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A Revisit to High-rate Mode-II Fracture Characterization of Composites with Kolsky Bar Techniques

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Nowadays composite materials have been extensively utilized in many military and industrial applications. For example, the newest Boeing 787 uses 50% composite (mostly carbon fiber reinforced plastic) in production. However, the weak delamination strength of fiber reinforced composites, when subjected to external impact such as ballistic impact, has been always potential serious threats to the safety of passengers. Dynamic fracture toughness is a critical indicator of the performance from delamination in such impact events. Quasi-static experimental techniques for fracture toughness have been well developed. For example, end notched flexure (ENF) technique, which is illustrated in Fig. 1, has become a typical method to determined mode-II fracture toughness for composites under quasi-static loading conditions. However, dynamic fracture characterization of composites has been challenging. This has resulted in conflictive and confusing conclusions in regard to strain rate effects on fracture toughness of composites [1].

Currently the quasi-static ENF technique has been implemented to high-rate testing, i.e., Kolsky bar technique. In quasi-static ENF characterization, the forces applied to both sides of the specimen are balanced, $P = F_1 = 2F_2 = 2F_3$, so that the mode-II fracture toughness can be calculated with the common force, P, [2]. However, when the ENF specimen is subjected to impact loading, the force may not be equilibrated due to inertia (or stress wave propagation) effect in such a relatively large scale specimen. The validity of loading condition in dynamic characterization needs to be carefully verified. In this study, we employed a Kolsky bar with highly sensitive polyvinylidene fluoride (PVDF) force transducers to check the forces on the front wedge and back spans. High rate digital image correlation (DIC) was also conducted to investigate the stress wave propagation during the dynamic loading. The specimen material is glass fiber reinforced epoxy composite. A thin Teflon film was inserted into the composite during manufacturing process, leaving a precrack in the specimen.

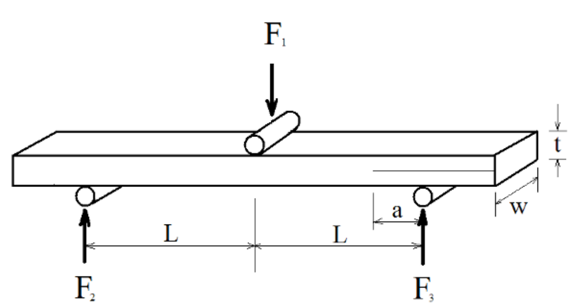

Fig. 1. Typical ENF specimen

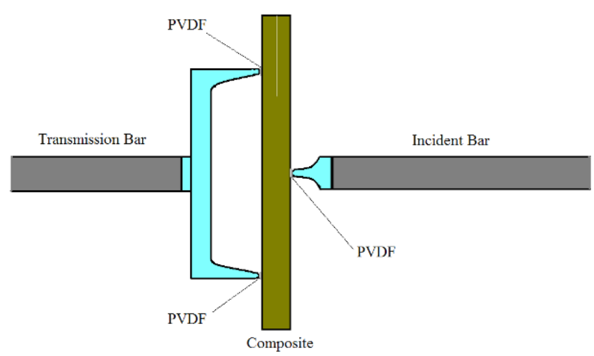

Fig. 2. The ENF specimen with PVDF transducers in Kolsky bar experiment

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The PVDF is a kind of piezoelectric film force transducer with high sensitivity, even though the sensitivity is nonlinear to the applied force. After careful calibration, the PVDF film transducer was made into small square pieces that are embedded on the front wedge and back spans, as shown in Fig. 2. Figure 3 shows typical outputs from the three PVDF transducers as well as the strain gage on the transmission bar which is approximately 494 mm from the specimen back surface. In Fig. 3, the green strain gage signal has been synchronized to the specimen back surface based on conventional calculation of the distance divided by the bar longitudinal wave speed of 4900 m/s. Figure 3 clearly shows that the forces applied on the specimen are not balanced. Particularly for the first 60 microseconds, $F_1 >> F_2 + F_3$. Furthermore, the forces at both back spans are not the same, $F_2 > F_3$. The force signal from the strain gages is observed to lag behind the PVDF signals. This might be because it takes much longer for the stress signal to travel from the spans to the bar end. During this stage, transverse wave is involved, the wave speed of which is much slower than longitudinal wave. Since the forces are not equilibrated, the quasi-static analysis is no longer valid to calculate the fracture toughness.

