PERIDYNAMIC STUDIES OF INTERACTIONS BETWEEN STRESS WAVES AND PROPAGATING CRACKS IN BRITTLE SOLIDS

By

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A DISSERTATION

Presentation to the Faculty of
The Graduate College at the University of Nebraska
In Partial Fulfillment of Requirements
For the Degree of Doctor of Philosophy

Major: Mechanical Engineering & Applied Mechanics

Under the Supervision of Professor Florin Bobaru

Lincoln, Nebraska

November, 2015

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University of Nebraska, 2015

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The dynamic interaction between propagating cracks and stress waves is a complex and challenging problem responsible for the evolution of failure and damage in brittle materials. The peridynamics formulation is used here to study damage and fragmentation induced by impact in a glass plate and intersonic crack propagation in a unidirectional fiber-reinforced composite (FRC). We first show how the peridynamic model is able to explain how cracks form in impact of a thin glass plate. The computational results are compared with those from experiments. Peridynamics captures all of the different types of crack systems seen in experiments, including some fine roughness on the surface of the Hertz cone-crack, when this crack turns and grows transversal through the plate thickness. Understanding how and why various cracks are initiated, and propagate in the brittle material can help us, in the future, understand how to control crack growth and design better protective systems.

In the second part of the thesis, an improved peridynamic model for FRCs is introduced. We test the model against a well-known experiment in which, under mixed-mode impact loading conditions, a crack reaches intersonic propagation speeds and generates a shock wave as it propagates. These characteristics of brittle fracture in unidirectional FRCs are

reproduced by our peridynamic model. Moreover, using a sufficiently small nonlocal region, the model captures the crack propagation speed measured in experiments. We explain why the crack starts propagating long after the first stress wave reaches the tip of the pre-crack. We also provide a critical assessment of other types of peridynamic models for FRCs proposed recently in the literature. In FRCs, the micro-structure and anisotropy lead to complicated stress/strain states that are further influenced by interactions between elastic waves and propagating cracks. We verify these models for wave propagation examples and then use them to model fracture and damage evolution and provide guidance on which models should be used and why.

Acknowledgements

I would like to thank many people for their support and guidance. I would like to thank my adviser Dr. Florin Bobaru for all his support, for his patience. He not only gave me lots of help of my research, also he let me know the top level of this research area, and lots of excellent researchers in this area.

I would also like to thank Dr. Ruqiang Feng, Dr. Joseph Turner, Dr. Petronela Radu and Dr. Chian-Fong Yen serving on my committee. Dr. Ruqiang Feng and Dr. Chian-Fong Yen, I would like to thank you for being the readers for my dissertation.

I gratefully acknowledge the financial support offered through research grants and contracts with ARL (project coordinator Dr. Chian-Fong Yen), ARO (program manager Dr. Asher Rubinstein), and AFOSR MURI Center for Material Failure Prediction through Peridynamics (Dr. David Stargel, Dr. Ali Sayir, and Dr. Fariba Fahroo). I would also thank Dr. Jian Yu and Dr. Chian-Fong Yen (both from the Army Research Laboratory) for performing the experiment described in Chapter 2.

Thanks to my parents, they always support me and encourage me anywhere and anytime.

I also need to thanks for my master advisor (Professor Shang Xinchun from University of Science and Technology Beijing), he is my first teacher in Mechanics. Thanks for my colleges from my lab (like Ziguang Chen and the other people) and other professors' labs (Ping Hu, Christopher Kube), they are always very patience with my questions, and very generous with their suggestions.

Thanks for my friends I knew here during the last few years. They made my life happier, and filled with good memories.

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1.1 Literature review

1.1.1 Literature review of intersonic crack propagation in composite materials

Failure patterns induced by impact on a glass plate are fascinating in their complexity, from a visual point of view. A number of experimental results on silica glass failure from impact are reviewed in (Walley, 2014). Different types of damage have been observed in glass. The Hertzian cone crack that forms is driven by the maximum tensile stress under quasi-static loading (see (Hertz, 1881)); circumferential cracks near the site of impact, sometimes called "band cracks" appear due to reinforcement between the Surface wave, propagating along the material's surface, and longitudinal of shear waves bouncing off of the back side of the impacted plate (see (Bowden & Field, 1964)). The damage front and fragmentation in tempered or untempered glass has been analyzed experimentally in, for example, (Jannotti, Ghatu , & Arun , 2015). Modeling efforts directed at capturing the complex waves and crack interactions that are produced when a glass plate is impacted by a projectile have failed, so far, to fully explain the reasons behind the complex failure patterns. Perhaps one of the most advanced, to date, modeling of failure in brittle ceramic plates from impact is the recent contribution in (Seagraves & Radovitzky, 2015).

1.1.2 Literature review of intersonic crack propagation in composite materials

The term “intersonic crack speed” denotes the crack tip speed which lies between the shear wave speed and longitudinal wave speed of a material. In this section we review the literature on experiments and modeling and simulation of intersonic crack propagation. It has been observed that interfacial crack tip speeds rapidly approached and exceed the shear wave speed of the more compliant material in a composite (Lambros and Rosakis 1995a,b). The loading and bond strength were such as to promote crack growth along the interface between the two dissimilar materials (PMMA-steel and PMMA-aluminum). Composite materials involve preferable crack paths in the form of weak planes of lower fracture toughness (inhomogeneous in terms of their fracture toughness). Intersonic crack growth happens in two-phase materials, and unidirectional fiber-reinforced composites are natural candidates for studying maximum permissible speeds of cracks in opening and shear modes.

The analytical value for the critical speed of mode II crack propagation in isotropic materials along a plane of elastic symmetry, at which intersonic crack growth is possible to be $2^{1/2}C_s$ (Broberg, 1999). Broberg developed a cohesive zone model to investigate model II crack propagation in orthotropic materials.

