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TEST AND MATERIAL SPECIFICATIONS FOR DYNAMIC DELAMINATION STUDIES OF Z-PINNED LAMINATES

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MATERIAL AND TEST RECOMMENDATIONS

Objective: demonstrate inference from test data of a mixed mode dynamic cohesive law that represents the crack-shielding effects of through-thickness reinforcement (e.g., z-pins) in a laminate.

We choose this material rather than a laminate without through-thickness reinforcement because through-thickness reinforcement is technologically important but not yet well understood, especially in the dynamic regime. Furthermore, our experience with the static case is that through-thickness-reinforced laminates are much easier to study scientifically as a first challenge; the zone lengths over which pins act in the crack wake are so long and the effects of the shielding on the crack propagation are so strong that delamination experiments are information-rich and their analysis relatively easy.

Regimes of dynamic behavior.
Our recent simulations confirm a conclusion of earlier studies (Sridhar *et al.*, 2001) that three regimes can be identified in dynamic delamination: 1) low crack velocity, when the system behaves as if quasi-static and inertial effects are negligible; 2) high velocity, where the kinetic energy that must be supplied to the delaminated sublaminates is so dominant that the fracture energy associated with material failure is negligible; and 3) intermediate velocity, where inertia and the fracture energy associated with material failure are matched and the system's behavior depends relatively strongly on the nature of the fracture (material separation) process. For deducing a cohesive law that exhibits dynamic effects (rate dependence) from experiment, only the regime of intermediate velocity (typically a few tenths of c_s) is information rich.

Stable configurations/failure mode transition
As in the static case (Massabò and Cox, 1999), our new calculations show that a specimen with a long initial traction-free crack (notch) tends to spawn stable cracks, i.e., cracks for which the critical energy release rate rises with crack length; and this configuration tends to supply growth data that are relatively sensitive to the cohesive law. For stable conditions, the notch should be at least comparable to the anticipated cohesive zone length, say 20 – 40 mm.

For the longer notch lengths, there is some chance that pins will begin to fail at the notch root before the delamination reaches the end of the specimen. This would be interesting to see; but we would prefer to study delamination alone first. Unfortunately, it is not possible to predict the notch length for this transition a priori. We suggest starting with a 20 mm notch and leaving open the possibility of increasing it in later tests by machining existing specimens.

Specimen thickness
We recommend a specimen thickness in the range 7 – 15 mm. Thinner specimens might be technologically important in certain applications, but for this study they have severe disadvantages including: 1) delamination tends to be complicated by departure of the crack from the desired fracture plane, dominance of fracture-surface friction effects over other crack-shielding effects, oddities in the pin deformation mechanics associated with very short pin length, and high levels of waviness in the in-plane plies; and 2) the specimens are vulnerable to failure of the loading arms. With thicker specimens, we

hope for clean delamination paths, surviving loading arms, consistent pinning and in-plane fiber dispositions (more easily controlled processing), and more intelligible pin deformation behavior.

Mode disentanglement

Our simulations to this point suggest that separating modes from a single test configuration might be difficult. There is a tendency for a single test to present a modest mode variation with crack length that yields information predominantly for a single mode ratio or restricted range of ratios. Combining data from distinct test configurations is therefore an attractive option for analyzing mode effects (but of course more work). Three recommended test configurations are shown in Fig. 1.

We anticipate that configuration 1 will be predominantly (ideally purely) mode I; configuration 3 is approximately mode II (but with significant mode I); while configuration 2 is mixed mode (shear arises because of wave propagation along the displaced loading arm). For initial work, we recommend that at least configurations 1 and 3 be tested.

Specimen length and width

The recommended total specimen length is 120 mm for each of configurations 1 – 3. This is several multiples of the anticipated cohesive zone length but hopefully not so long that the deflections become awkwardly large. We recommend a specimen width of 20 mm. This should be enough to assure that specimen-to-specimen fluctuations due to discreteness of the pins and edge effects are modest.

