", NASA Technical Memorandum 2004-213019, Army Research Laboratory Technical Report TR-3190, May 2004.

[7] ABAQUS Version 6.4 Analysis User's Manual, Volume IV. ABAQUS Inc, 2003.

[8] R. Krueger and P.J. Minguet, "Skin-Stiffener Debond Prediction Based on Computational Fracture Analysis", Hampton, VA, NIA Report No. 2005-06, NASA/CR-2005-213915, 2005.

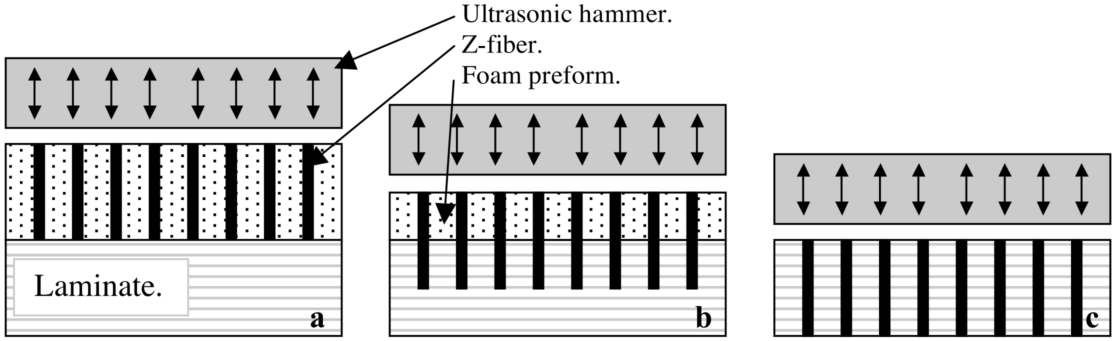

Figure 1. (a) Z-fibers held in foam preform positioned on laminate. (b) Ultrasonic hammer drives Z-fibers into laminate. (c) Completion of Z-fiber insertion. Preform material removed during insertion.

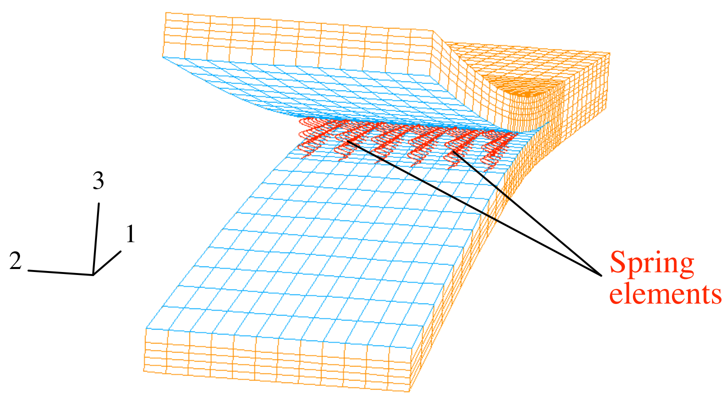

Figure 2. Finite element mesh of a DCB specimen containing spring elements.

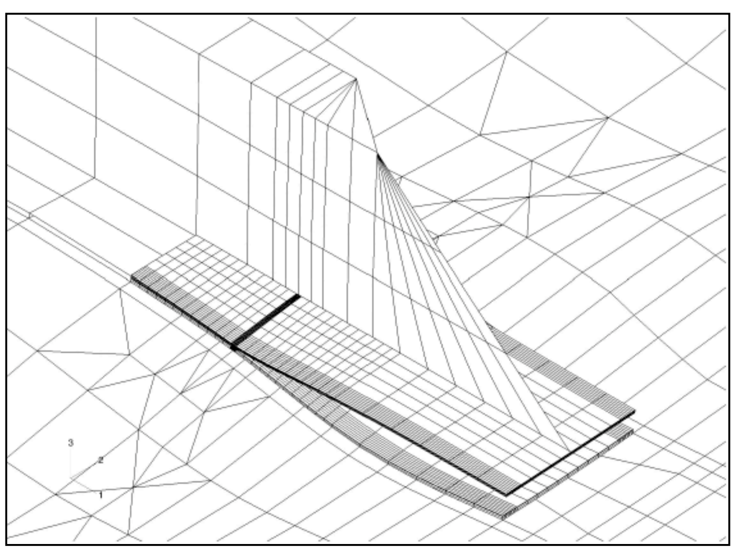

Figure 3. Local finite element mesh of delamination region in skin/stringer panel model.