Effect of Loading Rate on Cohesive Zone Law for Mode-I Loading Of Polycarbonate Sheet

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Abstract: The essential work of fracture concept is very popular to characterize the plane stress toughness of ductile material. The essential work characterizing the resistance of a structure to ductile fracture is important for many applications, from structural design to impact protection. The EWF approach is a means of separating the energy associated with fracture into two parts. One essential work of fracture (*We*) in its inner fracture process zone, and the plastic work (*Wp*) consumed by various deformation mechanisms in the outer plastic zone. In the present work test geometry, namely the double-edge notched tension (DEN-T) specimens, are used to evaluate the essential work of fracture for crack propagation. Also using the normalizing method proposed by Cotterell etal. (2005) to determine the traction separation law for plane stress condition of DEN-T specimens of Polycarbonate. The main objective of the work is to apply the well-developed concept of EWF to derive the cohesive stress-critical opening relationship. This relationship is generally known as cohesive law.

***Index Terms* – Fracture Mechanics, Fracture Toughness, Essential work of Fracture, Cohesive Zone Law, Polycarbonate.**

I. Introduction.

Fracture toughness is necessary to be found as a failure of engineering structures can occur for many reasons, including uncertainties in the loading or environment, flaws in the materials, lacks in Design, and deficiencies in construction or repairs. Often catastrophes occur because engineering structures contain cracks-arising either during fabrication or during service, and the consequences can be deadly. Failure has been witnessed in many of applications involving aeronautics, automobiles, bridges, and highways, and great damage has been done to human life and economics. Flaws in materials are obvious, and complex factors are often involved in the scope of the whole picture. The philosophies of mechanics for constant media break down when engineering structures contain flaws. Over the previous forty years, contributions have been made for the understanding of crack-related structural failures and various approaches were introduced to deal with the problems. The Strength of materials is lower than can be predictable from theoretical calculations because the applied stress is amplified by small internal defects, also known as Griffth cracks. These cracks act as stress concentrators. Fracture mechanics originates from this concept. It aims for a computable characterization if the conditions under which a load-bearing solid containing a sharp flaw will fail Material science looks into the microscopic composition and crystallographic defects of materials and provides us with understandings about the basics of crack formation and crack propagation. Fracture mechanics aims at studying the dynamic force on a macroscopic crack and the material's resistance to fracture.

A. Essential Work of Fracture

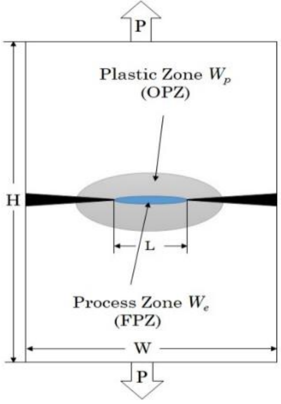
Fracture toughness of the material is determined by many methods like Crack Tip Opening Displacement method, J-Integral method, and EWF method. The EWF method is a newer concept introduced to find fracture toughness which was suggested by broberg[3]. In this approach, the crack tip is divided into end region where the fracture process takes place and other is outer process zone where the plastic zone formed on an outer region of crack. This method was first applied by B.Cotterell and J.K.Reddel[21]. In this method it is proposed that when previously cracked ductile solid, such as toughened polymer blend is being loaded the fracture process and plastic deformation takes place in two regions inner process zone or end region and outer process zone shown in [Fig 1] when crack propagates the amount of work dissipated in plastic zone is not related with fracture process but only the work is done in fracture process zone in material constant. This method is an experimental approach the total work of fracture (W_f) is divided into two parts:

1. Essential work of fracture (W_e),

2. Non-Essential work of fracture (W_p).

The essential work of fracture is work done in the end region and the non-essential work of fracture is energy dissipated in the creation of plastic zone. The total work of fracture is given by

$$W_f = W_e + W_p \qquad (1)$$



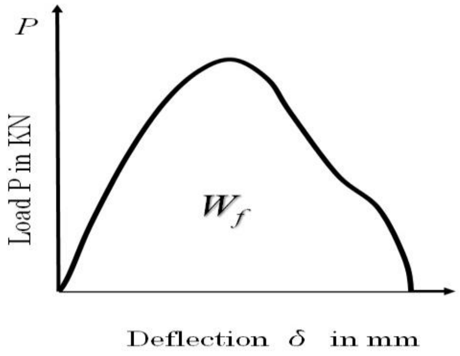


Figure 1.1: Schematic Diagram of Fracture Specimen

Figure 1.2: Load Displacement Curve of Fracture Specimen

A brief description of the technique is given here for a DEN-T specimen Fig. 1.1,where W is the width of the specimen, H the length of the specimen, L the ligament length, t the thickness of the specimen. The total work of fracture is calculated by the area of the load-displacement plot as shown in Fig.1.2, where P is the load, Δ is displacement. The essential work scales with the fractured area, while non essential work scales with the volume of the outer plastic deformation zone. For both metals and polymers, it has been seen that the volume of the outer plastic zone is proportional to L^2 , where L is the initial length of the ligament. Thus,

