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Measuring Shear Fracture Toughness with a Modified Shear Test Specimen

ABSTRACT: Shear fracture toughness is an important material behavior that needs to be determined and considered in many industrial fields. At the same time, shear testing is one of the complex material testing areas where available methods are few, often need special arrangements and most of the methods do not strictly satisfy the definition of pure shear. In this study, a modified shear test specimen was proposed to measure the shear fracture toughness by uniaxial loading in a tensile testing machine. High Density Polyethylene (HDPE) was used as test material for the experiments. The specimen was created in order to suit the most common used tensile test machine. The specimen was then optimized by using Finite Element Analysis (FEA) to find the geometry and the size of the pre-notch to avoid the mixed mode loading and minimize effects of normal stresses. For the specimen in discussion, an upper and lower limit of usable ligament length can be found. Finally, a method for determining the fracture toughness was discussed according to the essential work of fracture.

KEYWORDS: shear test specimen, polymers, fracture toughness, finite element simulation

Introduction

Shear fracture toughness needs to be determined in many application areas. One of these is within package industries for manufacturing of bottle, jar, screw caps and tamper evident attachments where HDPE is one of the frequently used materials. For a rapid yet reliable package development process with (FEA), knowledge of detailed and accurate material property is crucial [1]. Investigation for any material properties such as elasticity, plasticity and mode I fracture response have been studied by many authors and are mostly found by tensile test of standard dogbone or rectangular specimen. On the contrary, fewer works can be found in testing for determination of shear continuum and fracture properties. Iosipescu and V Notched rail tests are most commonly used shear test procedures. These tests require additional fixtures [2-4]. This paper addressed to use a modified shear test specimen earlier

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developed by authors of this article [1] to find a method to determine the shear fracture toughness K_{IIC} . Previously, a similar shape of shear specimen was proposed by Banks-Sills et al [5] and modified by many authors, including Gao et al to be used for polymer material [6]. HDPE has excellent ductility and large work hardening that develops stable necking when undergoes plastic deformation [7]. This makes the shear testing difficult by contamination of normal loading prior to failure. Kwon and Jar used side grooved double edge notched (DEN) specimen to guide Iosipescu test of HDPE toward pure shear [8, 9].

The theory of Essential Work of Fracture (*EFW*) has recently been used to find the energy consumed to create new fracture surfaces [10-13]. Based on *EFW* concept, double edge notched tensile (DENT) test method is mostly used to determine mode I fracture toughness when necking in the fracture process zone is small [14]. The specific work of fracture (*SWF*) is extrapolated to zero ligament length in order to get the K_{IC} value. A range of usable ligament length in relation to the specimen width and thickness was found to be between $5t$ (t is thickness) and $3w$ (width) [10]. There is a debate on the range and some authors have claimed the maximum ligament length to be $2w$ [15]. However, in pure shear case the range differs depending on testing method. In standard Iosipescu tests, it was found that the minimum ligament length is same as thickness (t) but no study of maximum limit was not mentioned [8].

This study aimed to investigate the process to propose shear fracture toughness determination method for a modified shear test specimen by taking HDPE as an example. Based on shear testing specimens proposed by earlier authors [5, 6] a further modification of specimen geometry was done by means of intensive trial and error optimization of different shape parameters in numerical analysis. Specimen shape that has highest shear to tensile stress ratio without unwanted mixed mode loading or twisting was chosen that supported the experimental observation. This modified shear test specimen was then used successfully together with *EFW* theory for shear fracture toughness determination. Suitable ligament length range was proposed. The approach used was a combination of physical experiment and numerical simulation.

Experimental Method

The geometry of the modified shear specimen in this study is shown in Fig. 1. After an optimization study of the effect of notch distance, notch length, notch angle by experiment and complemented by numerical simulation, the geometry was proposed by the authors previously and modified further for this study [1]. Specimens were prepared both by CNC machine and high precision water jet from flat sheet of HDPE supplied by a packaging material manufacturer. CNC cut provided a better surface finish over the water jet cut. Different lengths of notches were cut in the specimens separately with the help of a sharp knife. The effective test specimen that can be imagined as cross section containing the notches [4] is referred to as Zone of Interest (ZOI) in later discussions. The rest part of the specimen acts to hold the ZOI in proper orientation to load it in shear. Thickness of the specimen was 1 mm and notches with length a , were with an angle of 30 degrees. For *EFW*

study, w is the specimen width and $w-2a$ is the ligament length L_0 [Fig. 2(b)]. Notches were cut get samples of specimens with ligament lengths of 1, 2, 3, 4 and 5 mm.

FIG. 1—Shear test specimen geometry. (a) Whole specimen, (b) Effective test specimen.

