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# Experimental Investigation on Dynamic Crack Propagation Through Interface in Glass

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## ABSTRACT

Experimental analyses are conducted to investigate the dynamic crack propagation through the interface in glass. Failure wave, which is a dense crack network initiated from a surface, is a characteristic of dynamic failure of glass. It has been observed that the cracks driven by a high dynamic load may stop at an interface even though the stress wave goes through it. The cracks can also pass through the interface if the stress is high enough. To understand the behavior of the failure wave, the interaction between a propagating crack and an interface needs to be investigated. In this study, the behavior of a single dynamic crack as it interacts with an interface is investigated. High speed photography and optical methods are employed to visualize the phenomena. A notched glass sample having an interface is impacted with a projectile. A single crack is initiated at the notch tip by the dynamic loading and propagates into the interface. The crack stops if the interface has no adhesive. The crack passes through the interface if it has a very thin layer of adhesive. The crack branches into multiple cracks if the interface has a finite thick layer of adhesive or the impact speed is very high. The branch patterns depend on the thickness of adhesive layer and loading condition.

## INTRODUCTION

Glass has been used in transparent armors. It is desired to predict the impact response and failure behavior of the armors. However, the phenomenon of dynamic failure of glass under a high speed impact is very complicated and successful models have not been developed. Under intensive dynamic loading, glass has a unique dynamic failure phenomenon known as failure wave. It is referred as dense crack networks propagating behind shock waves. Comminuted materials having very low tensile strength are created behind the failure wave, which affects the resistance to impact. This phenomenon has been explored in many studies but has not been understood completely [1,2]. If there is an interface in the way of the failure-wave propagation, the failure wave initiates with the interface and may stop at the interface even though stress waves pass across the interface. After pausing at the interface, the failure wave may reinitiate from the interface [3]. There are many cracks in the failure wave that interact with each other, making it difficult to investigate the phenomenon quantitatively in experiments with proper instrumentation. On the other hand, the theory and experimental analysis on single crack growth has been studied extensively [4,5]. Therefore, to understand the interactions between the failure wave and the glass interface, a feasible approach is to first understand the interaction between a single dynamic crack and an interface, and then expand the scope to include the interactions among cracks.

The single crack propagation at the interface has been investigated by many studies. It has been known that a crack may stop at the interface of two different media when it propagates in perpendicular to the interface. The static stress field of the crack tip ending in an interface has been obtained analytically; and it was found that the rate of singularity and the principal stress direction depended on the properties of two media [6]. The crack behavior at the interface of duplex specimen has been investigated with photoelasticity. A crack growth initiated by static loading stopped abruptly at the interface; but it penetrated the interface when the load was high enough. The stress intensity factor decreased at the interface and increased sharply after the crack reinitiated at the second medium [7]. A crack growth initiated by a drop weight in bi-material was investigated with the method of caustics. The stress intensity factor was found to increase before the interface, decrease abruptly at the interface

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and increase again at the second medium. When the crack penetrated, it paused for tens of microseconds at the interface and reinitiated at the second medium. It was also observed that the crack branched into multiple cracks in some cases [8]. The crack propagation driven by low impact loading through interfaces was investigated with photoelasticity. The crack behavior was found to depend on the strength of adhesive. Cracks were arrested at the interface having low strength adhesive because two media were detached due to their weak bonding [9].

All those experiments were conducted under static or low impact loading conditions on brittle polymers such as epoxy or Homalite, which does not have any failure wave phenomenon. It is more challenging to investigate the dynamic fracture of glass because of its much faster crack speeds and lower photoelastic constants. The single crack propagation at an interface of glass driven by a dynamic load has not been investigated yet, which is the focus of this research.

## EXPERIMENTS

To produce high dynamic loading, a projectile is discharged into a glass specimen. In this study, a 63.5 mm light gas was employed to produce consistent high velocity impact. Figure 1 shows the configuration of the experimental setup. The couples of lasers and sensors detect the passage of the projectile. The velocity of the projectile is obtained from the sensor signals by comparing the time interval between the projectile passing through the two sensors. The high speed camera triggered by the laser and sensors begins to record the images of crack propagation at the instant when the projectile impacts the specimen.

