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Effect of Nano-particles on Energy Release Rate in Mode I Fracture Using Corrected Beam Theory

Abstract

The main objective of this paper is evaluation of nano-particles effect on energy release rate in nano-composites mode I fracture. Nano-composite samples with woven glass fibers and alumina nanoparticle have been fabricated using VARTM process as co-cured and underwent Double Cantilever Beam tests according to ASTM D5528 standard. To calculate the energy release rate in Mode I fracture, corrected beam theory data reduction scheme has been utilized for different percentage of nano particles.

Key words: Nano-composite, Energy release rate, Mode I, Fracture.

1. Introduction

Critical strain energy release rate (G_C) is a measure of fracture energy and is alternatively called the toughness or fracture toughness. Although in isotropic material G_C is simply related to the critical stress intensity factor (K_C), their relationship is much more complicated for orthotropic materials. Whenever the plastic deformation at the crack tip is not small or the plane strain condition does not exist, which is the case in many structural components, other fracture parameters, such as the *J*-integral or crack opening displacement, can be used to study the fracture behavior [1]. The most applicable method used for the determination of interlayer fracture resistance of composites is the measurement of the strain energy release rate. Strain energy release rate (SERR) is constant when the crack growth resistance is independent of the crack length (α). In this case, the SERR is equal to the failure toughness, $G_{I,0}$ in Mode I. To determine $G_{I,0}$ under pure open loading (mode I), the double cantilever beam (DCB) test has been considered as a standard method (ISO 15024:2001 [2]; ASTM D5528-01 [3]). Ghabezi and Farahani [4, 5] have conducted an experimental study on bridging and cohesive mechanism of adhesive bonded joints including nano-composite and nano-adhesive for mode I fracture considering different approaches to calculate energy release rate. Alfano et al. [6] investigated the application of cohesive zone model (CZM) concepts to study mode I fracture in adhesive bonded joints. In particular, an intrinsic piece-wise linear cohesive surface relation was used in order to model fracture in a pre-cracked bonded double cantilever beam specimen. Finite element implementation of the CZM was accomplished by means of the user element (UEL) feature available in the FE commercial code ABAQUS. Yasser Zare [7] studied the roles of the dispersion/accumulation of nanoparticles and interphase condition on the tensile modulus and strength of polymer Nano composites by original or developed models and equations. The main focus is performed on the concentration, size and modulus of nanoparticles as well as the thickness, modulus and strength of interphase. Chaeichian et al. [8] synthesized a hybrid ternary system of thermoplastic /clay /thermoset to produce a tougher unsaturated polyester without reducing the glass transition temperature or the elastic modulus. Mixed mode fracture resistance of epoxy-based nano composites reinforced with carbon nanoparticles of three different shapes is studied by Shadlou et al. [9].

The present study includes an experimental study on energy release rate in mode I fracture growth in laminated nano composites. Polymer based nano composite samples with glass fibers and alumina nanoparticle has been fabricated and underwent DCB tests. In this study corrected beam theory (CBT) is used to calculate energy release rate values in different nano composite samples.

2. Materials

In this study, vacuum assisted resin transfer molding (VARTM [10, 11]) was used to fabricate experimental samples. The preform was comprised of six glass fiber layers (200g; 30×20cm), a layer of Dacron fabric strips, and a distribution layer. The selected polymer resin was comprised of two components mixed with the weight ratio of 12%: (1) epoxy-based EPH 1012, and (2) EPH 112 as hardener (E=2.73 GPa, σY=74.62 MPa). In this work, Alpha - alumina nanoparticles with 99% purity, average nanoparticle size (ASP) of ~80nm, and specific surface area (SSA) of smaller than 10m2/g (Notrino Company) is used.

3. Tests

To obtain mechanical specifications, tensile test was applied on different pieces. Results are presented in Table 1. A code (Code-X), in which X represents nanoparticle content of composite (%), is introduced to nominate Nano composite samples.

Table 1: Mechanical Properties of Nano-composites samples (ASTM D3039).

