INTERACTION OF DYNAMIC CRACKS WITH INCLINED INTERFACES

Vijaya B. Chalivendra, Soonsung Hong, Ares J. Rosakis, Irene Arias, Jaroslaw Knap and Michael Ortiz
California Institute of Technology, USA

ABSTRACT

Catastrophic failure of any brittle structure under dynamic loading consists of dynamic crack initiation, propagation, curving, branching (both micro and macro) and branching instability. However, the failure is much more complex in case of layered materials which has interfaces. In these materials, other than above crack mechanisms the crack can also deflect to propagate along the interface or penetrate through the interface when it reaches the interface. In order to understand these features, a detailed experimental investigation is essential. Simple specimen configurations have been designed to look into these features both qualitatively and quantitatively. Dynamic photoelasticity coupled with high-speed photography is used to capture real-time crack propagation. An initial experimental study has already been conducted to identify important parameters that affect the penetration and deflection behavior. It has been observed that incoming crack tip velocity and mode mixity have influence on the nature of crack propagation along the interface. To validate these observations, an extensive set of well controlled experiments will be conducted. In parallel to these experiments, a series of large scale simulations using cohesive zone interfacial elements will be performed. The above mentioned specimen configurations are well designed to have very simple boundary condition. The specimen is wedge loaded dynamically so that other edges of the specimen are stress free. To perform these simulations, two set of inputs are necessary. The first one is to provide valid loading boundary conditions and the second one is to incorporate accurate cohesive zone laws in the dynamic fracture of the simulated specimen. To meet the first input, a modified Hopkinson bar setup has been used to accurately control initial and boundary conditions. In case of second input, an inverse formulation approach will be used to extract cohesive zone laws for both mode-I and mixed mode conditions.

1 INTRODUCTION

Cracks usually propagate in homogeneous, brittle solids under locally mode-I conditions, at sub-Rayleigh wave speeds typically below the crack branching speed (Freund[1] and Broberg[2]). Even though crack accelerates under increasing far-field loading, it reaches critical speed beyond which it becomes energetically more favorable to propagate with multiple, branched crack tips rather than as a single entity. However, if a crack is constrained to propagate along weak path, the weak path traps the crack, suppress any tendency of branching or kinking out of weak plane and permits very fast crack growth approaching 80 to 90% Rayleigh wave speed of parent material (Rosakis et al.,[3]). When the mode-II cracks are made to propagate along such weak paths, they tend to go even faster with speeds that are within intersonic regime of the solid (Rosakis et al., [3]; Coker and Rosakis [4]). Literature reveals that extreme mode-I and mode-II cases have studied both experimentally and theoretically. However, little amount of work has been reported about the dynamic mixed-mode crack growth along weak paths. Recent observations identified a speed jump or dramatic speed increase as the crack transitions from a purely mode-I crack to as unstable mixed-mode interfacial crack (Xu et al.,[5]). In the present work, the effect of incoming velocity of mode-I crack and mode-mixity of the propagating interfacial crack on the nature of crack propagation such as deflection and penetration on the interface will be investigated. In parallel to these experiments, a series of large scale simulations using cohesive zone interfacial elements will be performed. To perform these simulations, two set of inputs are necessary. The first one is to provide valid loading boundary conditions and the second one is to incorporate accurate cohesive zone laws in the dynamic fracture of the simulated specimen. To meet the first input, a modified Hopkinson bar setup has been used to accurately control initial and boundary conditions. In case second one, an inverse formulation approach will be used to extract cohesive zone laws for both mode-I and mixed mode conditions. Cohesive zone models have been widely used to simulate and analyze complicated nonlinear fracture process in ductile or quasi-brittle materials, as well as to describe adhesion and frictional-slip between two elastic bodies. The cohesive models with various constitutive laws have provided simple and unified descriptions on diverse nonlinear fracture processes, such as interface decohesion between dissimilar materials, void-growth in ductile metals, crack brigding in quasi-brittle materials like concrete or composites and crazing in glassy polymers. It has been observed that some global behaviors of mechanical processes are sensitive to details of cohesive-zone constitutive laws in computational simulations of cooperative separation processes such as crack branching or fragmentation.