$$W_f = w_e L t + w_p \beta L^2 t \qquad (2)$$

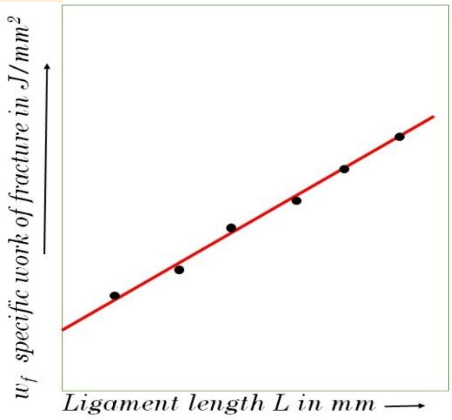


Figure 1.3: Data Reduction Method of the EWF

Where, β is a shape factor related to the shape of the outer plastic zone. The quantities we and wp are known as specific essential work of fracture and specific non essential work of fracture respectively. Normalising both sides by the initial ligament area Lt, we have

$$w_f = w_e + w_p L \qquad (3)$$

By performing several tests with different ligament lengths L, a plot of the total work of fracture, $w_f = W_f/Lt$, with ligament length L can be obtained, whose intercept is equal to w_e and slope to $w_p\beta$ as shown in Fig. 1.3.

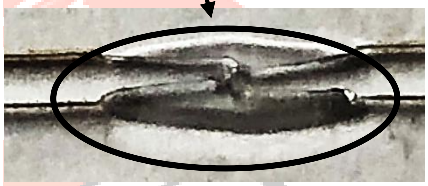
B. Cohesive Zone Model (CZM)

Cohesive zone (CZM) modeling is an emerging technology capable of simulating crack initiation and crack propagation with multiple crack locations in one model. The concept of CZM was first proposed by Barrenblatt in 1959 [22], to study perfectly brittle material and Dugdale in 1960 [23] to study yielding of thin ideal elastic-plastic steel sheets containing slits. CZMs have been used to simulate the fracture process in a number of material systems, including polymers [24],metallic materials [25], ceramic materials [26], bi-material systems in polymer matrix composites [27], metal matrix composites[28], and fiber reinforced plastic composites .They have been used to simulate fracture under static, dynamic, and cyclic loading conditions. It is not the purpose of this paper to review all of those models and applications, but to outline some of the key works relevant to the present study. Needleman was one of the first to use polynomial and exponential types of traction-separation equations to simulate particle debonding in metal matrices.Xu and Needleman further used the above models to study the void nucleation at the interface of particle and matrix material, fast crack growth in brittle material under dynamic loading, and dynamic crack growth along the interface of bi-materials. Tvergaard and Hutchinson used a trapezoidal shape of the traction-separation model to calculate the crack growth resistance in elastoplastic materials. Tvergaard used a quadratic traction-displacement equation to analyze interfaces. Camacho and Ortiz [26] employed a linear cohesive fracture model to propagate multiple cracks along arbitrary paths during impact damage in brittle materials. Geubelle et al. utilized a bilinear CZM to simulate spontaneous initiation and propagation of transverse matrix cracks and delamination fronts in thin composite plates subjected to low-velocity impact.

II. Experimental Work.

The polycarbonate material was supplied by Lexan polycarbonate of grade 9030 of 0.8 mm thickness and of 2440 x 1220 mm. From the sheet the DENT specimen as prepared of 150mm length and 30mm width. The specimen was notched by razor to produce Double Edge Notched Tension specimen as shown in Fig 2.1 with ligament ranging from 4mm to 9mm.Three to four test is carried out for single ligament length and at a various loading rate of 10, 20, 30, 40, 50 mm/min. The test was performed on Lloyd UTM of 5 Kn capacity. The machine has manual mechanical jaws. The machine is servo motor controlled. The material should be ductile as per requirement of EWF method. In literature mostly aluminum and polymer are used to apply EWF method. Polycarbonate is selected for present work as it is widely used in Automobile industry and structural component. The geometry of test specimens is taken as specified in ASTM B557M for the material property. The geometry of test specimen is taken as Double edge notch tension (DENT) for application of EWF method. DENT specimen is preferred as plane stress condition prevails owing to the collinear notches in specimen cut from thin sheets.