Sample	Nano Wt%	Tensile Strength (MPa)	Ultimate Strain %	Young Modulus (GPa)
Code-0	0	279.7	0.03	9.48
Code-0.2	0.2	289.4	0.031	9.33
Code-0.43	0.43	312.7	0.03	10.42
Code-1	1	308.9	0.033	9.36
Code-2.1	2.1	301.2	0.027	11.36
Code-4.1	4.1	297	0.027	11

ASTM D5528 is a testing specification that determines the opening Mode I interlaminar fracture toughness of continuous fiber-reinforced composite materials using the corrected beam theory (Figure 1).

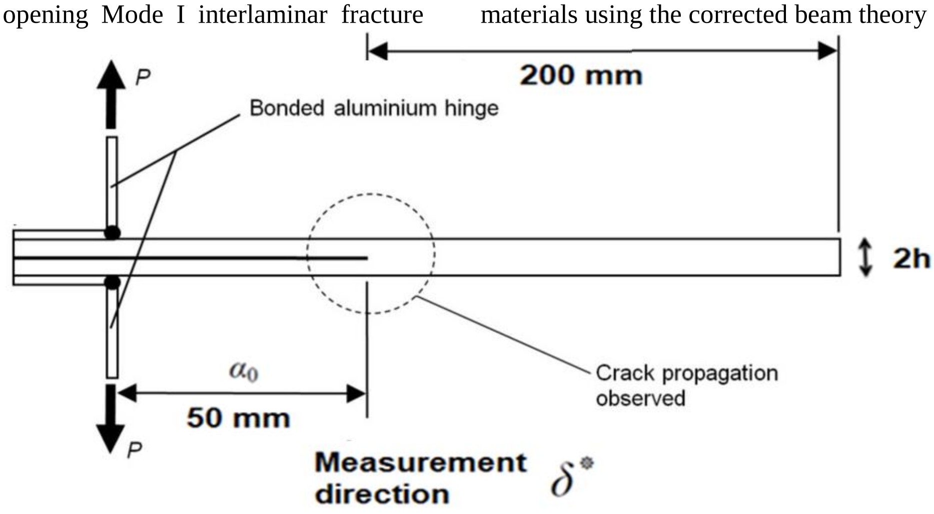


Figure 1: DCB test dimensions, 2h=4.5±1.0 and width=20mm.

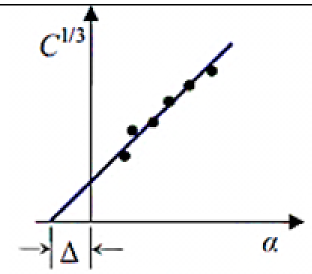
Tensile test was applied on DCB samples with the rate of 2mm/min. During each test, the force-displacement curve (P-δ) and relative displacement of pre-crack tip (δ*) were recorded as a function of time.

4. Experimental Results

The CBT method is proposed by ASTM D5528-01 standard. Table 2 explains the parameters required in data reduction methods for mode I fracture.

Where, |Δ| is the modification factor for the rotation of crack-tip, and is calculated by creating the linear regression of the cube root of the compliance (C1/3) based on the length of delamination.

Table 2: Parameters of Data Reduction Methods for Mode I.

CBT	
$G_I = \dfrac{3P\delta}{2b(\alpha + \lvert\Delta\rvert)}$	

The analysis of experimental results from DCB tests is done aiming to calculate two values, namely the mode-I critical fracture energy and initial fracture toughness (GI,0). In this study, CBT data reduction method for mode I was used to create the corresponding R-curve in Mode I. The force-displacement curves of DCB samples with different nanoparticle wt% are presented in Figure 2.

