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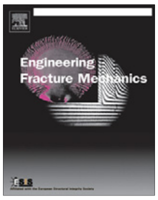

Crack initiation and path selection in brittle specimens: A novel experimental method and computations

O. Barkai [a], T. Menouillard [b,1], J.-H. Song [c], T. Belytschko [b], D. Sherman [a,*]

[a] *Department of Materials Engineering, Technion-Israel Institute of Technology, Haifa 32000, Israel*
[b] *Theoretical and Applied Mechanics, Northwestern University, Evanston, IL 60208-3111, USA*
[c] *Department of Civil and Environmental Engineering, University of South Carolina, Columbia, SC 2920, USA*

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ABSTRACT

We present a novel experimental method aiming at investigating aspects of dynamic crack propagation in brittle materials under in-plane, quasi-static, mixed mode loading. The method consists in gluing a precracked specimen into a rectangular hole in an aluminum frame using thin layers of epoxy resin. The driving force for crack initiation and propagation lies in the mismatch between the coefficients of thermal expansion (CTE) of the aluminum frame and the specimen, following modest heating of the assembly on an electrical heating stage. The main advantages of this method are in its avoidance of gripping problems and of the need to employ a complicated loading device. An important benefit of this method is the ability to analyze, numerically, the assembly containing the specimen as a boundary value problem by means of finite element analysis without any prior assumptions regarding the boundary conditions.

The method enables investigation of various aspects of dynamic crack propagation in brittle materials, including crack initiation, crack path selection criteria, and surface instabilities under a relatively low energy–speed regime. To validate the method's applicability, we first evaluated the fracture toughness, K_{IC}, of soda lime glass specimens. We then performed fracture experiments of slow and fast crack propagation in these specimens under combined tensile and shear stresses, which revealed the paths selected by the cracks. These paths were calculated using quasi-static finite element analysis (FEA), code Franc2D, and the dynamic eXtended FEA Method, using the criteria for crack path selection. It was found that the crack paths obeyed the law of local symmetry ($K_{II} = 0$) for both the quasi-static and dynamic crack propagation.

1. Introduction

Brittle materials are currently gaining increasing attention due to their use as the main building blocks in high-tech industries, such as in the production of solar cells, Micro-Optical-Electro-Mechanical-Systems (MOEMSs), Nano-Electro-Mechanical-System (NEMS) industries, and in-bio inspired devices. The exact way in which cracks in brittle materials initiate and propagate is considered relevant not only from a scientific point of view, but also for design and maintenance purposes, which have considerable economic importance.

Investigating crack propagation in brittle specimens is challenging due to the need to generate controlled deformation of only a few tens of microns on the boundary of the specimen in order to initiate and propagate the crack. Such boundary

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[*] Corresponding author.
E-mail address: dsherman@technion.ac.il (D. Sherman).
[1] Present address: STUCKY SA, Rue du Lac 33, 1020 Renens VD 1, Switzerland.

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conditions must be well defined if they are to be implemented as a boundary value problem for numerical analysis. Any deviations from the required deformation could lead to additional damaging mechanisms and energy dissipation that will be ignored or badly interpreted in the calculations, due to the high sensitivity of brittle materials to the fine details of loading.

The most challenging issue is that of how to grip brittle specimens while preventing undesired deformation and unexplained failure. Several methods for gripping and loading of brittle specimens when investigating crack propagation under quasi-static loading have been presented in the literature: fracture under bending [1,2], fracture of a compact specimen by introducing a wedge in a wide notch [3], mounting the specimen in a steel frame [4], and double cleavage drilled compression (DCDC) test method [5]. Thermal stress has been employed as the driving force for crack initiation and propagation, especially for MEMS devices [6].

The first objective of this study was to delineate and test a novel and simple method for gripping and loading precracked brittle specimens under mixed mode loading. The mismatch of the coefficients of thermal expansion (CTE) was exploited as the driving force for crack initiation and propagation. We fractured the soda lime glass specimens, representing a brittle and isotropic material, under both slow and intermediate crack speed regimes.