Figure 2.1: DENT Specimen Before and After Testing



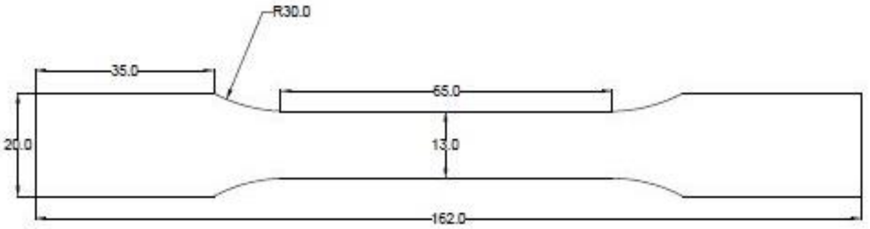


Figure 2.2: Dogbone Specimen

The primary objective of the tensile test is to determine the stress-strain behavior of a Polycarbonate material. Uniaxial tensile test performed to get material parameters such as ultimate strength, yield strength, elongation and Young's modulus. A flat specimen of the uniform cross section is pulled until it ruptures. The original cross-section area, gauge length is measured prior to conducting the test and applied load and gauge displacement are continuously measured throughout the test using comport based data acquisition. Based on the initial geometry of the sample, the engineering stress-strain curve can be easily generated from which numerous mechanical properties such as yield strength and elastic modulus, can be determined. A standard specimen as per ASTM B557 is prepared in a rectangular cross-section along the gauge length as shown in Fig.2.2 Both ends of the specimen have sufficient length and surface condition such that they are firmly gripped during testing.

III. Results and discussion

The load-displacement curve of dogbone specimen of polycarbonate is shown in the figure. 3.1 The polycarbonate exhibit to fail in the ductile manner the results obtained are as shown in table.3.1. The polycarbonate is found highly rate dependent.

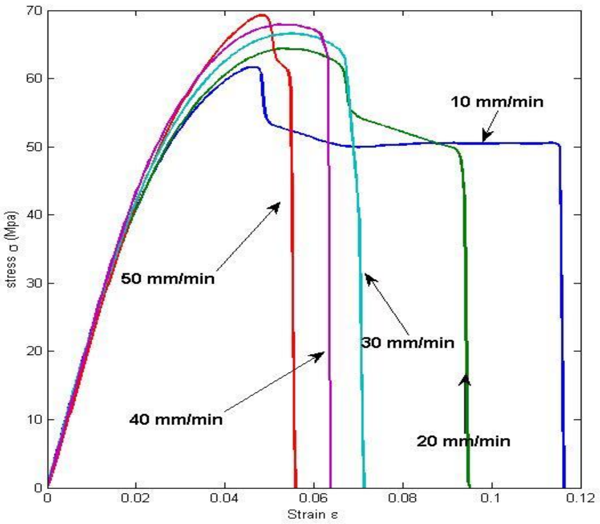


Figure 3.1: Stress-Strain Curve of Polycarbonate

Property	10 mm/min	20 mm/min	30 mm/min	40 mm/min	50 mm/min
σ_y	61.64	69.25	66.59	66.59	67.88
σ_{flow}	53.95	54.14	52.91	60.5	62.9
ε_y	0.048	0.047	0.054	0.060	0.052
$\varepsilon_{failure}$	0.11	0.094	0.071	0.066	0.055
E (Gpa)	2318	2337	2340	2348	2355

Table 3.1: Material Property at Different Loading Rate

The EWF tests on DENT specimens produced load displacement *(P-δ)* curves at various ligament lengths shown in the figure. The noteworthy feature of the curves it should be self-similar as shown in figure 3.2 and entire ligament should yield before crack initiation which is the basic requirement for applying EWF approach. For plain stress condition and to avoid nonlinearity the ligament length restriction following condition should be used $L \geq 3t - 5t$ and $L < W/3$[6]. Figure 3.5 shows plots of the specific total work of fracture w_f, which is calculated from the total area under the *(P-δ)* curves and related to the ligament area, versus ligament length, *L*

