EXPERIMENTAL STUDIES OF MIXED MODE SPONTANEOUS FRACTURES EXPANDING ALONG WEAK PLANES

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ABSTRACT

Modern engineering materials, such as concrete, composites (nano-composites), and functionally graded materials, contain large amount of internal interfaces which are either coherent (interfaces separating different components of the material) or incoherent (faces of micro-cracks or micro-voids). This type of material characteristic is also very common in biomaterials, such as bones, tissues etc. These interfaces usually serve as the sites of catastrophic failure in applications. To fully understand the failure modes of these materials and so as to provide useful information to the material manufacturers, carefully designed experiments are needed. Specimen of the simplest geometry will be investigated, which is a plate made out of two halves bonded together by glues. The two halves are either made of same materials (homogeneous case) or different materials (inhomogenous case). Both the homogeneous and inhomogeneous cases have been extensively investigated by Rosakis and his co-workers using impact induced stress wave loading (Mode I and Mode II). The homogeneous case also was studies by dynamic crack face loading (Mode I) by Knauss and others. In this study, the loading we used is the static tension combined with dynamic triggering. In this way, we can observe the dynamic fracture expansion starting from a small incipient crack. The fracture propagation is controlled by the far-field static loading and the triggering is used to create the small initial crack and has no effect on the fracture propagation followed. With enough static loading, this initial crack is unstable and will propagate dynamically. Hence, we call this type of dynamic fractures as spontaneous fracture, which is the main material and structure failure mode under static loading. We study both the Mode I spontaneous fractures and mixed-mode (Mode I and Mode II) spontaneous fractures of both homogenous and inhomogeneous cases using dynamic photoelasticity combined with high-speed photograghy. The experimental results can also be used to validate theoretical results of self-similar dynamic fractures done by Freund and Broberg.

1. INTRODUCTION

In recent years, there has been an increasing demand for specialized lightweight, high-strength structures with their usage extending to the areas of space, deep oceans, and in increasingly hostile environments [1]. The optimal design leads to materials made of several phases of special properties, one such example is composites. The existence of interfaces in new generation of structural materials has refocused the attention of engineers to the problem of dynamic crack growth along pre-determined crack paths which are often identified as the boundaries between the phases of heterogeneous solids. Materials with internal interfaces can also occur naturally. One example is the bone of animals as shown by Gao et al. [2]; the other example is the earth crust containing lots of pre-existing faults. In addition to the possibility of failure starting from pre-existing micro-cracks in each material phase, the interfaces between material phases are additional sites of catastrophic failure. Because the interfaces are usually weaker than the individual constituent, the interfacial failure is the dominant failure mode of this type of this type of material. The scenario of dynamic failure of model composites under impact done by Xu and Rosakis [3] illustrated this point

The simplest model material with interfaces is a plate made out of two halves bonded together by glues. The two halves are either made of same materials (homogeneous case) or different materials (inhomogenous case). The homogeneous case was studies by dynamic crack face loading (Mode I) by Washabaugh and Knauss [4]. They bonded the interface of two identical brittle polymers partially, and applied electromagnet pulse force directly on unbonded part of the interface. They demonstrated that for weak bonding, the resulting dynamic Mode I crack can reach the theoretical limiting speed (i.e., Rayleigh wave speed c_R) asymptotically. The influence of the interface on the Mode II fracture is more significant. In homogeneous materials, Mode II crack can not maintain the straight crack path. In order to maximize the energy release rate, it always curves so that locally, the loading is Mode I [5]. The (weak) interface forces a crack to propagate dynamically along a specific path (i.e., the interface) and thus removing its freedom to choose a path that will allow it to remain locally mode-I, results in a number of very interesting phenomena. As shown by Rosakis and his co-workers [6], under shear dominant stress wave loading, the resulting Mode II crack along a bonded interface separating two identical polymers can reach an intersonic speed (between shear wave speed c_S and longitudinal wave speed c_P). This result conformed to the earlier theoretical and numerical predictions of maximum speed of Mode II fractures, where a crack path was pre-determined [7, 8]. They also have shown a unique phenomenon of pulse mode of shear fracture propagation along a bonded weak interface separating different materials [9]. The pulse mode vs. crack mode of shear fracture propagation has been a hot subject in earthquake community [10, 11].