MTS universal testing machine was used for uniaxial loading of specimens. The specimen was vertically oriented and two ends (5 mm) were fixed with hydraulic grips. The load was applied by lifting up the upper grip at a speed of 10mm/min to induce tension. Finally, three repeatable force-displacement curves were obtained for each ligament length.

Finite Element Simulation and Essential Work of Fracture

The aim of the complementary simulation was both to check the usability of proposed specimen and reduce the number of tests required to perform the regression and extrapolation on SWF . The shear specimen with the exact geometry and dimension was constructed in commercial finite element analysis software Abaqus 6.13 [16]. The Material parameters were used from previous related publications [1, 15] that could replicate the experimental shear load displacement curve for this specimen. An elastic-plastic progressive damage constitutive model was used. A key material property during shear failure i.e. shear strain at failure was chosen as 0.75. Abaqus explicit was used for analysis that enables propagation of crack along notches. Solid element C3D8R 8 node brick was chosen with optimized mesh size. Boundary condition was same as physical testing.

In order to determine the fracture toughness, the theory of EWF has been applied. As described before, the method has been mostly used in mode I study of fracture. For example, for DENT test, the energy balance equation can be expressed as:

$$w_f^I = w_e^I + \beta_p^I w_p^I L_0 \quad (1)$$

Here, w_f^I is SWF , w_e^I is specific essential work of fracture, w_p^I is density of plastic work, L_0 is ligament length and β_p^I is shape factor of the plastic deformation zone. The superscript I indicates mode I fracture.

For determination of shear fracture toughness of HDPE, use of EWF was adopted earlier by Kwon and Jar [8, 9] with a standard Iosipescu test and they proposed a SWF expression as in

Eq 2. There are two shape factors, β , one depending on ligament length and another on thickness. Superscript II indicates shear deformation.

$$w_f^{II} = w_e^{II} + \beta_{p,L}^{II} w_{p,L}^{II} L_0 + \beta_{p,t}^{II} w_{p,t}^{II} t_0 \quad (2)$$

As it is pointed out by Shafiquel et al [1], the proposed shear specimen has a similar loading case compared to a standard Iosipescu test. Therefore, the same approach was adopted on this modified shear test specimen. Extrapolation of SWF (w_f) to zero ligament length gave an estimation of EWf . A second extrapolation was performed on EWf to zero thickness. It was a two point extrapolation using specimen thickness 0.5 and 1 mm. The first extrapolation eliminated specific energy consumption by ligament rotation and second excluded plastic deformation energy [8].

For EWf determination, numerical load-displacement was calculated for ligament length L_0 of 0.3, 1, 2, 3, 4 and 5 mm and thickness t of 1 and 0.5 mm. In the post processing of the test result and video, visual deformation and mode change was observed as well as relevant stress and area under stress-displacement curve i.e. SWF was calculated. Experimental SWF values for ligament length 1, 2, 3, 4 and 5 mm and thickness 1 mm was validated for finite element usability check.

Result and Discussion

Specimen deformation started with a pure shear loading in the ZOI but failure depended on notch length. When there was no notch or the notch was very small compared to the width ' w ', initial shear loading (mode II) shifted to a tensile loading (mode I) on the ligament and the specimen failed at overall large strain with significant necking. With the increase of notch length, this shift of mode started to reduce till a value of ' a/w ' when dominantly mode II loading and failure can be claimed. A set of deformations during the test is shown in Fig. 2,

FIG. 2—Deformation at different applied displacement in an ongoing tensile test of shear specimen with 0.5 mm notch.

Since the key observation was to find this threshold range value of the ligament ' $w-2a$ ', a series of simulation and experiments were performed with varying notch length ' a ' with fixed width ' w ' as well as varying thickness. Fig. 3 shows the force and displacement curves for

different notch length from the experiment. It was found that the notch length has a significant effect on mode change; generally a larger notch encourages greater shear stress than normal stress during at the onset of failure. Without notches or with very small notches, the specimen is initially also loaded in shear at small strain, but as the strain increases, ZOI rotates its orientation to have a mixed mode I and II fracture. Eventually, before failure, mode I dominates.

FIG. 3—Force vs Displacement response for experiment on different notch length.

Sharp mode change was visible for zero notch length as a wave in the force displacement response shown in Fig. 3. A same phenomenon was observed for very small notch length. The mode mix during loading was then examined by numerical simulation. Fig. 4 shows the partial view of the shift from mode II to the mixed mode of I and II in numerical simulation as the notch length is reduced to zero.

FIG. 4—Partial views of mode shift in FEM. To left 1 mm notch (no shift), to right without notch (shift).