2 EXPERIMENTAL PROCEDURE

A novel wedge loaded plate specimen configurations were designed to produce a single, straight dynamic mode-I crack. Typical specimen configurations used in this study are shown in figure1. The major advantage of dynamic wedge loading is the generation of a negative non-singular stress which enhances the crack path stability and prevents branching (Cotterell and Rice [6]). These specimens were made out of Homalite-100, which is a brittle bifringent material. The thickness of the specimens is 9.5 mm. Homalite-100 was chosen because its dynamic fracture behavior has been well documented in the literature (Dally [7]; Fourney et al.,[8]; Kalthoff [9]). The reason for choosing such a large specimen sizes is to prevent the effect of reflected waves arriving from the free boundaries on both mode-I and mixed mode crack propagation within the range of field of interest. Four different interfacial angles (α) were considered in this study. To create weak interfacial bond strength, Loctite 384 adhesive was used to bond the interfaces. The adhesive interfacial fracture toughness is approximately half of that of Homalite-100.

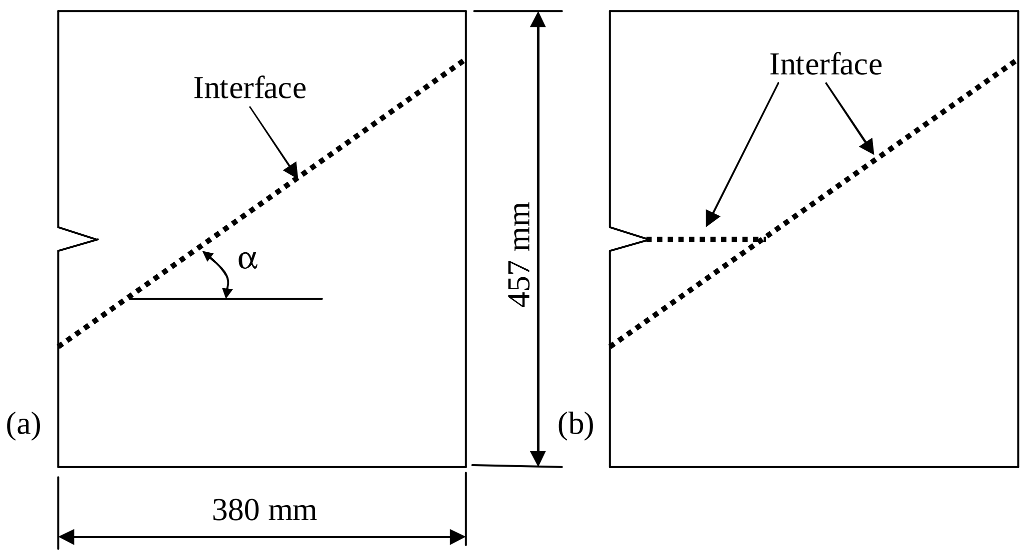

Figure 1: Specimen configurations

The specimens were loaded using modified Hopkinson bar set as shown in figure2. The reason for using Hopkinson bar is to control the symmetry of loading. A steel wedge is inserted into the specimen notch and the specimen is held against the steel bar. A steel projectile of 50mm is used impact the steel bar. This impact generates a compressive pulse which passes through the bar and the wedge and loads the specimen. Strain gages were mounted on the bar and on the notch faces of the specimens. These pulses were used to determine boundary conditions which are used in the simulation. Dynamic photoelasticity in conjunction with high-speed camera is used to capture isochromatics associated with propagating crack.

3 EXPERIMENTAL OBSERVATIONS

In order to study the effect of incoming mode-I crack tip speeds on the nature of crack propagation along the interface, two specimen configurations as shown in figure 1 have been considered. A typical projectile velocity of around 30 m/s is considered to generate mode-I crack in both cases. A first set of experiments for case of specimen configuration shown in figure 1(b) were performed. The figure 3 represents the series of isochromatics of dynamically propagating cracks along both horizontal and inclined interface of 30^o.