Dynamic processes in a cracked body roughly fall into two basic categories: dynamic crack propagation and dynamic loading of bodies with stationary cracks. In order to solve the dynamic fracture propagation theoretically, there are usually two assumptions: steady state assumption and self-similar assumption [7, 8]. So far, experimental work has been done on materials with interfaces are primarily dynamic loading and can only be idealized as steady state far away from the starting crack tip. In addition, no dynamic mixed mode fracture has been studied experimentally. Some materials with interfaces, especially those applied in civil structures, would fail spontaneously, meaning static loading and sudden dynamic nucleation or triggering to start the dynamic propagation of fracture. The spontaneous fractures starting from zero initial crack length would be a good example of self-similar fracture idealization, and we can compare the experimental results with available theories [7, 8]. Motivated by the above mentioned reasons, we will design and conduct series experiments of spontaneous fractures along interfaces separation same or different materials. Furthermore, we will apply both Mode I and mixed Mode (Mode I and Mode II) far-field static loading. The different characteristics of fracture propagation, such as fracture surface morphology, fracture speed, etc., can be investigated under different ratio of far-field loading mode mixity.

2. EXPERIMENTAL DESIGN

The experimental design follows the design of laboratory earthquake experiments [12], where the loading is compression and the interface is incoherent. In our case, we have coherent (glued) interface and the far-field loading is tensile (Fig. 1A). We use transparent photoelastic polymers in our experiments. The bonded specimen has a dimension of 150 mm by 150 mm. The coherent interface between the two halves is inclined at an angle α to the horizontal. Variations in α will change the mode mixity of the far-field load. We use dynamic photoelasticity combined with high-speed photography as diagnostics. The circular polarizers are so orientated that isochromatic fringe pattern results and recorded by the high speed camera which can operate at a speed up to 10^8 frames per second. A unique aspect of the experimental design is related to the choice of the rupture triggering mechanism, which is the critical part of the design of spontaneous fracture problem. The spontaneous fracture is nucleated at the center of the coherent interface by producing a small crack by exploding wire technique (Fig. 1B). A thin wire of 0.1 mm in diameter is inserted in a small hole of approximately the same diameter in the interface. An electronic condenser is then discharged turning the metal into an expanding plasma wave, which creates a small initial crack. For large enough far-filed loading, this initial crack is unstable and will propagate dynamically. In Fig. 1B, one photograph of isochromatic fringe pattern produced by explosion in the incoherent interface between two plates is also shown. We can see clearly the P wave front, S wave front and the head wave which starts from the point where P wave front intersects with the interface and is tangent to the S wave front in the picture.

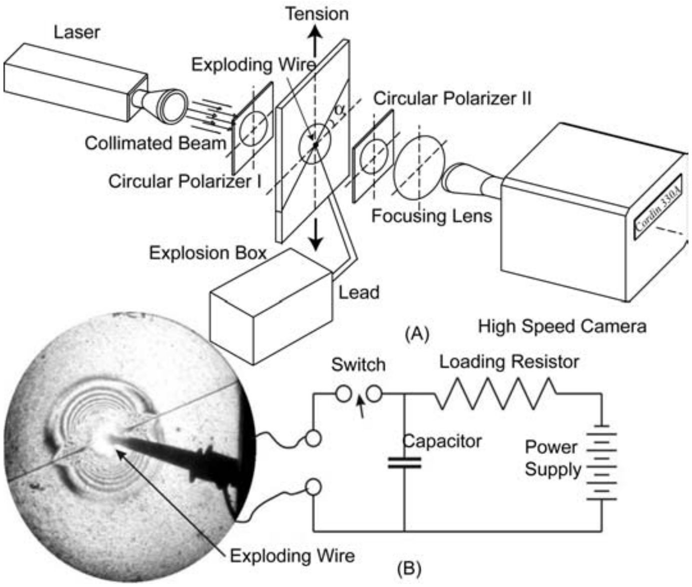


Figure 1: A, The schematic drawing of photoelasticity technique combined with high speed photograghy; B, The schematic drawing of exploding wire technique.

