SAND2011-1432C

Dynamic Mode-II Characterization of A Woven Glass Composite

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Delamination of laminated composites has been a reliability issue in applications. Fracture toughness is a critical indicator of resistance to such a delamination. Quasi-static experimental techniques determining fracture toughness have been well developed. For example, end notched flexure (ENF) technique has been commonly used to determine mode-II fracture toughness. However, dynamic fracture characterization of composites is much more challenging. Such immature dynamic techniques have resulted in conflictive and confusing description of rate effects on fracture toughness of composites. Currently dynamic mode-II characterization employs three-point bending with a Kolsky bar on an ENF specimen and uses the same analysis as quasi-static ENF technique. The quasi-static ENF analysis is applicable to dynamic experiments only when the forces at both ends of the ENF specimen are equilibrated. However, both the weak delamination strength of composites and the complicated loading structure of the three-point bending embedded to the Kolsky bar make it difficult to compare the forces at both ends of the ENF specimen. Polyvinylidene fluoride (PVDF) thin film force transducers have been introduced to directly measure the forces at both ends of the composite ENF specimen [1]. The results showed that the forces at both ends of the specimen were far from equilibration in conventional Kolsky bar experiments. This requires proper pulse shaping design in dynamic three-point bending experiments with Kolsky bar. In this study, we modified the Kolsky bar techniques with proper pulse shaping and applied PVDF force transducers directly on the contact surfaces of loading in dynamic mode-II characterization of a glass woven composite.

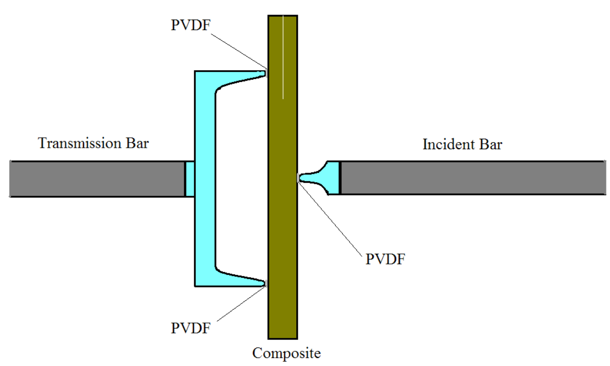

Fig. 1. Schematic of testing section

Figure 1 shows the testing section of the Kolsky bar for dynamic three-point bending experiments. Three PVDF force transducers are directly attached to the specimen surfaces in contact with the front loading wedge and back span supports. The PVDF film used in this study is commercially available and has a thickness of 110 μm. The piezoelectric response of the PVDF has been carefully calibrated with Kolsky bar system within a large stress scale. The surfaces of the PVDF in contact with the loading wedge and spans were protected with a thin steel piece. By contrast, the other surfaces of the PVDFs were directly attached to the specimen surface in order to avoid additional inertia involved in the force measurement. A ø1/8×0.02” annealed copper disk was attached to the impact surface of the incident bar as a pulse shaper to properly modify the profile of the incident pulse such that the force equilibrium on both ends of the ENF composite specimen can be achieved. Figure 2 shows the oscilloscope record from the strain gages on the incident bar. The modified incident pulse possesses a rise time of approximately 130 μs, which is 10 times longer than that in conventional Kolsky bar experiments. Since the composite exhibits low delamination strength, nearly all incident pulse is reflected back as the reflected pulse, as shown in Fig. 2. The PVDF at the impact wedge end is the first to sense the load on the specimen. This load produces transverse wave travelling towards both upper and lower ends of the specimen, which are sensed with the PVDFs attached to the back surface of the specimen. The PVDF signals are shown in Fig. 3. Figure 3 clearly shows the forces at both back span supports are equilibrated, while the sum of both is equal to the force at the front loading wedge after the first 113 μs. It takes the transverse wave approximately 30 μs to propagate from the central wedge to the end span supports, which corresponds to approximately 600 m/s of transverse wave speed. This is consistent with the DIC result previously conducted [2]. It takes another 83 μs to achieve force equilibrium. It is noted that the specimen has achieved force equilibrium prior to constant-speed loading. After the force is equilibrated, the forces on both sides of the specimen are built up simultaneously until the crack starts to propagate. Figure 3 also shows the speed history of the impact wedge. Figure 3 confirms that the specimen has achieved stress equilibrium before the impact speed reaches a constant of 5.6 m/s. In addition, the specimen failed (crack propagation) at the constant impact speed, which is important to study the rate effect. Figure 4 shows the shear strain on the specimen obtained from DIC analysis. The DIC images were taken with a Phantom V12.1 at a speed of 83,000 frames per second. Figure 4 indicates that the crack started to propagate at *t = 253 μs*, when the front force on the specimen reached a maximum (Fig. 3).

