EXPERIMENTAL INVESTIGATION AND MODELING ON DYNAMIC FAILURE MODE TRANSITIONS IN LAYERED COMPOSITE MATERIALS

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ABSTRACT

We examine the deflection/penetration behavior of dynamic mode-I cracks propagating at various speeds towards inclined weak planes/interfaces of various strengths in otherwise homogenous isotropic plates. A dynamic wedge-loading mechanism is used to control the incoming crack speeds, and high-speed photography and dynamic photoelasticity are used to observe, in real-time, the failure mode transition mechanism at the interfaces. Simple dynamic fracture mechanics concepts used in conjunction with a postulated energy criterion are applied to examine the crack deflection/penetration behavior. It is found that if the interfacial angle and strength are such as to trap an incident dynamic mode-I crack within the interface, a failure mode transition occurs. This transition is characterized by a distinct, observable and predicted speed jump as well as a dramatic crack speed increase as the crack transitions from a purely mode-I crack to an unstable mixed-mode interfacial crack.

1. INTRODUCTION

Composite materials and structures have been extensively used in aerospace, civil and marine structures. One important research focus is their complication dynamic failure modes. As shown in Fig.1 (a), both matrix cracks and delamination were observed in a Naval sandwich structure after projectile impact. Possible dynamic failure mode transitions may occur during the impact process since these two types of cracks were connected [1]. Indeed, even for a very simple layered or bonded structure such as a brittle polymer plate with a weak interface [2], two incident "matrix cracks" will have interesting failure mode transitions as shown in Fig. 1(b). This leads to a quite fundamental problem in dynamic failure mechanics. When dynamic cracks propagate in homogenous, brittle solids, they can only do so under locally mode-I conditions and at sub-Rayleigh wave speeds typically below the crack branching speed [3-4]. Even if the applied far-field loading is asymmetric, the dynamically growing crack will curve and follow the path that will result to locally opening (mode-I) conditions at its tip making mix-mode and pure mode-II crack growth in homogeneous materials a physical impossibility. The situation is entirely different if a crack is constrained to propagate along a weak preferable path in an otherwise homogenous solid. In this case and depending on the bond strength, the weak crack path or bond often traps the crack, suppresses any tendency of branching or kinking out of the weak plane and permits very fast crack growth much beyond the speeds observable in monolithic solids. Although the extreme mode-I and mode-II cases have recently been studied experimentally and theoretically, very little is known about the dynamic mixed-mode crack growth along weak paths, a situation that has only recently been analyzed by Geubelle and Kubair [5] and about the transition of an incident dynamic mode-I crack into a mixed-mode crack as it encounters a weak plane or interface. In the present work, we examine the incidence of dynamically growing cracks at inclined interfaces of various strengths. Our first goal is to observe this phenomenon experimentally and to establish and validate a dynamic deflection/penetration criterion. We then concentrate on the deflection behavior and examine mixed-mode crack growth along an interface.

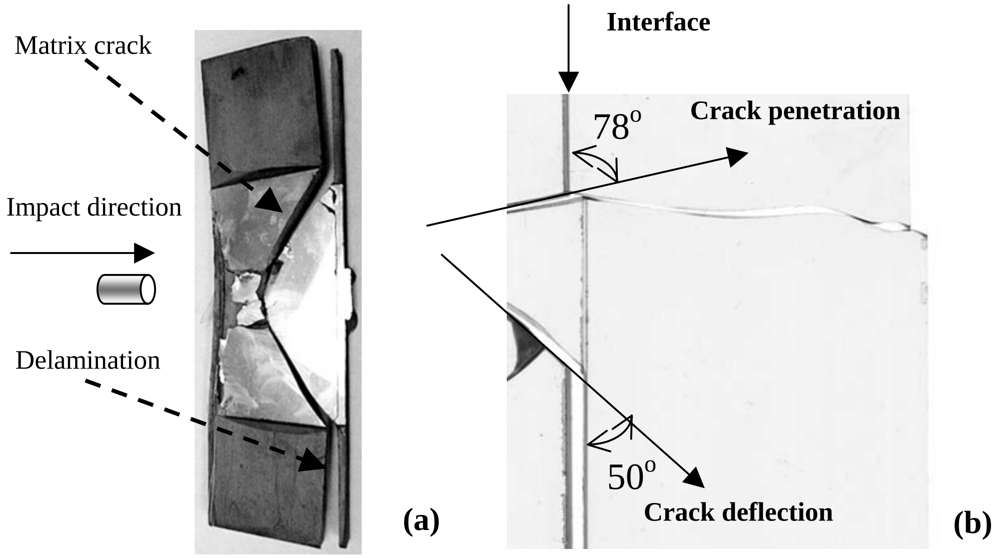

Fig.1 Common dynamic failure mode in a composite sandwich structure (a) and in a model layered structure of a polymer plate with a weak interface (b) after impact