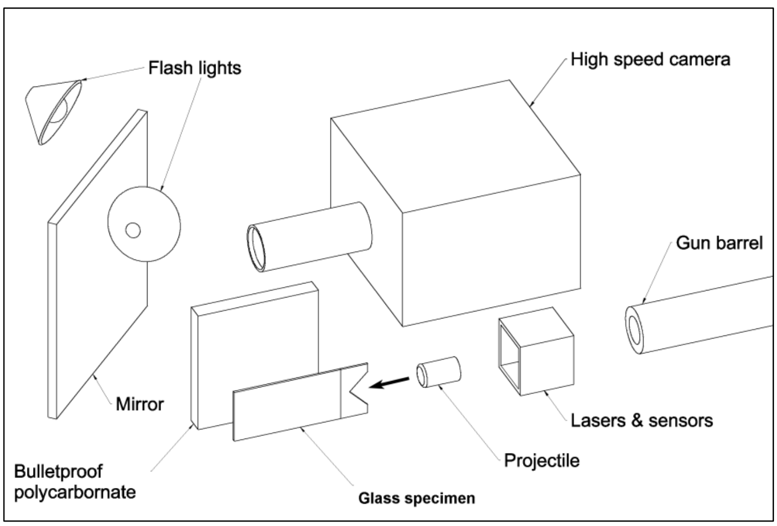


Figure 1. Configuration of experimental setup

Figure 2 shows the dimensions of the projectile and specimen. The projectile strikes the notch, initiating a dynamic crack at the tip of the notch. The specimen is sufficiently long to prevent a reflected tensile wave from separating the glass specimen at the interface. The glass specimens were made with commercial soda-lime glass and Loctite E-30CL epoxy glass bond. The thickness of adhesive is controlled with shims and was measured with an optical magnifier. The projectile material requires low hardness and strength to prevent damage on the glass surface where the projectile initially contacts. Otherwise, the contact surface is subjected to developing fragmentations immediately when a harder projectile touches, because of the brittleness of glass. Smooth-On Featherlite™, casting polyurethane, was chosen for its low hardness and light weight. High speed images and post-mortem observations verified that the cracks always initiate at the notch first instead of at the contact surfaces between the projectile and the glass specimen.

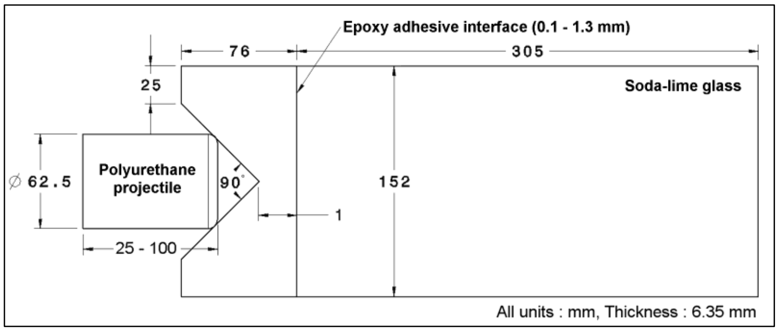


Figure 2. Dimensions of projectile and specimen

To obtain more quantitative information about the crack propagating in the glass plates, the method of caustics was employed to track the tip of cracks and to estimate stress intensity factors. The glass has very small photoelastic constants and the corresponding size of caustics is very small. The size of caustics in glass is only a few millimeters, making it difficult to obtain the exact value of stress intensity factor of each crack [10]. However, it is still possible to estimate the change of the stress intensity factor and compare the relative value of each branched crack.

## RESULTS

The high speed camera recorded the images of crack propagation and its interaction with the interface at a frame interval between 5 μs and 20 μs. Figure 3 shows the crack propagation on a specimen having two glass panels touching along the interface without adhesive bonding. The propagating crack from the notch tip stopped at the interface. Similar phenomenon was observed in another study [9], where a crack was observed to be arrested at the adhesive interface because the two sides of the interface were detached before the crack arrived. Besides the initial cracks, more cracks developed from the interface toward the notch later, which were generated by the tensile waves reflected from the side edges of the specimen, as shown in the image on the right side of Figure 3.