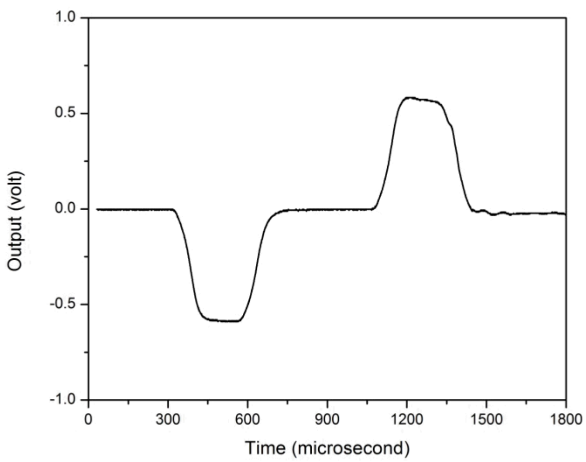

Fig. 2 Oscilloscope record of incident and reflected pulses

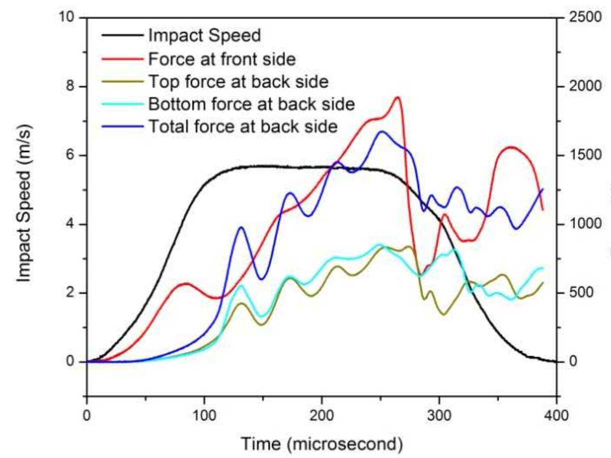

Fig.3 Impact speed and force histories

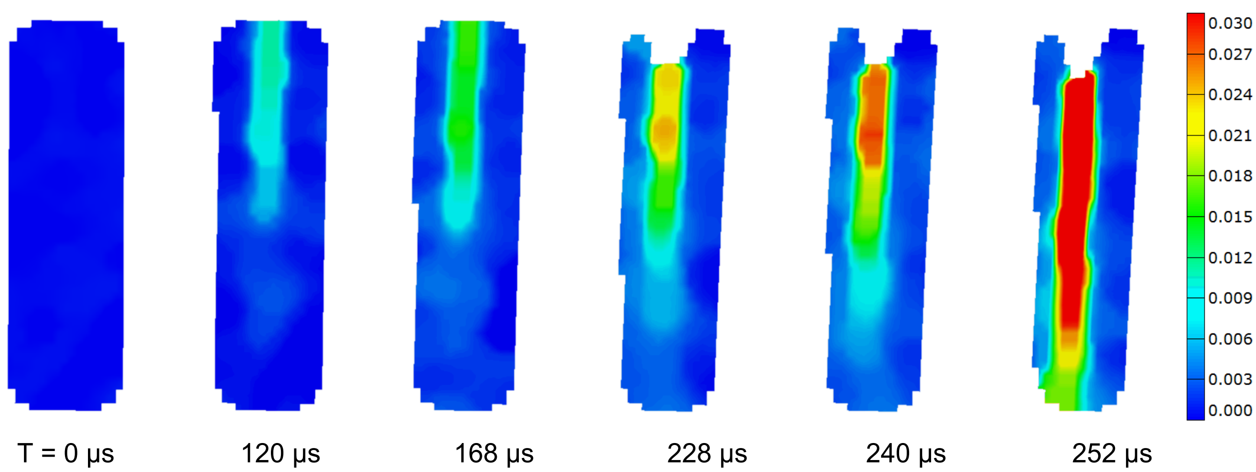

Fig. 4 Shear strain (E_{xy}) obtained from DIC results

Now the mode-II fracture toughness can be calculated with the quasi-static analysis [3],

$$G_{IIC} = \frac{9a^2P^2C}{2w\left(2L^3 + 3a^3\right)} \qquad (1)$$

where $C = \delta / P$, which is the slope in the displacement-force curve; P is the force when the crack starts to propagate. The specimen geometry parameters used in Eq. (1) are defined in Fig. 5. Note that $P = F_1 = F_2 + F_3$. For the specimen used in this study, $t = 6.7\ mm$, $w = 10\ mm$, $L = 25\ mm$, $a = 6.35\ mm$. C is calculated from Fig. 6, $C = 5.86\times10^{-7}$ m/N, and the maximum force was also measured from Fig. 6, $P = 1922.3\ N$. The mode-II fracture toughness wass then calculated as $G_{IIC} = 1227.1\ J/m^2$ at the impact speed of 5.6 m/s. Following the same procedure but at different impact speeds, the rate effect on the mode-II fracture toughness of the composite is able to be determined.