2. EXPERIMENTAL PRODEDURES

Homalite-100 was selected as our model photoelastic material because its dynamic facture behavior has been documented widely in the literature. Indeed the variation of dynamic fracture toughness of monolithic Homalite with crack speed has been studied in the early years of the dynamic fracture discipline [6-7]. A novel wedge-loaded plate specimen was designed to produce a single, straight dynamic crack propagating towards a weakly bonded, inclined interface as shown in Figure 2(a). The wedge is inserted into a pre-notch and when it is impacted by a projectile, the wedge opens the notch faces producing a single mode-I crack which is driven towards the inclined interface. The initial crack tip speed is related to the impact speed of the projectile. The specimen's sizes were large enough such that the major stress waves reflected from free boundaries entered the field of view, 20 μs after the incident crack reached the interface. After numerous preliminary tests, the in-plane specimen size was fixed to be 457 mm long, 254 mm wide and the plate thickness was 9.5 mm. Inclined interfaces were cut and covered several characteristic interfacial angles. These angles were 10, 30, 45, 60 and 90 degrees. To provide different interfacial strengths and fracture toughnesses, two kinds of adhesives, Weldon-10 and Loctite 384, were used to bond the interfaces and to create weak interfaces of toughness less than

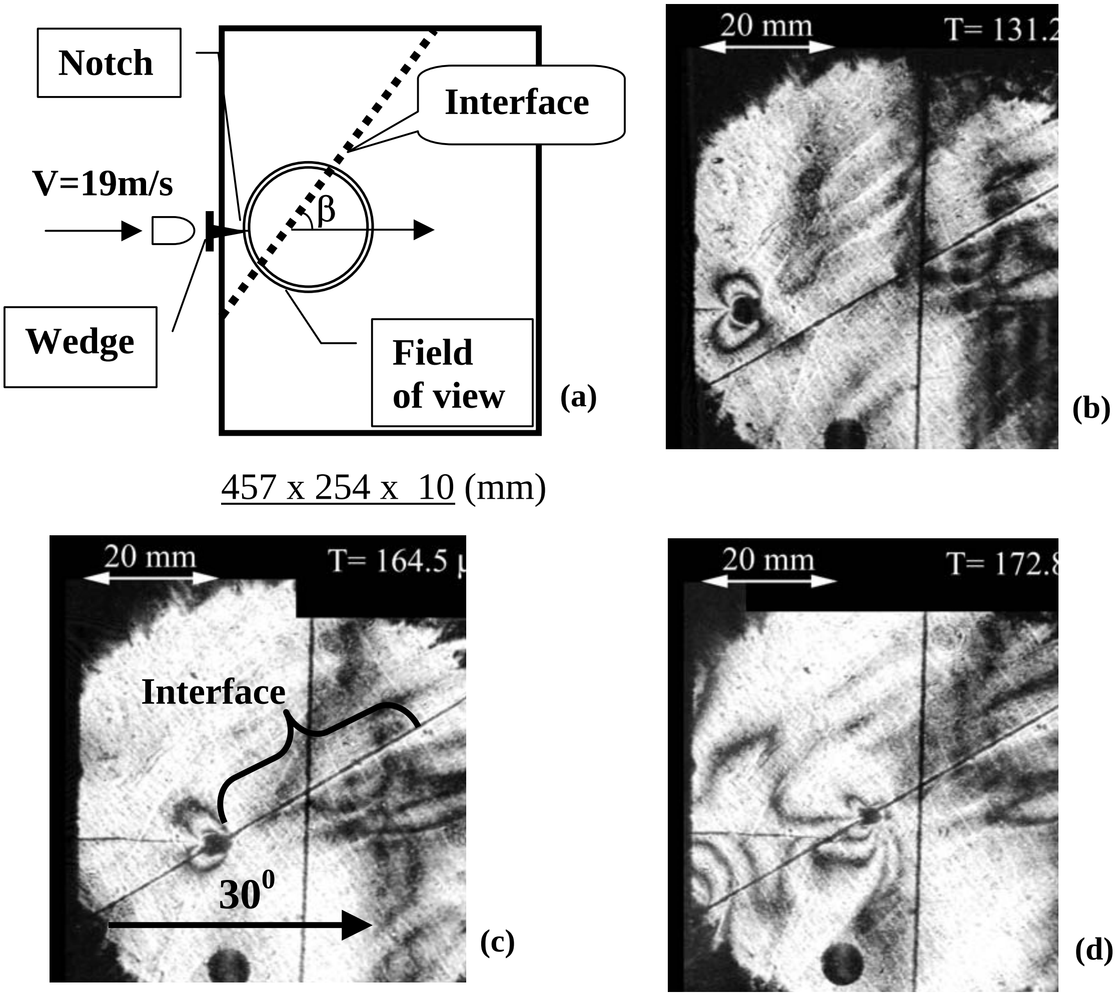

Fig. 2. Crack deflection process at a weak interface (interfacial angle 30 degrees) in a large Homalite-100 plate. The vertical line appearing in every image is the camera streak line. Another inclined thin line reveals the position of the interface. The dark circular spot, at the lower corner of each photo, is a scaling mark .

that of monolithic Homalite. The Weldon-10 adhesive is considered to be a “strong” adhesive. The Loctite 384 formed a “weak” bond. The average thickness of all adhesive layers was less than 20 μm [8].

