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Numerical and experimental approaches for the determination of two-parameter fracture mechanics in wedge splitting loading

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Abstract:

We have studied the stable crack propagation in Polymethyl methacrylate (PMMA) using a Wedge-splitting loading. A two-parameter fracture mechanics approach, describing the near-crack-tip stress field, was applied to determine the stress intensity factors K_I , K_{II} and the T-stress. The crack propagating is investigated quantitatively by both numerical modeling and experiment using Finite Element Method (FEM) and Digital Image Correlation (DIC). The computation of the parameters, K_I , K_{II} and T-stress, is carried out using the integral J method and compared with the result obtained by the Digital Image Correlation (Q4-DIC software). The stress intensity factors K_I , K_{II} and T-stress were estimated within 10% and 15% uncertainty. It is verified that in these experiments, the positive T-stress leads to an out-of-plane crack propagation satisfying $K_I=Cst$ and $K_{II}=0$.

Keywords: Digital Image Correlation, Finite Element Method, Stress intensity factor, T-stress

1 Introduction

In brittle or quasi brittle materials such as ceramics, rocks and glass, crack propagation is the fundamental mechanism leading to material failure. As such, its understanding and modeling have attracted much attention (*see. e.g. [1-3] for reviews in this topic*). In such materials, the fracture propagation is dominated by the near-tip stress field. The stress intensity factors K_I and K_{II} (singular stresses) gives the magnitude of the stress field ahead of a crack tip for each mode of fracture. Classically, the crack propagation conditions are given as a function of those factors: the path verifies $K_{II}=0$ and fracture propagates when a critical mode I stress intensity factor is reached. There are experimental evidences that the stress contributions acting at largest distance from the crack tip may affect fracture mechanics properties [4]. The constant stress contribution (first “higher-order” term of the Williams stress expansion, denoted as the T-stress term) is the next important parameter. It is well known that for crack growth under mode I loading (i.e., $K_{II} = 0$) the straight crack path is stable when $T < 0$ and unstable for $T > 0$ [5].

In the brittle or quasi-brittle materials, it is often difficult to determine the fracture mechanics parameters K_I , K_{II} and T-stress during the propagation of the crack due to the unstable character of fracture (dynamic fracture). To avoid this problem, we have developed an experimental set-up named the wedge-splitting tests (WST). With this test, the fracture propagates with a finite velocity [6-7]. In spite of its advantages, the fracture parameters for the WST are not widely reported. The purpose of this paper is to study, using both numerical and experimental approaches, the variation of stress intensity factors K_I , K_{II} or T-stress as function of crack path position. Digital Image Correlation (DIC) is used to follow the crack propagation. Based on displacements evaluation, crack tip position, stress intensity factor and T-stress are determined. Secondly, we performed a numerical analysis of near-crack-tip stress field using the Finite Element Method (ABAQUS 6.6 software) [8]. In the numerical approach, the wedge displacement load versus crack tip position data was used as boundary load conditions to calculate both stress intensity factors K_I , K_{II} and T-stress. Their values are compared with the result obtained by the Digital Image Correlation (Q4-DIC software) [9]. Finally, the performances of the two global approaches are compared and applied to the verification of the classical crack propagation criterions.

2 Experimental configuration

The experimental setup is shown in figure 1a and b. A vertical load is applied by means of a metallic wedge at the mouth of the notched sample. To minimize friction between wedge and lateral supports, two lines of rollers are used. During testing, the wedge pierces the sample and the crack generated at the tip of the notch propagates in stable way. The crack grows until it reaches the bottom of the sample, splitting it into halves [10].