The first observation of intersonic crack propagation speed in fiber-reinforced composites was presented in (Coker & Rosakis, 2001). For asymmetric impact loading, the experiments revealed highly unstable and intersonic shear-dominated crack grow along the fibers. The crack propagation speed reached a region between the shear wave speed and longitudinal wave speeds of the composite.

In (Yu, Pandolfi, Ortiz, Coker, & Rosakis, 2002), the authors used an anisotropic cohesive model of fracture to simulate the Coker and Rosakis's experiment. Because in this work the cohesive zone method was used, the authors need to pre-define the region where damage may happen. This is one limitation of the cohesive-zone method. The double shock caused by the propagating crack is observed, the shock wave propagation speed is not compared with the experimental results. Moreover, the double shock of the near-tip is suggestive of intermittent frictional interactions between the crack flanks. These intermittent frictions agree with the experimentally observed hot spots. The observed and computed hot-spot structures agree both in geometry and in the magnitude of the temperature elevation. In this study, the shock wave propagation speed is not mentioned.

Contact and friction behind the crack tip are accounted in a finite deformation anisotropic visco-plastic model by finite element method to model dynamic crack propagation in fiber reinforced composites (Dwivedi & Espinosa, 2003). They showed two numerical examples, bimaterial crack extension test, and simulation of Coker and Rosakis experiment on unidirectional fiber-reinforced composite plate. They also use the cohesive zone method, and the damage region needs to be pre-defined. With this visco-plastic and friction model, the intersonic crack propagation in fiber reinforce composites is captured. The question is are visco-plasticity and friction essential in the intersonic crack propagation phenomenon? They do not address this question.

(Huang, Wang, Liu, & Rosakis, 1999) computed the crack propagation speed in composites. They show that shock wave resulting from the crack propagating at a higher speed than shear wave, are seen from the 30m/s and 40m/s impact velocity. The

simulation shows that very high friction in the crack surfaces has an effect on crack propagation. Increased friction reduced the crack speed after initiation, but the maximum crack speed at steady state remains unchanged. Increased friction smears the shock wave and increased its inclination with respect to a vertical direction. The increase in friction coefficient spreads the region of compressive stress over a large area in front of the crack tip.

The generalized interpolation material point method (GIMP) to simulate dynamic crack growth (Daphalapurkar & Lu, 2007), captures intersonic crack speed and the shock wave behind the crack tip. The micro crack ahead the main crack is observed in their simulation. A daughter-crack is formed ahead of the trialing mother-crack-tip. The material failure part of this paper also use the idea of cohesive zone, the potential damage zone needs to be pre-defined. They capture complex stress patterns corresponding to wave travelling over the trailing crack surfaces, which are not exactly comparable with experiment. Their suggestion is that, in the actual experiments, crack surface contact plays a role and it could even influence the shock wave trailing behind the crack tip.

Dynamic crack growth along a polymer composite-Homalite interface is shown in (Coker, Rosakis, & Needleman, 2003). Three experiments (different impact location, impact speed) are presented; the calculations are based on a cohesive surface formulation. In addition, their experimental observation of a mother-daughter crack mechanism allows a subsonic crack to evolve into an intersonic crack.

1.3 Thesis outline

The outline of this thesis is as follows:

- Chapter 2 – We show that the peridynamic model is able to explain how cracks form in impact of a thin glass plate. We will also compare the simulation results with experimental results. We will show the progression of cracking and damage in glass, and how different types of cracks are generated by stress waves.

- Chapter 3 –We develop an improved peridynamic model of fiber-reinforced composites and use it to simulate intersonic crack growth experimentally observed in asymmetrically loaded unidirectional fiber-reinforced composite plates. This peridynamic model is able to capture the splitting crack growth when the specimens is under asymmetric shock loading and the crack speed reaches intersonic values, which is between the shear and longitudinal wave speeds of the composite. The peridynamic results show the formation of a shock wave caused by the crack propagation very similar to that reported in the experiments.

- Chapter 4 – We briefly review the several peridynamic FRC models for a unidirectional fiber-reinforced composite lamina. Dynamic wave propagation is tested with different peridynamic FRC models. We choose these different models to verify which of these reproduces the intersonic crack propagation in FRC. We discuss the effect of these different peridynamic models for a homogenized composite on the crack pattern on FRC.

- Chapter 5 – We present conclusions and future work.

Chapter 2

Evolution of impact-generated fracture and fragment in a thin glass plate

Dynamic crack growth, as the initiation of material failure, remains a challenging problem after more than a century of research. The interaction between stress waves and propagating cracks is difficult to simulate because such interactions often lead to a variety of failure types, including diffuse damage, localized cracks, and fragmentation. Capturing all of this complex behavior is not a simple task. Peridynamics can capture well all of these failure modes. We consider small projectile impact (150m/s) on a thin glass plate with a polycarbonate plate as backup. We discuss how cracks are generated in the thin glass from impact. From the experiment, we observed a variety of types of cracks (e.g. Hertzian cone crack, first and second ring cracks, radial cracks, parallel cracks, boundary cracks and fine roughness on the transverse crack surface). The peridynamic model is capable of capturing the essential features of the physics of failure in a thin glass plate, including very fine details of the structure of cracks, their origin, and evolution.

2.1 Introduction

In the present work, we provide a detailed discussion of the evolution of failure and damage in a thin glass plate impacted by a small projectile. For this purpose we use a simple peridynamic model with a linear-elastic and brittle micro-scale constitutive relation (see (Hu, Wang, Yu, Yen, & Bobaru, 2013), (Bobaru, Ha, & Hu, 2012)). We