Dynamic photoelasticity setup was used in this study. Two sheets of circular polarizer were placed on either side of the specimen. A coherent, monochromatic, plane polarized laser output is collimated to a beam of 100 mm in diameter. The laser beam is transmitted through the specimen. The resulting fringe pattern is recorded by a high-speed camera. During the impact test, a projectile was fired by the gas gun and impacted the loading wedge to trigger the recording system and to dynamically initiate the mode-I incident crack. Details of experiments were reported by Xu and Rosakis [1,8]. Under the dynamic deformation, the generation of isochromatic fringe patterns is governed by the stress optic law. For the case of monochromatic light, the isochromatic fringe patterns observed are proportional to contours of constant maximum in-plane shear stress, $\hat{\tau}_{\max} = (\hat{\sigma}_1 - \hat{\sigma}_2)/2$.

3. RESULTS AND DISCUSSION

3.1 Crack Deflection/Penetration at a Weak Interface

Figure 2 shows the crack deflection process at a weak interface whose interfacial angle is 30 degrees. In Figure 2(b), a dynamically propagating mode-I crack (surrounded by symmetric fringe patterns) is seen to propagate towards the interface. The vertical line appearing in every image is the camera streak line, which is used for positioning and reference purposes. Another inclined thin line reveals the position of the interface. The dark circular spot, at the lower corner of each photo, is a scaling mark of 6.35 mm in diameter. Around 164 μs after impact, we notice that the crack tip fringe pattern has already started to lose some of its symmetry. Around 170 μs (Figure 2(d)), this mode-I incident crack has already transited into a mixed-mode crack at the interface whose fringe pattern at the crack tip was clearly asymmetric with respect to its propagation direction. In fact, a close look at this pattern reveals that its line of symmetry is still parallel to the horizontal line although the crack propagates along the inclined weak interface. Also, the caustic (or shadow spot surrounding the crack tip) size at the crack tip was significantly reduced in comparison to the caustic sizes in Figures 2(b) and (c).

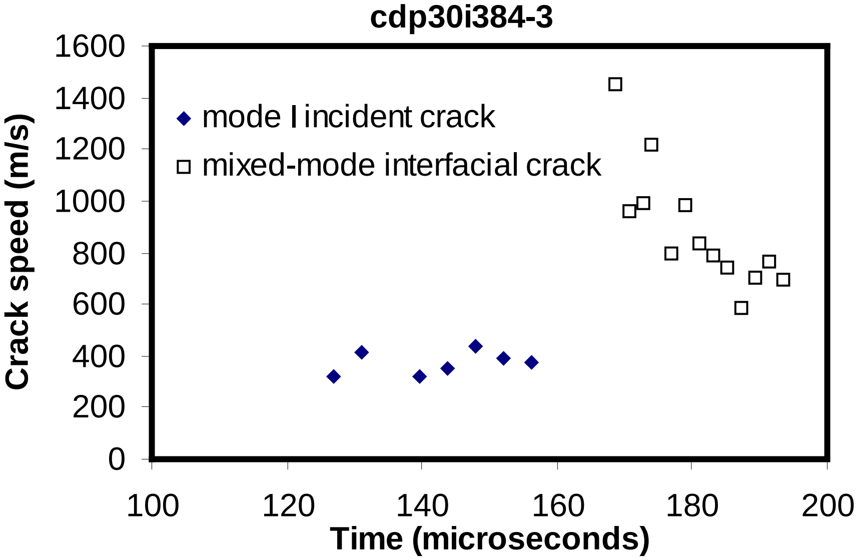

Fig. 3 crack speed history before and after crack deflection at a weak interface (interfacial angle 30 degrees).

The abruptness of the transition behavior between a mode-I incident crack and a mixed-mode interfacial crack can be graphically witnessed by the impressive jump in crack speeds across the interface. Figure 3 shows the crack speed history as the incident mode-I crack develops and transitions into a mixed-mode interfacial crack. Before the crack deflection, the crack tip speed is approximately 400 m/s, which is a speed very close to the branching speed of Homalite-100. As shown in Figure 3, after crack deflection, the speed jumped by as much as 800-1000 m/s and then decreased as it propagated further along the interface. Other experiments were conducted for different interfacial angles of 45 and 60 degrees respectively and strong interfacial bonding [8]. The above results clearly elucidate the role of interface inclination on the nature of failure mode transition. In the following section, we will concentrate on the modeling and prediction of the dynamic interfacial crack.