Required data

The load vs load-point displacement should be recorded. Snap-shots of the crack displacement profile should be recorded at each approximately 10 mm of crack advance. The crack profile refers to the vector crack displacement field $\boldsymbol{u}(\boldsymbol{x})$ along the whole crack length (excluding the notch). Strain field maps for the whole specimen that would confirm the absence of significant nonlinearity away from the crack might be useful too. Data for crack lengths ranging from 100 mm to approximately 50 mm are desirable, corresponding to a small multiple of the anticipated bridging zone length. Any other information that can be collected will help the inverse modeling.

Load point displacement rate

We wish to achieve crack propagation rates in the range 0 – 0.3 c_s (approximately 0 – 300 m/sec). The optimal load-point displacement rate depends on the details of the wave and fracture mechanics of the specimen and we should expect to determine it a posteriori. Load point displacement rates in the range 0 – 50 m/sec are probably good.

Materials and recommended pin density

We suggest using a balanced quasi-isotropic carbon-epoxy laminate. The pin material (fiber choice) is not too important, although we recommend fibrous over metallic pins. We recommend that specimens with three pin area densities be prepared, say 1%, 2%, and 4%. Data for pins of two different radii would be interesting too (see (Chang *et al.*, 2005; Chang *et al.*, 2006a; Chang *et al.*, 2006b) for an indication of the information possible from tests on a similar set of pinned laminates). Pin diameters of 11 and 20 mil (0.3 and 0.5 mm) are interesting and representative of industry standards. It would help to keep the side of the square array of pins as small as possible (values around 3 to 5 mm would be very good): the bridging mechanisms are assumed to be uniformly distributed in the analyses. In the coming years, data on the effects of pin density and size could be analyzed by dynamic micromechanical models to create materials design guidelines.

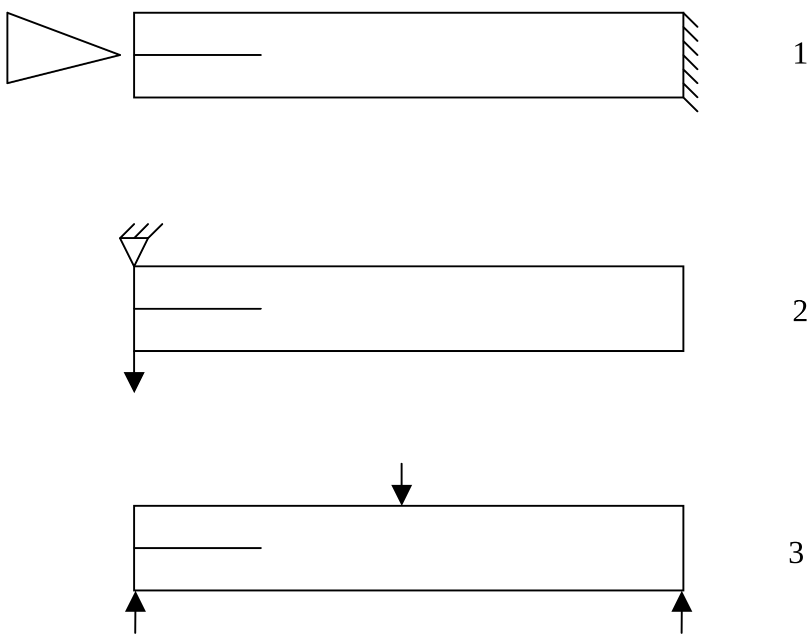

Figure 1. End-notch specimen loaded in various ways. Configuration 1 shows a flying wedge. An acceptable alternative configuration loads the specimen via tabs on the two loading arms.

The pinning should be omitted over the intended notch and the notch should be prepared by using Teflon tape or similar method. If the specimens are prepared with a 40 – 50 mm notch made in this way, then we would have the option of reducing the notch length easily before testing (e.g., to 20 mm).

For the initial round of tests, we recommend pins that are nominally normal to the laminate. Angled pins offer interesting variations in toughness and strength (Cartié *et al.*, 2004; Cox, 2005), but their study might be deferred in this project to control the amount of work being undertaken.

Specimen/test matrix
For our first cohesive law analyses, it will be sufficient to have just two or three tests for each specimen configuration at each of three (say) loading rates and a single material choice. As we proceed through the study, these tests should be repeated for other specimens in the material (pin parameter) matrix. We suggest preparing enough material to prepare say 30 specimens for each material choice.

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