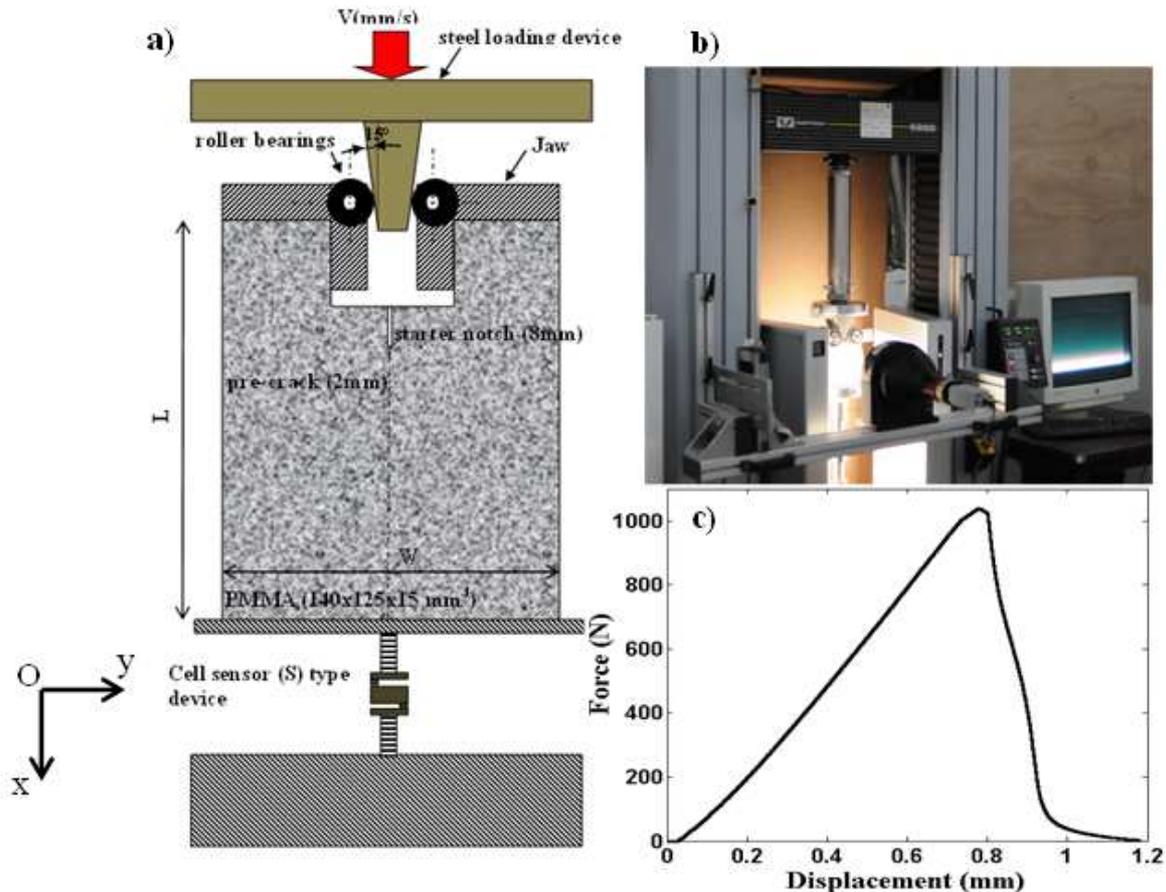


FIG. 1 – a) Experimental set-up of the Wedge Splitting loading. b) A telecentric lens is used to minimize artifacts induced by out-of-plane motions. c) Typical load- wedge displacement curve from PMMA fracture test.

The material used is Polymethyl methacrylate (PMMA) from Altuglas International (Perspex sheets). This material is brittle with a Young's modulus $E = 2800$ MPa and Poisson's ratio $\nu = 0.33$. The specimen is prepared from rectangular plates of length $L = 140$ mm, width $W = 125$ mm, and thickness $H = 15$ mm. A notch is machined i) by cutting out a $25 \times 25 \times 15$ mm³ parallelepiped from the middle of one of the $W \times H$ edges; ii) by subsequently adding a 8 mm long $800 \mu\text{m}$ thick groove with a diamond saw; and iii) by finally introducing a seed crack (~ 2 mm-long) with a razor blade. The test is conducted at room temperature (20°C), under displacement control at $1 \mu\text{m/s}$ using a testing machine of 1 kN capacity (Instron 5882).

The specimens exhibited a linear load-displacement diagram prior to fracture, confirming the predominantly linear elastic behavior of the material (FIG.1c). During the test, the surface of the sample is observed, with a CCD camera, (pixeLINK®, definition: 2500×1600 pixels, digitization: 8 bits) operating at 0.1 Hz and equipped with a telecentric objectif (GO Edmund, Techspec® gold series, Max distortion: 0.35%, telecentricity: $< 0.2^\circ$). For a realistic simulation, we need to obtain the typical wedge displacement-crack length curve from mechanical test and the crack path trajectory. These informations are directly measured from the location of crack tip via the camera using Digital Image Correlation (FIG. 2a and b).