The two transparent polymers we use are homalite 100 and polycarbonate. The material properties are listed in Table 1. The wave speeds are measured using ultrasonic method and other values are taken from Dally and Riley [13].

Table 1: Summary of optical and mechanical properties of photoelastic materials

Material Property	Homalite 100	Polycarbonate
Young's Modulus E (MPa)	3860	2480
Poisson's Ratio ν	0.35	0.38
Stress fringe value f_σ (kN/m)	23.6	7.0
P Wave Speed C_P (km/s)	2.578	2.276

S Wave Speed C_S (km/s)	1.262	0.949
Density ρ (kg/m^3)	1230	1129

3. PRELIMINARY EXPERIMENTAL RESULTS

A few preliminary results will be shown here. In Fig. 2, we show the experiment of homogeneous case under Mode I loading. The uniaxial far-field tension is 6 MPa. In Fig. 2A, we can see two crack-tips featured by shadow dots and the fringe pattern is quite symmetric. From Fig. 2B, we can estimate the speed of left crack as $\mathrm{v_L{=}678\ \ m/s}$ and the speed of right crack as $\mathrm{v_R{=}808\ \ m/s}$. It is worth noticing that the two crack speeds are constant within the error of measurements. In all of our experiments, we only record the process before the cracks see edge effects (waves reflected back from edges) and hence the cracks are effectively in infinite media.

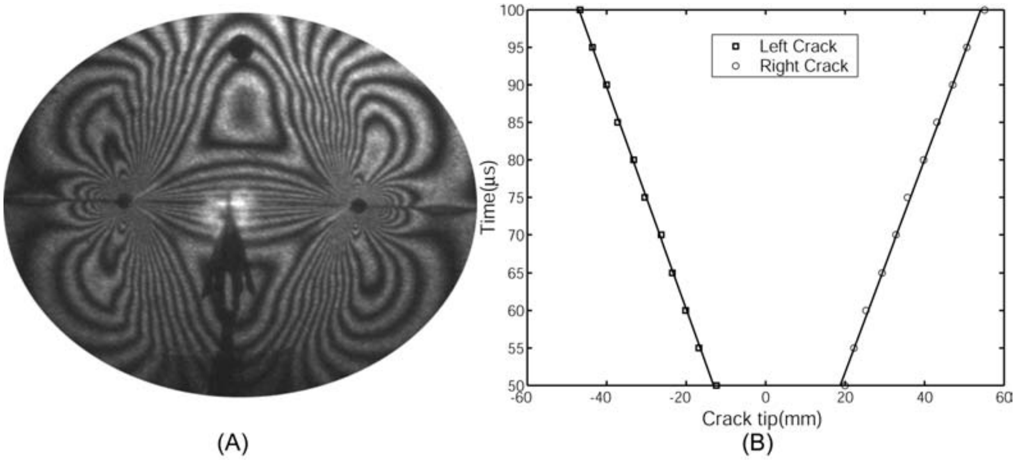
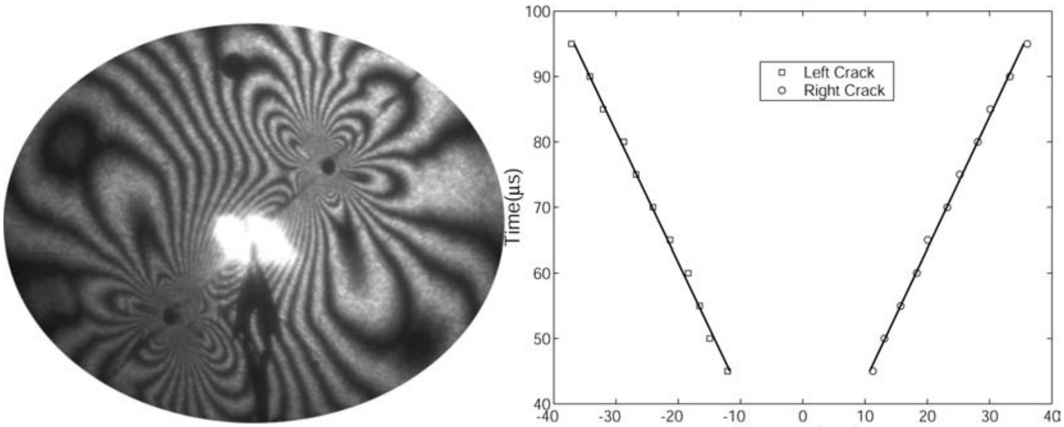


Figure 2: Homogeneous case (polycarbonate + polycarbonate) under Mode I loading. A, One isochromatic fringe pattern; B. The time history of two crack-tips.