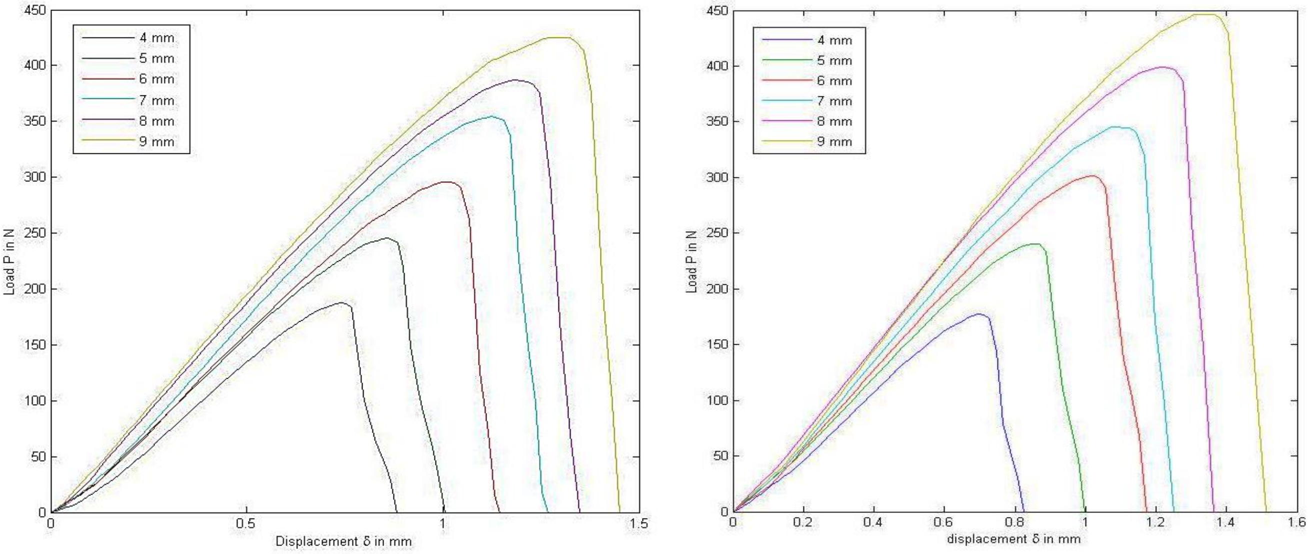


Figure 3.2: (Left) Load-displacement curve for 10 mm/min and (Right) Load-displacement curve for 20mm/min

A. Extraction of Traction Separation Law or Cohesive Zone Law from EWF Concept

This method has been suggested by Cotterell et al. (2005 the cohesive law relationship for the end region can be found by a normalization process [24]. Here, the elongation to fracture Δ_f be estimated for a DENT specimen as:

$$\Delta_f = \delta_c + \frac{\alpha^{\epsilon}}{2} L$$

where δ_c is identified with the opening across the end region at which separation occurs in a fully propagating crack and α^{ε} is the crack tip opening angle defined as the angle formed by the sides of a propagating end region. The crack opening can be found out by extrapolating straight line relationship between ultimate elongation and ligament length to zero ligaments as shown in figure 3.3. The value of δc are 0.388 mm, 0.399 mm, 0.377 mm, 0.376 mm, 0.39 mm for 10, 20, 30,40, 50 mm/min respectively 0.8mm thick polycarbonate sheet. A few other quantities need to be defined before we can formulate the traction-separation law. The nominal stress σ_{max} is defined as:

$$\sigma_{max} = \frac{p_{max}}{Lt}$$

Where P_{max} is the maximum load come across from the specimen. As the ligament length decreases the stress in the ligament becomes more uniform and in the limit of the ligament length tending to zero, tends to σ^0_{max}. The stress σ^0_{max} has been shown to be bounded by the necking stress for a power law hardening material. The σ^0_{max} can be found by extrapolating straight line relationship between maximum stress and ligament length to zero ligament as shown in figure 3.3.