Table 1 shows the changes of the mode of failure in numerical simulation. It had been defined by roughly comparing the tensile (σ_{22}) and shear stress (σ_{21}) components along the shear band connecting the notch tips. It can be found that the notch length had a significant influence to the fracture mode which confirmed the experiment results. It presents the trend of the effect of notch length on mode shift. The threshold ' L_0 ' was found to be above 1mm and below 4 mm when thickness was 1 mm.

TABLE 1—Numerical failure behavior at different ligament length ($t=1\text{mm}$).

L_0	1	1.5	2	3	4	5
Mode of failure	I+II	II	II	II	II	I+II
σ_{22} (MPa)	14	8.6	7	3	5	11
σ_{12} (MPa)	19	18	18	14.8	19	16

FIG. 5—Experimental specific work of fracture at different ligament length.

FIG. 6—Comparison of experimental (average) and numerical specific work of fracture at different L_0 .

SWF from experiment is shown in Fig. 5 and compared with that from numerical simulation in Fig. 6. A practice in mode I fracture is to consider the linear range of value to extrapolate for EWf [15]. When compared to Fig. 6, the stable range of ligament length usable for EWf determination is between 1 mm and 4 mm for 1 mm thick specimen (as this region shows a linear relation). Above and below this range induces mode mix which is also supported by the result presented in Table 1. Numerical simulation helped to get the SWF values for 0.5 mm thick specimens of the same range of L_0 as 1mm thick specimen and the results are shown together in Fig. 7.

FIG. 7—Specific work of fracture for different ligament lengths and thicknesses.

A probable reason for having an unsuitable range of ligament length for EWf determination in the proposed shear specimen is mode shift. The observation suggests the usable range to be $2t < L_0 < w/2$.

By extrapolation of ligament length, EWf for 1 mm thickness was 11 KJ/m² and for 0.5 mm thickness, 9.3 KJ/m². Secondary extrapolation to zero ligament thickness provided essential work of fracture without influence of ligament length and also thickness, which was 7.6 KJ/m².

A Linear Elastic Fracture Mechanics (LEFM) study of HDPE done on the modified shear specimen by Shafiquil et al proposed a geometry correction factor for stress intensity factor determination as Eq 3 [1].

$$g_{II} \left(\frac{a}{w} \right) = 1.291 \sin \left(1.033 \left(\frac{a}{w} \right) + 2.607 \right) + 0.1429 \sin \left(45.53 \left(\frac{a}{w} \right) - 5.742 \right) + 0.06811 \sin \left(75.49 \left(\frac{a}{w} \right) + 2.27 \right) \quad (3)$$

Essential work of fracture in LEFM is equal to J integral which is equivalent to energy release rate (G_{II}). It is related to stress intensity factor according to Eq 4.

$$J = G = \frac{K_{IIc}^2}{E} \quad (4)$$

Fracture toughness was predicted by this method based on physical experiment is between 6-10 KJ/m². This is comparable the prediction through *EWf*.

A PRACTICAL APPLICATION OF THE SHEAR SPECIMEN:

The proposed modified shear specimen was used for finding the ultimate shear strength of a special epoxy adhesive known as Controlled Delamination Material (CDM). An aluminium (Al) specimen was divided into two symmetric halves along ZOI and later joined together by CDM. With the application of DC volt to the conductive substrates, the CDM joint weakens. This phenomenon was tested and the ultimate shear strength reduction was observed.

FIG. 8—Examination of shear strength reduction in CDM. (a) The specimen, (b) Force-Displacement response.

Fig. 8(a) shows the partitioned specimen which was glued by CDM and Fig. 8(b) shows force-displacement response of tensile shear test on the glued specimen before and after electrifying (applying DC voltage). An alternative to measure this shear strength can be according to ASTM B769-11 [18].

Conclusions and Future Works

In this study, a method to measure the shear fracture toughness was introduced together with the shape of a suitable specimen. The proposed specimen shape has a limitation of mode shift from mode II to a mixed mode I + II as shown by simulations and experiments. A means of avoiding this by introduction of sharp notches within certain length limits was discussed. The essential work of fracture can be determined with stable ligament length in a range of 1mm to 4 mm for 1mm thickness of proposed specimen geometry, which roughly matches the shift

range from mode II to mixed mode I+II from numerical observations. It was also found that suitable ligament for *EWf* determination together with proposed specimen to be $2t < L_0 < w/2$. Fracture toughness was obtained by double extrapolation of the specific essential work of fracture within the ligament length range. The values were comparable with the fracture toughness obtained by a linear fracture mechanics study of HDPE. Finally, this specimen was used to find the shear adhesion strength of CDM joint in Al interface as a practical application.

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