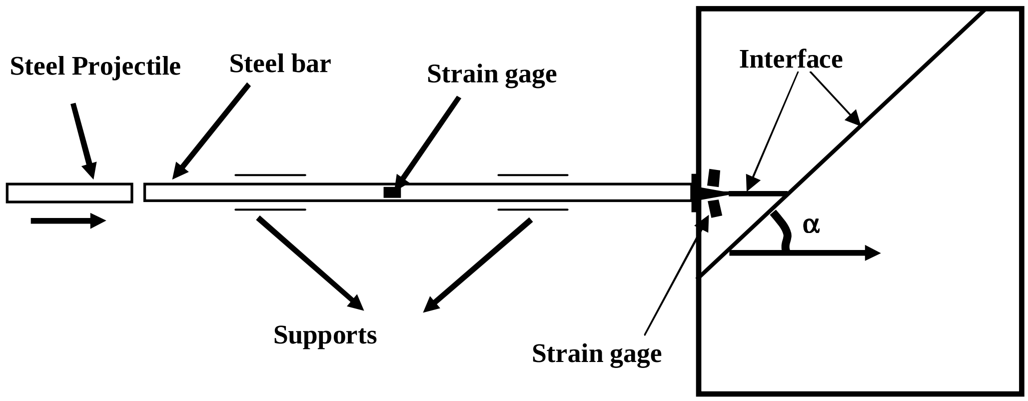

Figure 2: Modified Hopkinson bar loading setup

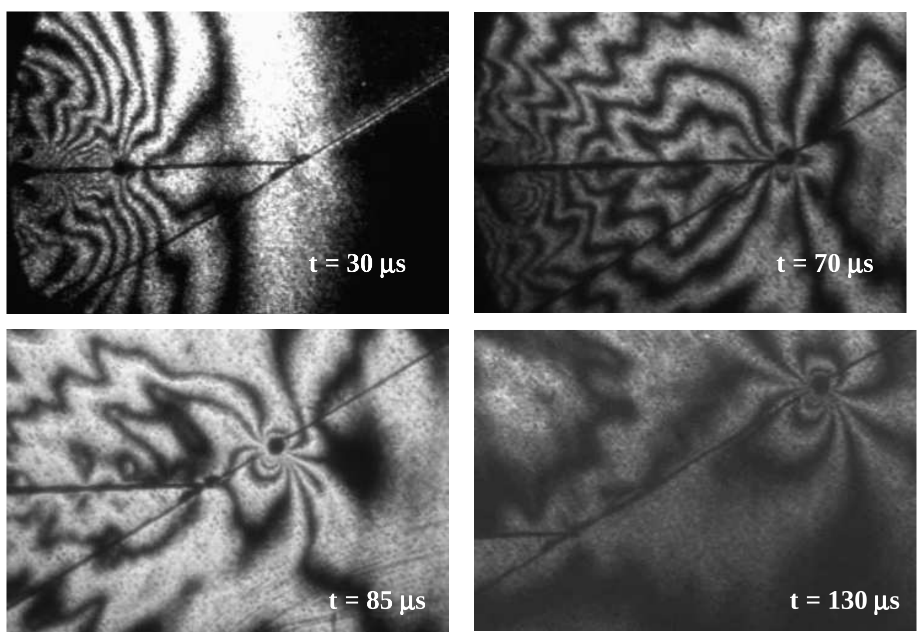

Figure 3: Isochromatics of dynamically propagating crack for an interface of 30^o

These experimental records were analyzed for cracktip position and crack tip velocity as a function of time. The crack tip velocity as function of crack tip position for interface of 30^o is shown in figure 4. The crack initiation takes place around 10 µs after the arrival of the loading pulse. The crack propagates with an average velocity of 825m/s on straight interface and propagates with slightly less velocity along the inclined interface. The crack arrives the inclined interface at an about 70µs after initiation.

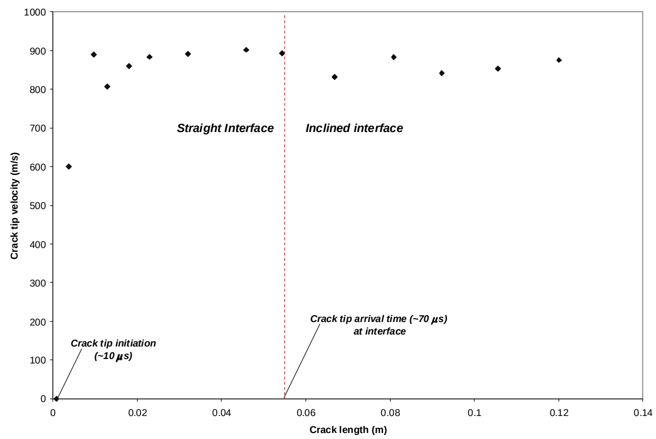

Figure 4: Variation of crack tip velocity with respect to crack tip position of dynamically propagating crack for an interface of 30^o

Using stress optic law and nonlinear least square method, the isochromatic fringes were analyzed. Initial results show that the mode mixity values increases as the inclination angle of interface increases.