3.2. Model Prediction for Dynamic Crack Deflection/Penetration

A dynamic fracture mechanics model was developed to predict the crack deflection vs. penetration at an interface in homogeneous materials [8]. To determine whether an incident crack will penetrate the interface, the normalized energy release rate for crack deflection and penetration is expressed as a function of incident angle β. An appropriate criterion for dynamic crack penetration through the interface is a ratio comparison between the dynamic energy release rates (driving force) and the fracture toughnesses (material resistance)

$$\frac{G^{d}(\beta, v_2)}{G_I^{d}(v_1)} \leq \frac{\Gamma_c^{IT}(v_2)}{\Gamma_{Id}^{MA}(v_1)} \tag{1}$$

where v_1 and v_2 are the incident crack speed and the possible deflected crack speed respectively. $\Gamma_{Id}^{MA}(v_1)$ is the dynamic fracture toughness of the bulk material while $\Gamma_C^{IT}(v_2)$ is the interfacial fracture toughness. We first start by applying this methodology to the experiments briefly discussed in Figure 1(b) [2]. In this case, the bond involved in a polyester adhesive and its interfacial fracture toughness is 0.56 MPa $\sqrt{m}$. The incident crack speed was about 300 m/s. The fracture toughness of Homalite at this crack speed is about 0.6 MPa $\sqrt{m}$, making the ratio $\Gamma_c^{IT}/\Gamma_{Id}^{MA}$ equal to 0.93. Figure 4 displays a graphic representation of the inequality (1). Indeed, according to the criterion, deflection into the interface will take place at $0<\beta< 59^{o}$ while the interface will be penetrated for $59^{o}<\beta< 90^{o}$. It should be noted that both cases displayed in Figure 4 are consistent with this prediction.

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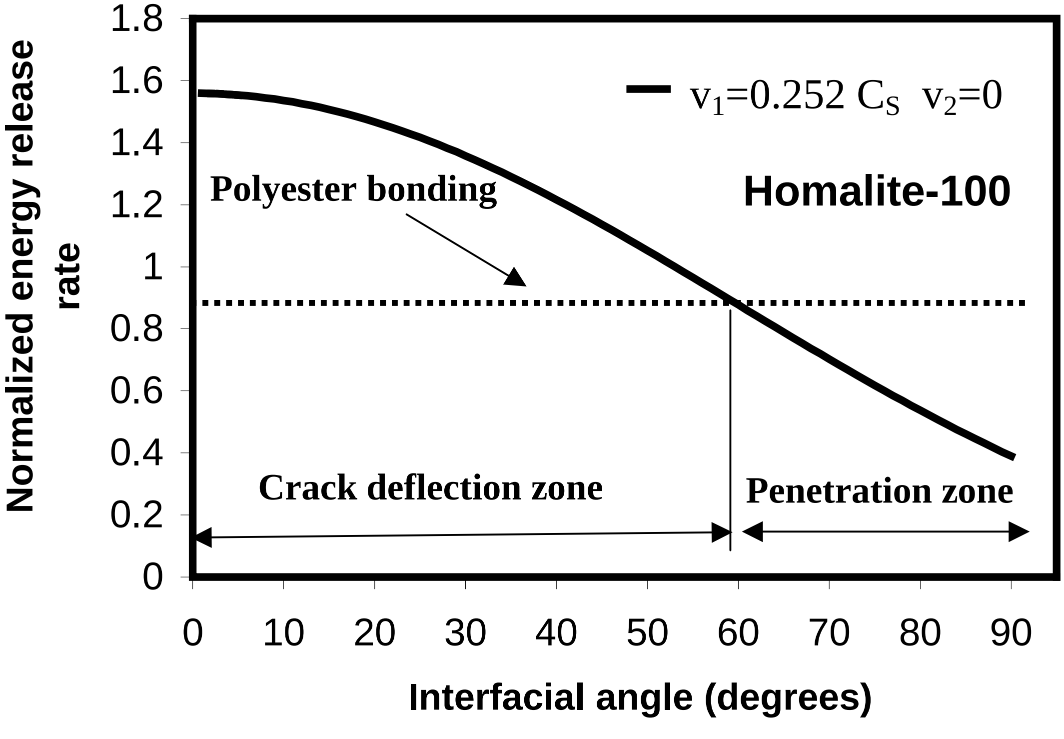

Figure 4. Prediction of the dynamic crack deflection /penetration regimes for a crack traveling at 300 m/s towards an interface bonded by a polyester adhesive.