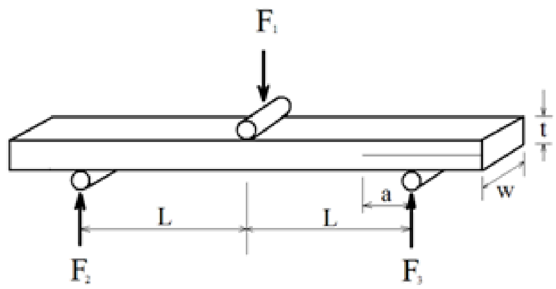

Fig. 5 Specimen geometry

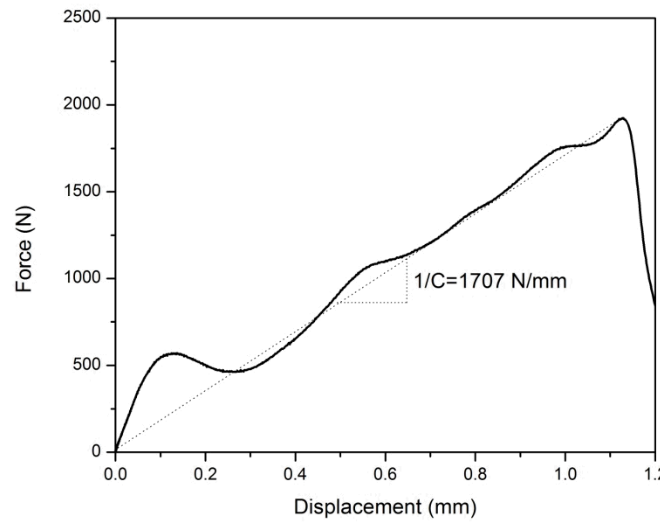

Fig. 6 Force-displacement curve

In summary, the quasi-static mode-II fracture toughness analysis can be applicable to dynamic experiments only after the testing conditions are validated. Pulse shaping needs to be properly designed such that the specimen can achieve stress equilibrium before the crack starts to propagate. The stress equilibrium needs to be carefully verified with appropriate measurements. Embedding PVDF thin film transducers has been demonstrated to be effective and straight-forward technique for stress equilibrium verification. In addition, proper pulse shaping facilitates a constant impact speed on the specimen, which is important to determine rate effect when incorporating quasi-static results.

ACKNOWLEDGEMENTS

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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