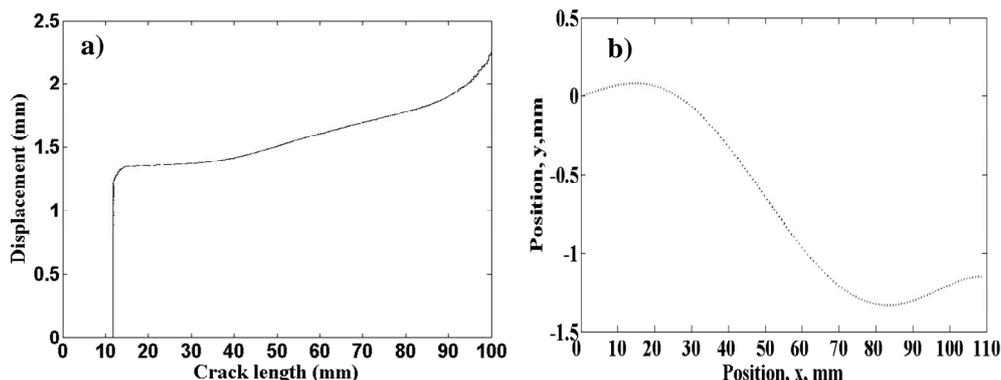


FIG. 2 – a) Displacement-crack length curve from PMMA fracture test, b) Crack path trajectory determined by DIC.

3 Finite element analysis (ABAQUS)

Two-dimensional linear elastic fracture mechanics is used to model the Wedge Splitting Test (WST) using a finite element method (ABAQUS 6.6 software). To be in agreement with the experimental conditions, the choice of plane-stress state conditions was assumed. The computation of the stress intensity factors and T-stress based on the domain integral J is carried out using six contours [8-11]. The loading wedge is modeled as rigid bodies. The specimen is loaded by applying a displacement to the wedge in the vertical direction using an experimental displacement versus crack length data in the loading boundary conditions and taking under consideration the crack path trajectory (*see Figure 2*).

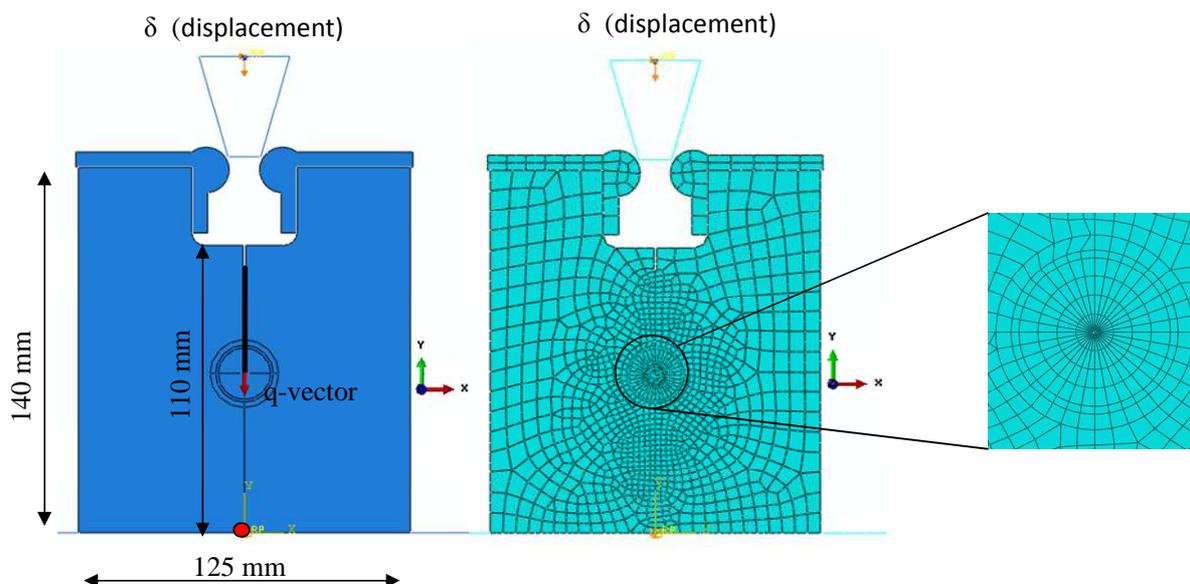


FIG. 3 – Partitioned two-dimensional Wedge Splitting Test and mesh strategy adopted around crack-tip.