The second objective was to verify the ability of numerical methods and fracture laws to accurately predict the path selected by a crack in brittle isotropic materials subjected to quasi-static tensile and shear stresses. The theories that predict crack propagation are based on stress criteria or energy considerations: according to stress criteria, a crack will propagate so that the tensile stresses at the crack tip are either maximal or, alternatively, vanishing shear stresses [7]; while the energy criteria state that the crack will propagate so that the strain energy density is minimized, or the energy release rate is maximized [8]. The law of local symmetry states that a crack will propagate such that the shearing stress intensity factor (SIF) vanishes, i.e. $K_{II} = 0$ [9]. These laws have proven adequate for the prediction of slow cracks, such as fatigue cracks in metals, and static numerical simulations by the finite element analysis (FEA) have provided good predictions of the crack path obtained experimentally [10–12]. The ability to predict crack path selection for dynamic cracks under mixed mode loading with the appropriate criteria has also been shown [13–17].

We employed the quasi-static, linear elastic, and isotropic Franc2D FEA code, developed by Ingraffea and co-workers [10,12] to calculate the path selected by a slow crack, as this code is capable of efficiently analyzing quasi-static cracked bodies subjected to mixed mode loading with several crack path selection criteria under a single run. The eXtended FEA Method developed by Krysl and Belytschko [14] and Song et al. [18] was used to compute the path selected by a dynamic crack propagated in quasi-statically loaded specimens. This method allows the crack to propagate independently of the structure of the mesh, due to the use of enrichment functions, and thereby avoids re-meshing during propagation of the discontinuity [16,18–20]. The variant of the method used [18] is based on the technique of Hansbo and Hansbo [21]. The law of local symmetry, $K_{II} = 0$, was used for the simulations of the path selected by a fast crack with a cohesive law [18,22]. The numerical analyzes showed an excellent agreement with the experimentally-observed crack path.

2. The coefficients of thermal expansion mismatch (CTEM) method

2.1. The assembly

This novel experimental method consists of gluing a precracked rectangular and thin brittle specimen inside a rectangular hole in a 10 mm thick aluminum frame (Fig. 1a) using 150 μm thick layers of epoxy resin. Loading the specimen is achieved by applying controlled heating to the assembly on top of a heating stage. The mismatch between the coefficients of thermal expansion (CTE) of the aluminum and that of the brittle specimen generates tensile and shear deformation fields at the glued edges of the specimen, which serve as the driving force for crack initiation and propagation, as shown in Fig. 1b. The shear deformation field, like the tensile deformation, is generated by the mismatch of the CTE of the specimen and the loading frame in the x direction along the glued edges of the specimen: it is zero in the mid span ($x = 0$), and linearly increases towards the far edge points of the glued zone with opposite signs. This deformation is one of the unique advantages of our novel loading device: while being small compared to the tensile deformation, it generates sufficient mixed mode loading for investigating crack path selection in brittle materials.

We distinguish between two major types of precrack location that are responsible for two different modes: pure mode I is achieved when the precrack is located at the midline, i.e. $y = 0$ (point A in Fig. 1b); while in-plane mixed mode is achieved when the specimen is notched at $y > 0$ (point B, Fig. 1b), resulting in a curved crack path.

Atomistically-sharp precracks were introduced in the specimens by thermal shock. The specimens were first notched at the required position to a length of ∼2 mm using a 150 μm thick diamond saw, followed by heating the specimens to 100–150 °C and then their immersion in a shallow water reservoir. This ensured stress singularity at the precrack tip. For those materials with relatively low fracture toughness, the assembly provides sufficient driving force for initiation and propagation of the crack still under the elastic regime of the epoxy glue, and without any damage at the interface between the epoxy glue and the other constituents of the assembly.

The aluminum frame was machined such that a gap of 300 μm was left for the two thin epoxy resin (Epon 815C) layers that glued the specimen. After gluing, the assembly was kept in a controlled temperature chamber at 23 ± 0.1 °C for four days for curing. After curing, the assembly was placed on a heating stage, and the temperature was increased at a moderate rate of about 0.5 °C/min. This loading is slow enough to obtain an homogeneous temperature through the thickness of the glass