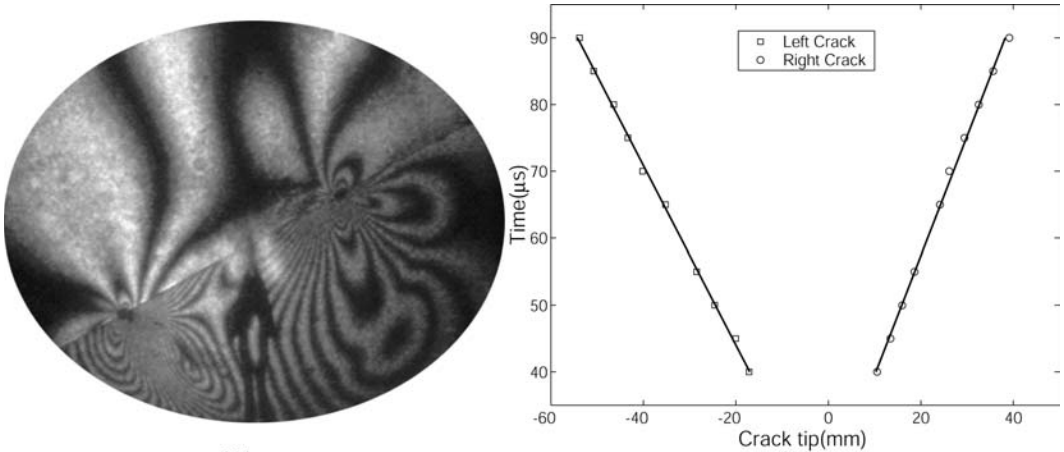
In Fig. 3, we show the experiment of homogeneous case under mixed loading. The mode mixity is 1 since the inclination angle $\alpha{=}45^\circ$. The uniaxial far-field tension is 8 MPa. In Fig. 3A, we can see two crack-tips featured by shadow dots and the fringe pattern is almost anti-symmetric with respect to the initiation point (explosion site). From Fig. 3B, we can estimate the speed of left crack as $\mathrm{v_L{=}500\ \ m/s}$ and the speed of right crack as $\mathrm{v_R{=}495\ \ m/s}$. Again, we have two constant crack speeds within the error of measurements.

In Fig. 4, we show the experiment of homogeneous case under mixed loading. The mode mixity is $\tan\psi{=}\mathrm{K_{II}/K_I}{=}1$ since the inclination angle $\alpha{=}45^\circ$. The uniaxial far-field tension is 8 MPa. In Fig. 4A, we can see two crack-tips featured by shadow dots and the two cracks are not symmetric with respect to the initiation point (explosion site). The reason is obvious since the left crack and right crack see different materials on two side of the crack path, for left crack, the left side of crack path is homalite while the right side is polycarbonate; the right crack sees exactly the opposite material combination. In Fig. 4B, we can estimate the speed of left crack as $\mathrm{v_L{=}745\ \ m/s}$ and the speed of right crack as $\mathrm{v_R{=}559\ \ m/s}$. Again, we have two constant crack speeds within the error of measurements but in this case, the two speeds are different due to the existence of material contrast across the interface.



(A) (B)

Figure 3: Homogeneous case (polycarbonate + polycarbonate) under mixed mode loading. A, One isochromatic fringe pattern; B. The time history of two crack-tips.



(A) (B)

Figure 4: Inhomogeneous case (homalite 100 + polycarbonate) under mixed mode loading. A, One isochromatic fringe pattern; B. The time history of two crack-tips.

4. Discussions

We have conducted spontaneous fracture experiments along a weak interface under different material combinations and different load mixity. From all of our experiments, there are a few interesting common features: 1. Crack speeds are constant; 2. Asymmetry of crack propagation in inhomogeneous case under mixed mode loading.

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