All other motions of the wedge are restrained. Surface-to-surface contact with a finite-sliding formulation is defined between the wedge and the rolling specimens, on the one side, and the specimen and the support, on the other. We assume that the contact is frictionless. The partitioning of the geometry is defined by the circular lines centered on the crack tip (FIG.3); this partitioning strategy facilitates the generation of a focused mesh. The remaining portion of the model is free meshed using the “medial axis” meshing algorithm.

4 Digital Image Correlation Analysis (Q4-DIC)

Digital image correlation is a technique that allows to determine displacement fields separating two digital images of the same sample at different stages of loading. We summarize the main points here, for more information the reader shall refer for instance to [9]. The DIC procedure applied herein

consists in measuring displacement field discretized with quadratic Q4 elements. The elements size was chosen to be equal to 8 pixels. This value is a good compromise between measurement uncertainty and spatial resolution. Extracting some mechanically meaningful information using the detailed map of displacement can be performed by identifying the amplitudes of relevant reference displacement fields namely, William's series. This field $u=u_x+iu_y$ take the following expression in the crack frame (crack tip at the origin, and crack path along the negative x axis) resorting to the complex plane, $z=re^{i\theta}$

$$u(z) = \sum_n [\omega_n \Omega_n(z) + v_n \Psi_n(z)] \quad (1)$$

Where amplitudes ω_1 and v_1 , associated with field Ω_1 and Ψ_1 , are the mode I and II SIFs, K_I and K_{II} , respectively. Amplitudes ω_0 and v_0 correspond to rigid body translations. Amplitudes ω_2 and v_2 give access to the T-stress component, and the rigid body rotation. The crack-tip is located by canceling out amplitude ω_{-1} of the first supersingular field.

5 Results and discussion

Experimental results were obtained from the displacement fields obtained with a mesh size of 8 pixels (1 pixel \rightarrow 44.2 μm), over a region of interest of 2500 x 350 pixels (FIG. 4).

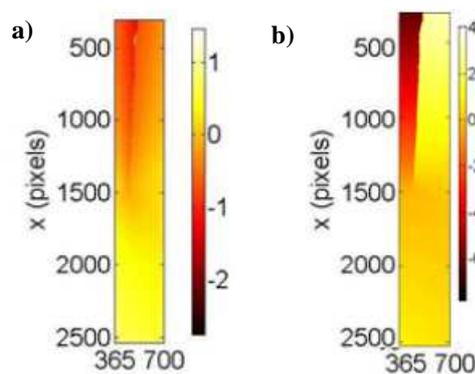


FIG. 4 – Horizontal (a) and vertical (b) component of the displacement field expressed in pixels as projected onto the basis of suited functions in post-processing of the measured displacement (1 pixel \rightarrow 44.2 μm).

From the amplitudes ω_n and v_n , it is possible to plot the SIFs and T-stress as function of crack length. In figure 5a and 5b, the SIFs obtained by DIC are shown together with the SIFs obtained by ABAQUS. In average the differences is 9%. For the DIC method, an error bar was estimated by extracting extreme positions of crack tip and measuring the corresponding change in K_I and K_{II} (average error bars were 11 %). For both methods, we found that K_I is constant from 40 mm to the end of sample, demonstrating that the crack propagation is stable (ie. The cracks propagates with a constant velocity), whereas K_{II} fluctuates around zero (FIG. 5b). Despite an average difference of 22 %, a good agreement is found in the case of the T-stress component when compared to the FE results. This difference is compensated by error bars (an average error bar were 15%) (FIG. 5c). Compared to the stress intensity factors, the error bar in the case of T-stress is higher because the T-stress is the coefficient of higher order terms of the displacement field expansions.