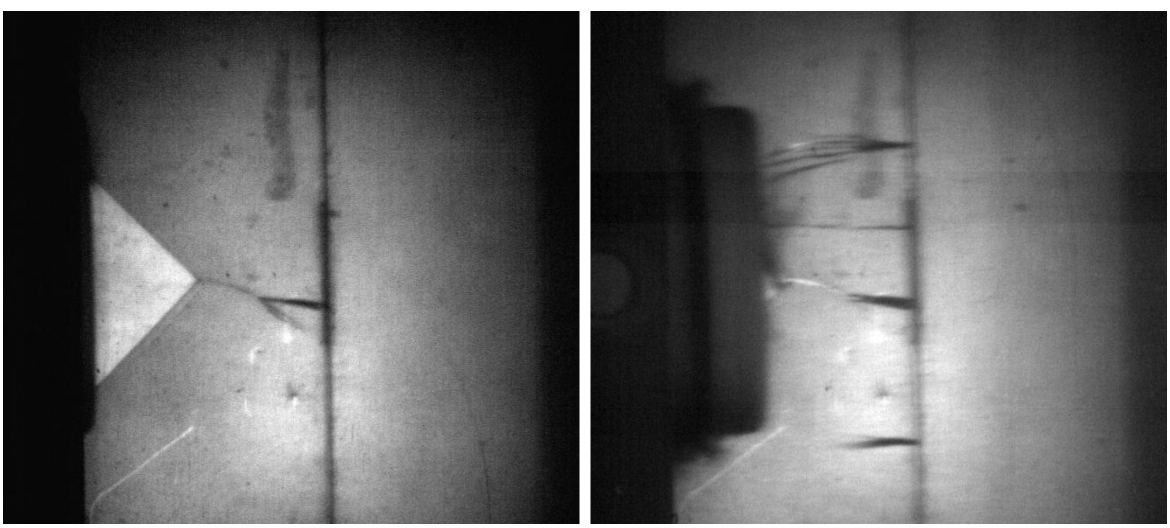

Figure 3. Crack propagation across an interface without adhesive (projectile: 217 g, 212 m/s, K.E.: 4880 J)

Figure 4 shows the crack propagation across an interface bonded with an adhesive layer of less than 0.1-mm thick. In this case, two glass plates were bonded without any shims. The images in Figure 4 show that the crack passed across the interface without deflecting or branching. The propagation of the crack paused at the interface for 5 μs approximately. A similar delay was also observed in another study [8].

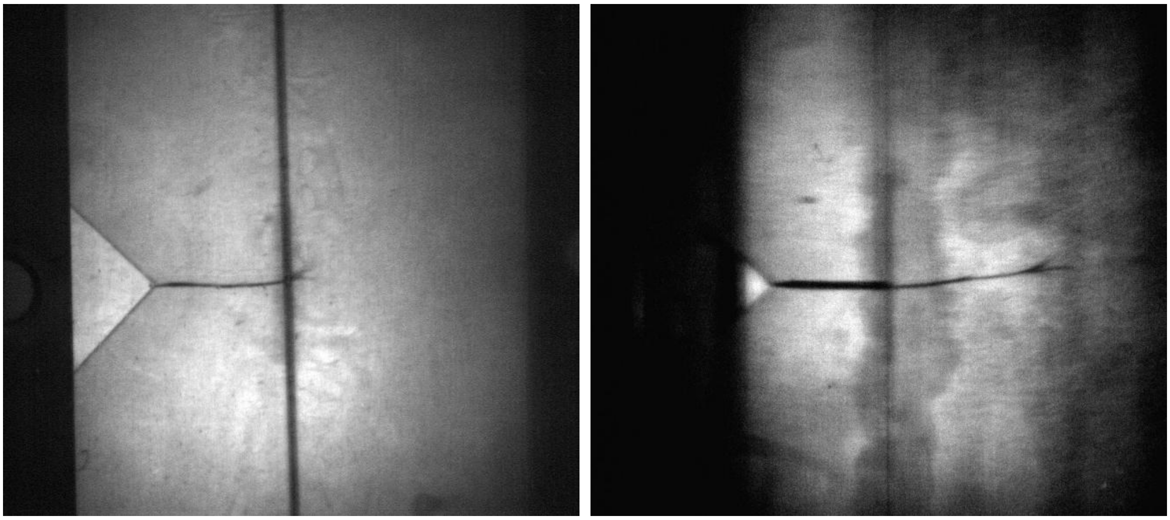

Figure 4. Crack Propagation across a very thin interface (projectile: 162 g, 229 m/s, K.E.: 4250 J)