4 NUMERICAL OBSERVATIONS

The approach is based on the use of cohesive models to describe processes of separation leading to the formation of new free surface. Within the framework of the conventional finite element analysis, the cohesive fracture models are introduced through cohesive elements embedded in the bulk discretizations. These cohesive elements bridge nascent surfaces and govern their separation in accordance with a cohesive law (Camacho and Ortiz [10]). The cohesive elements are introduced adaptively in the simulation, driven by the fracture criterion naturally introduced by the cohesive law. Cohesive theories of fracture intrinsically define a length-scale and a time-scale (Camacho and Ortiz [10]). The intrinsic length-scale is related to the extent of the fracture process zone. To avoid spurious mesh effects, the finite element size must resolve the process zone. Furthermore, cohesive element approaches force the fracture surface to conform to the element faces, but otherwise the crack paths are arbitrary. Consequently, a sufficiently fine mesh is needed to avoid nonphysically constraining the crack path. Nevertheless, with a resolved mesh, the present method affords accurate solutions, and in particular branching and fragmentation are easily handled.

Initial simulations were conducted to observe the deflection and penetration behavior for the specimen configuration as shown in figure5. It can be seen from the figure that qualitatively simulations show the features those are observed in the experiments. However, the discrepancies in these observations are currently under instigation. It was identified that these discrepancies can be rectified by incorporating valid boundary conditions and proper cohesive zone laws.

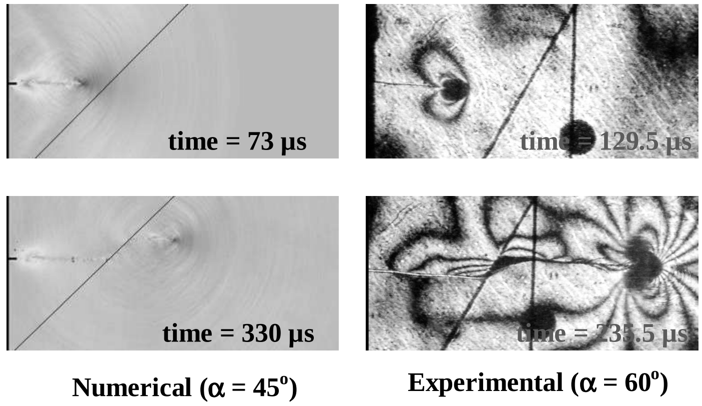

Figure 5: Qualitative comparison of numerical and experimental crack tip position

5 EXPERIMENTAL MEASUREMENT OF COHESIVE ZONE LAWS

In this work, experimentally measured crack tip deformation fields are used to determine the cohesive zone laws (Hong and Kim [11]). This approach utilizes the path-independent interaction J-integral applied to new eigenfunction expansions of the cohesive crack-tip field in the plane elasticity. The inversion methods will be suited for investigating micro-mechanics of cohesive – zone behaviors, such as the effects of cohesive-zone microstructures, mode mixity, and separation rates on cohesive-zone laws dependent on length and time scales.

The inversion scheme is scheme is applied to a crack located along a weak interface under mixed-mode loading to identify the cohesive zone laws of the interface. First, speckle interferometry technique is used to measure elastic deformation fields surrounding a crack located along a weak interface under mixed mode loading conditions. A schematic diagram of a four-beam spatial-phase-shifting speckle interferometer used in this study is shown in figure 6. The experimentally measured deformation fields around a crack-tip are used as an input data for the inverse analysis of the crack-tip cohesive zone problem. Then, the opening and shearing mode cohesive laws are extracted from the elastic deformation field and provided to numerical simulations as a constitutive property of weak plane.

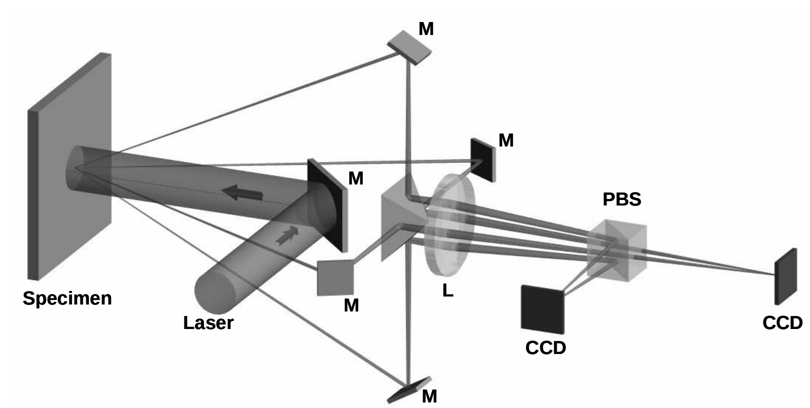

Figure 6: A schematic diagram of speckle interferometer

6 ACKNOWLEDGEMENTS

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