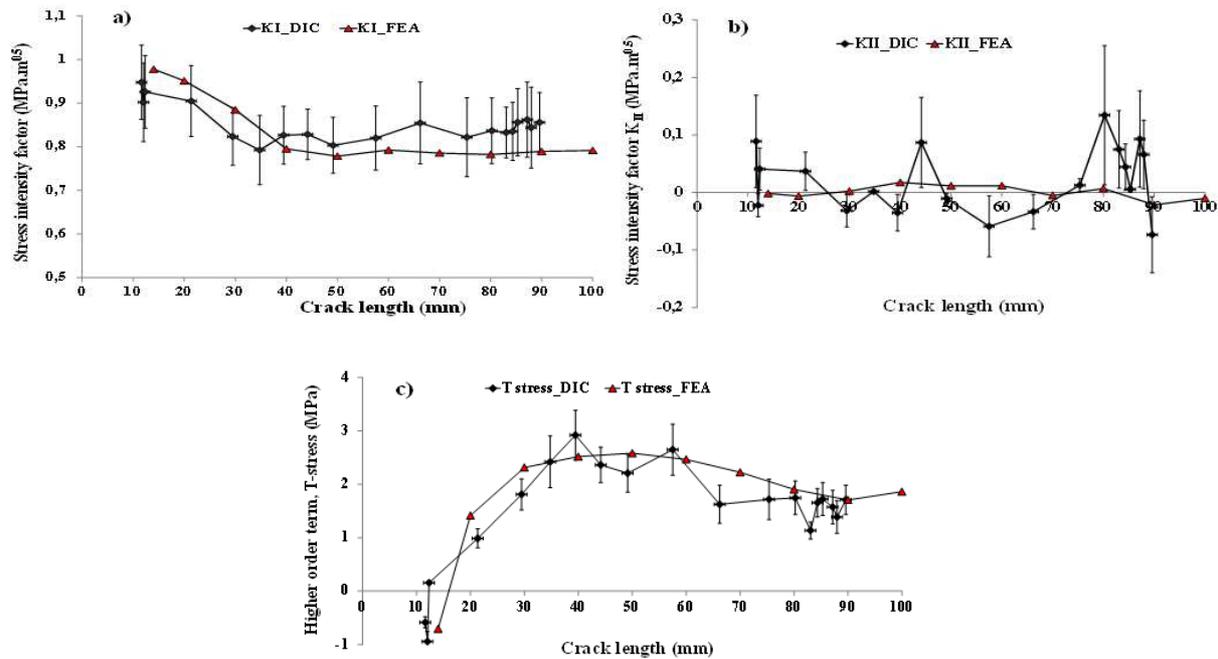


FIG. 5 – Comparison of (a)-(b) stress intensity factor, (c) T-stress determining using Finite Element Analysis and Digital Image correlation.

In both case, the T-stress varies from negative value for short cracks to positive value for crack lengths above 5 mm, contrary to the compact tension geometry, where T values are always positive [12].

Those measures confirms Irwin's criterion $K_I = K_c$ ($0.85 \pm 0.05 \text{ MPa m}^{0.5}$) during stable propagation and the Principle of Local Symmetry $K_{II} = 0$. It confirms also Cotterell and Rice crack path stability criterion. As soon the T-stress becomes positive, the crack path doesn't remain straight (FIG. 2b) and find another not straight path which satisfies nevertheless Irwin's criterion and the Principle of Local Symmetry. This is one more [13] experimental demonstration that this double criterion doesn't lead to a unique solution: the observed crack path is not the trivial straight one but another more stable bifurcated one.

6 Conclusions

In this study, we show that direct measurement of the crack tip displacement field is performed using Digital Image Correlation (Q4-DIC) which can be use to determine the stress intensity and the T stress. Good agreement is shown between this method and numerical modelisation. The stress intensity factor versus crack length remains constant whereas the T-stress varies from negative to positive. This later variation is different from the compact tension specimen, for which the T-term is always positive. Using Digital Image Correlation (DIC), the stress intensity factor and T stress were estimated with 10% and 15% uncertainty in a complex loading set-up without the need for a numerical modeling of the experiment. Our wedge splitting test is particularly attractive for fundamental research and model validation because of the enhanced length of stable crack propagation. This advantage allows us the identification of crack propagation parameters during all the propagation from one single test.

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