Figure 5 shows the behavior of a crack propagating through an interface bonded with an adhesive layer of 0.13-mm thick. The crack also paused at the interface for 10 μs approximately when crossing the interface. The crack then branched into multiple cracks after it passed across the interface. Comparing to the behavior of the crack interaction with a thin interface where no branching or defecting occurred despite higher impact energy as shown in Figure 4, this branching-after-interface phenomenon is an interesting phenomenon worth further exploration.

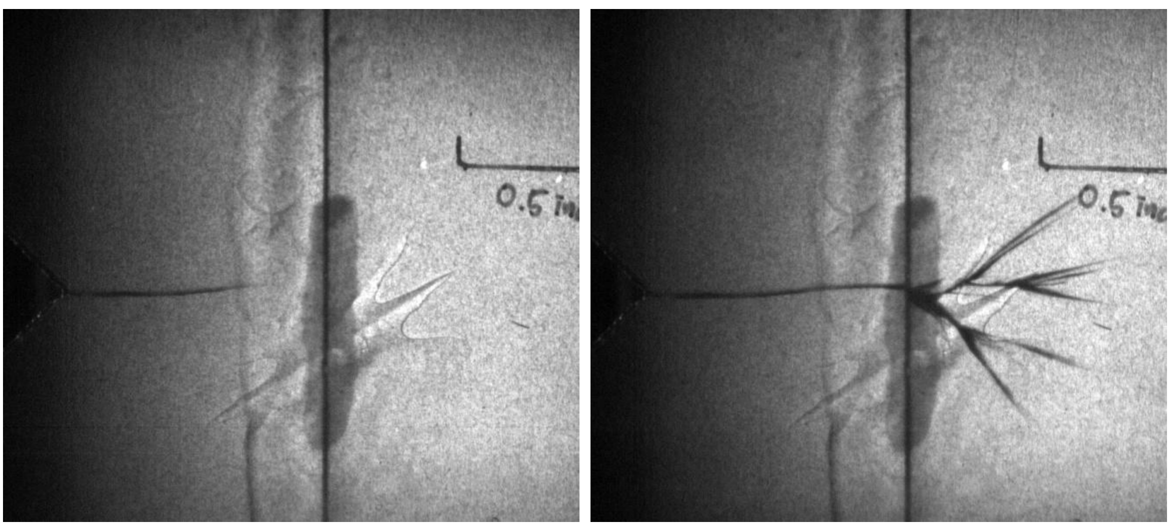

Figure 5. Crack propagation across a 0.13 mm-thick interface (projectile: 124 g, 192 m/s, K.E.: 2290 J)

It is suspected that the branching is caused by the accumulation of strain energy in the ductile adhesive layer that is suddenly released at the initiation of the crack after the interface. To further explore the relation between the available strain energy and the branching behavior, the specimen having a much thicker (1.3-mm) layer of adhesive was impacted as shown in 6. The crack had more branches than that happened in the specimen having the 0.13-mm thick adhesive layer as shown in Figure 5, in spite of similar impact energy. The thickness of the interface is concluded to affect the pattern of the crack branching.