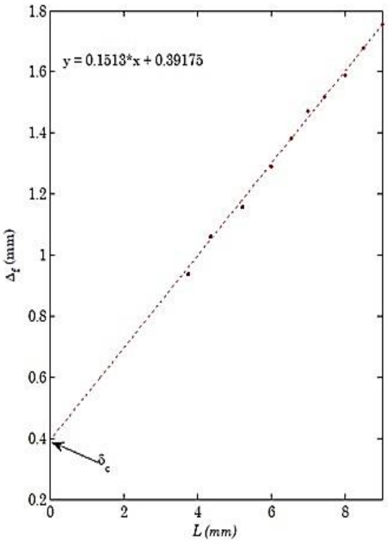


Figure 3.3 Ultimate Elongation V/s Ligament length

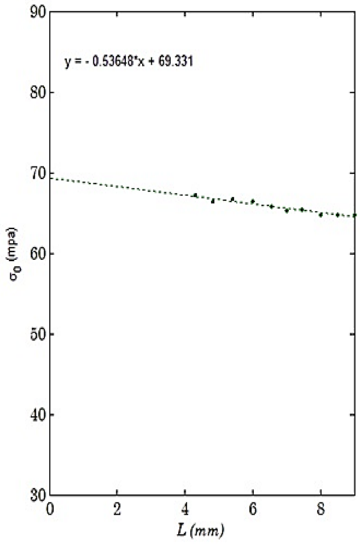


Figure 3.4 Maximum stress V/s Ligament length

The value obtained 63.02 Mpa, 62.8 Mpa, 62.71 Mpa, 71.0 Mpa, and 69.33 Mpa for 10, 20, 30, 40, 50 mm/min respectively for 0.8 mm thick polycarbonate sheet. The variation of the nominal opening stress $\sigma = P/Lt$ and the specimen elongation Δ, can be subjected to the following normalizations. From equation 4 and 5 the traction-separation can be derived.

$$\sigma_n = \frac{\sigma^0_{max}}{\sigma_{max}} \sigma \quad (4)$$

$$\Delta_n = \frac{\delta_c}{\Delta_f} \Delta \quad (5)$$

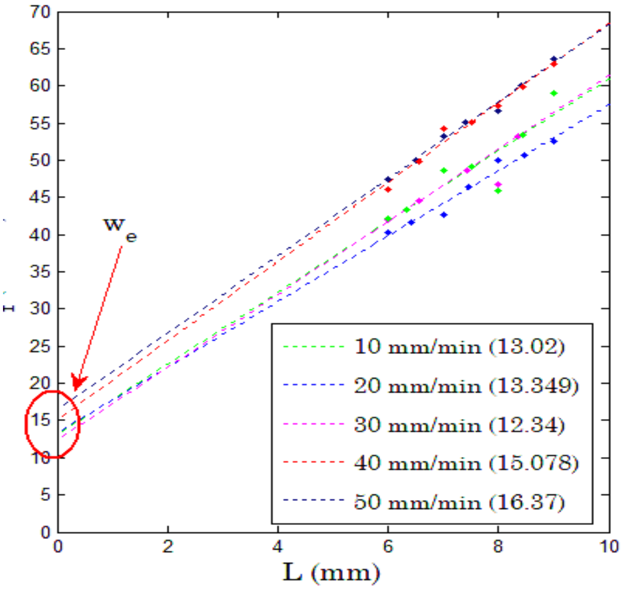


Figure 3.5: Specific work of fracture v/s ligament length.

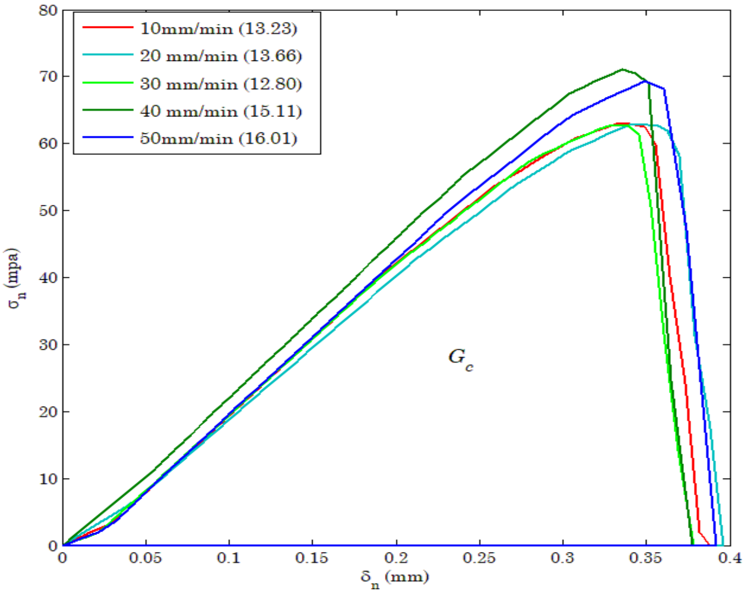


Figure 3.6: Normalize stress v/s Normalize displacement curve

IV. Conclusion.

The DENT specimen was used to find the cohesive zone law (G_c) and specific essential work of fracture (w_e) for the polycarbonate material. It specific essential work of fracture is 13.02, 13.34, 12.34, 15.07, 16.37 for 10mm/min, 20mm/min, 30mm/min, 40mm/min, 50mm/min respectively and The area covered by Traction separation curve are 13.23, 13.36, 12.80, 15.11, 16.01 which is nearly same as specific essential of fracture as said in literature.

It was found that the specific essential work of fracture and the cohesive energy is independent of loading rate for purely rate dependent material as the value are nearly same and the non-essential work of fracture is dependent on the loading rate.

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