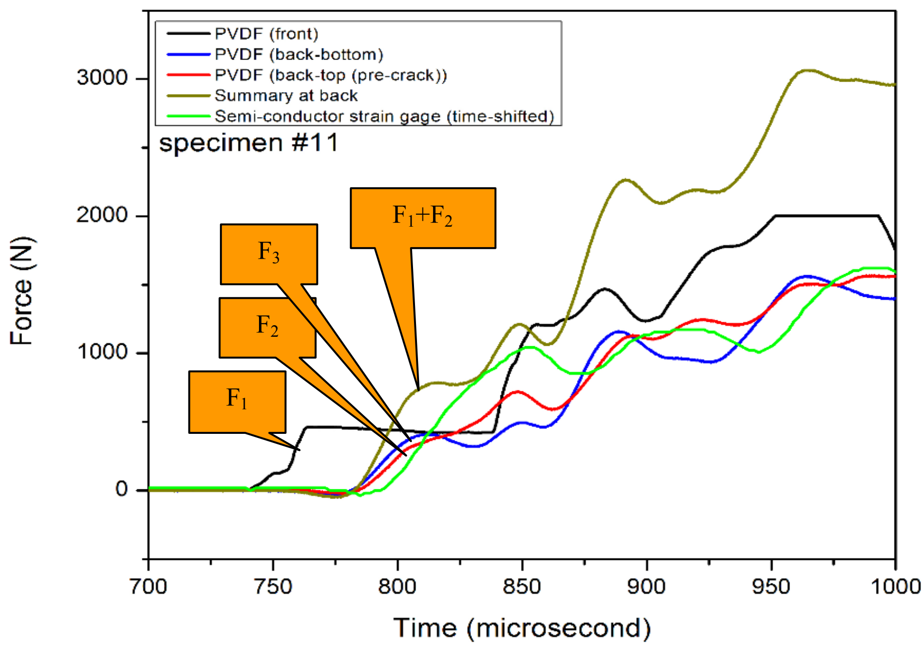

Fig. 3 The force histories in the ENF composite specimen

The non-equilibrated forces during dynamic experiment are due to relatively large specimen scale and slow transverse stress wave. When the wedge on the incident bar end starts to impact on the composite beam, a transverse wave is generated and then propagates from the center outward the top and bottom simultaneously. DIC method was used to monitor the real-time propagation of the transverse wave, the results of which are shown in Fig. 4. The time interval between the images is 5 microsecond. The pre-crack tip locates at the 3/5 between the upper span and the wedge, as shown with the black line in Fig. 4. Figure 4 shows the transverse wave front (yellow zone) propagates from the wedge towards the span. Only first two images were taken before the transverse wave arrived to the crack tip. The transverse wave speed is calculated as 1237 m/s from the two images. When the transverse wave arrived at the crack tip, the wave speed significantly reduced to 338 m/s because of drastically reduced flexural modulus due to the crack. However, the transverse wave propagates downward to the lower span at a nearly constant speed of 1237 m/s because there is no crack on the other half portion of the specimen. This may be the reason why the forces at the upper and lower spans are different.

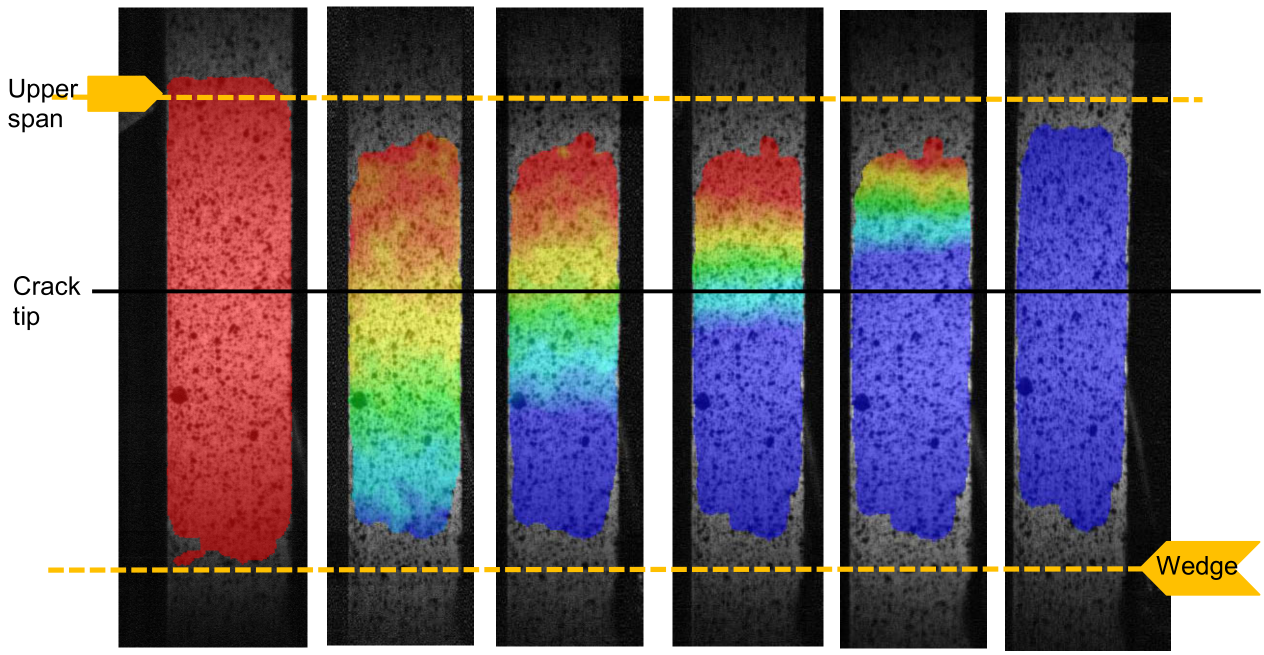

Fig. 4. Transverse wave propagation

It is calculated that the transverse wave takes nearly 45 microseconds to travel from the wedge to the upper span. Due to the large specimen size and relatively low transverse wave speed, the forces at the front wedge and back span surfaces are difficult to be balanced over the entire loading duration in a Kolsky bar experiment. Therefore, the quasi-static analysis for mode-II fracture toughness cannot be used for such a dynamic experiment. Instead, numerical simulation, such as finite element analysis, should be implemented together with the dynamic experimental data to determine the mode-II fracture toughness.

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REFERENCES

1. Jacob, G. C., Starbuck, J. M., Fellers, J. F., Simunovic, S., Boeman, R. G., 2005, “The effect of loading rate on the fracture toughness of fiber reinforced polymer composites,” Journal of Applied Polymer Science, 96:899-904.
2. Yang, Z., and Sun, C. T., 2000, “Interlaminar fracture toughness of a graphite/epoxy multidirectional composite,” Transactions of the ASME, Journal of Engineering Materials and Technology, 22:428-433.