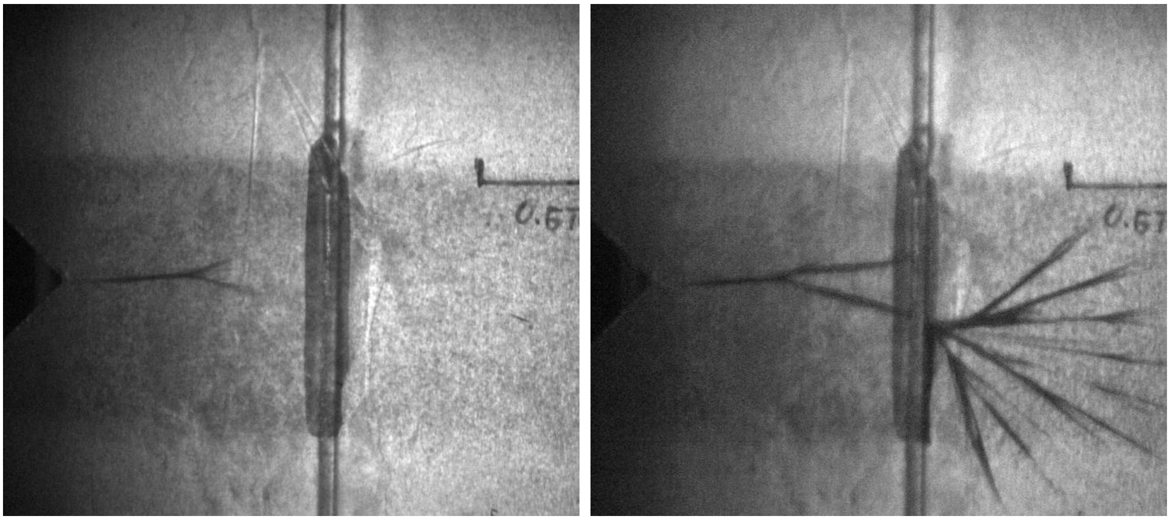

Figure 6. Crack propagation across a 1.3 mm-thick interface (projectile: 135 g, 200 m/s, K.E.: 2700 J)

It was also observed in this experiment that the crack branched before reaching the interface. The upper crack branch stopped at the interface while the lower branch penetrated the interface.
Another approach to vary the strain energy in the specimen is to increase the striking velocity of the projectile. Figure 7 shows the crack branching in the specimen impacted by the projectile at a higher speed of 660 m/s. With more energy available in the specimen, it is seen that the high-speed impact caused severe crack branching in the glass specimen after the interface. The initial crack also branched into multiple cracks at the very early time before reaching the interface. The dense crack in the glass after the interface is quite different from the other cracks in glass observed in normal static or low speed dynamic experiments, such as the ones shown in Figures 4 and 5.

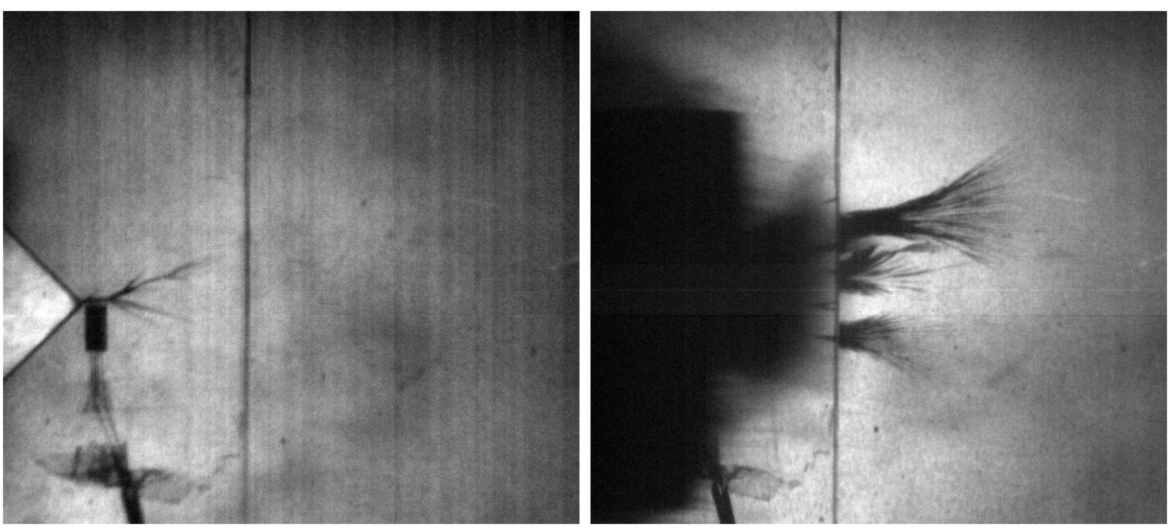

Figure 7. Crack propagation across a 0.38 mm-thick interface (projectile: 77 g, 660 m/s, K.E.: 16800 J)

To compare the relative stress intensity factors associated with each of the crack tip, the method of caustics was employed. Figure 8 shows the images of caustics from such an experiment. The vertical black line is the interface having a 0.5-mm thick adhesive layer. The horizontal black line at the center is a shadow that is not covered by laser pulses and should be ignored. The size of caustics is approximately 1 mm but the exact size can not be obtained due to low resolution of the images. As shown in the figure, the initial crack was branched before it reached the interface, which is similar to that of Figure 6. Comparing the sizes of caustics, crack 1 has the higher stress intensity factor than crack 2 initially. But when they reached the interface, crack 2 had a higher stress intensity factor; and it penetrated the interface and then branched in to multiple cracks. This phenomenon indicates that the main crack driving force may switch from one crack to another when the cracks approach an interface delaying their propagation. The information obtained from the caustics shed insights into why one crack penetrates the interface while other crack stops at the interface even though they are branched from a single crack.

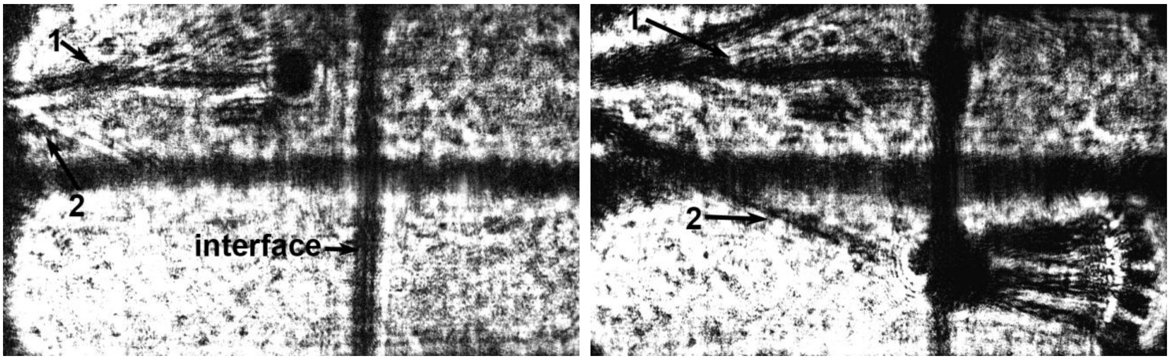

Figure 8. Caustic of crack propagation across a 0.5 mm-thick interface (projectile: 84 g, 262 m/s, K.E.: 16660 J)

## DISCUSSIONS

It is known that elastic energy in a specimen is transferred into a growing crack. The crack propagation speed is an important factor to dissipate the stored energy [4]. Under dynamic loading conditions, the energy in the specimen increases rapidly and a delay in crack propagation may let excessive energy store in the specimen. Such excessive energy leads to crack branching. The mechanism of crack branching have not been explained clearly. The definition of the critical conditions for crack bifurcation have been attempted in various ways such as a critical velocity, a stress intensity factor, a strain release energy, and a surface roughness [12,13]. Even though the definite model for crack branching does not exist this time, it is obvious that excessive energy in loaded specimen causes crack branching. The surface roughness transition known as mirror-mist-hackle of a fractured surface shows the excessive energy dissipation through the surface when a crack branches into multiple crack [13].

It is experimentally determined that the crack propagation is delayed longer as the thickness of adhesive increases. One of the reasons is that the crack speed in epoxy is much lower than that of glass. It was also observed that the initiation of crack in the glass after the interface takes a certain amount of time even when the duplex specimen did not have any adhesive layer [8]. If the duration of delay is very short, the stored energy in the specimen is not big enough to cause crack branching as show in Figure 4. However, if the impact velocity is high, even a short duration of delay can cause crack branching because of the excessive energy accumulated in the specimen. As show in Figure 7, very sever crack branching was observed in spite of a relatively thin 0.38 mm-thick adhesive layer.

## CONCLUSIONS

Projectile impact speed and thickness of adhesive layer affect the patterns of the crack propagation across an interface in notched glass specimens. The crack penetrates the interface with a very thin layer of adhesive at a moderate impact speed. The crack branches into multiple cracks if the layer has a finite thickness or the impact speed is high. The crack stops at the interface without any adhesion. The stress intensity factor of each branched crack may increase or decrease when the cracks approach the interface.

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