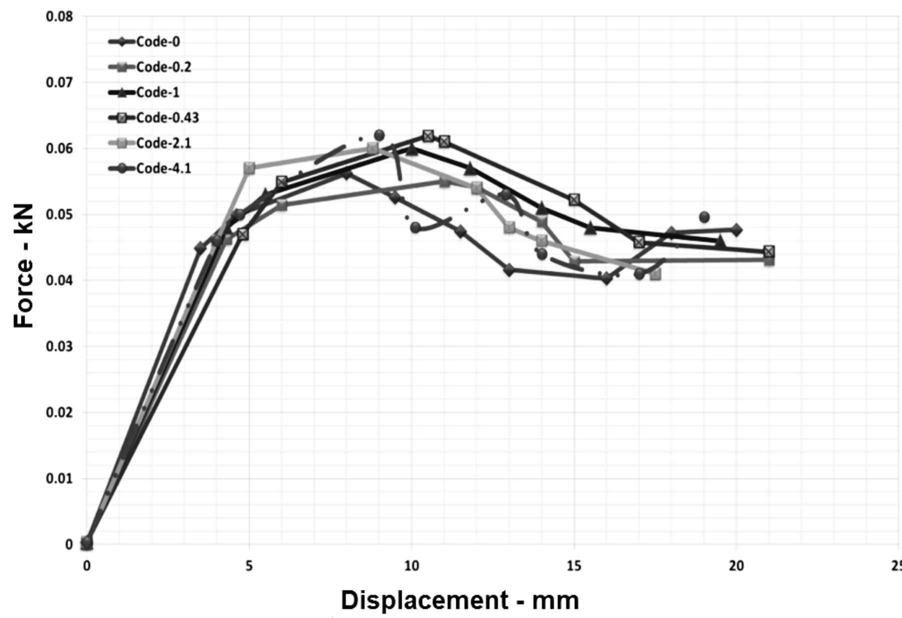


Figure 2: Applied force Vs. Displacement for DCB tests.

All experimental curves show an initial linear behavior that followed by a non-linear behavior indicating the initiation of the crack growth. When it reached maximum loading value, the slope of the force-displacement curve became mild with delamination progress. Specimens do not exhibit any drop of the load after a certain maximum load level, this seems to enter into a steady-state condition. The compliance C must be calculated to use in the ERR values. The ratio Ci = δi/Pi has been used directly for the calculation of the compliance for each value of αi. It is observed that the compliance of all tested specimens increases together with the cubic power of the crack length, without important changes in the slope. Hence, a linear regression based on the least square method was performed over the discrete C – α3 data sets from each DCB tests (Figure 3).

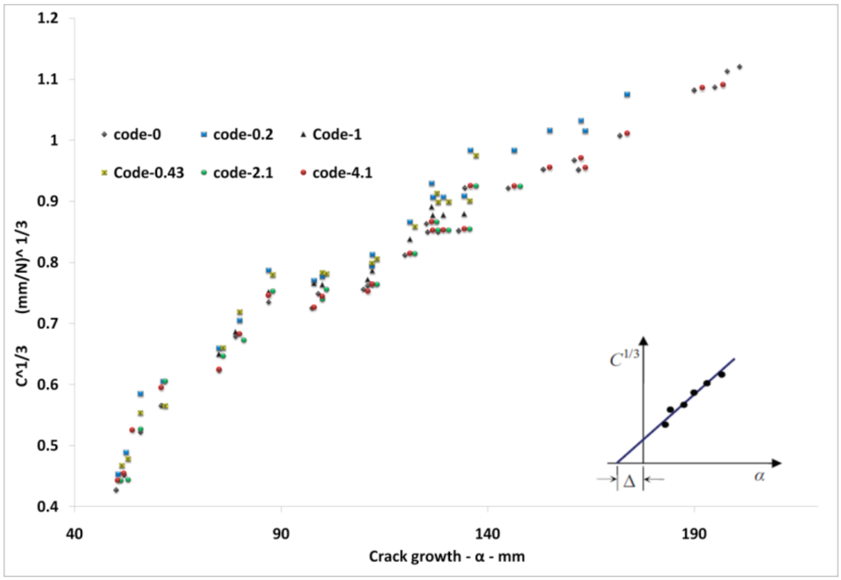


Figure 3: C – α3 data sets for DCB tests.

Figures 4 shows R-curves obtained with CBT method related to DCB tests. The GI increases with the growth of crack, which indicates the presence of a fiber bridging mechanism. After a certain crack length, it seems that GI converges towards a mean value (steady state fracture toughness, GI,SS).

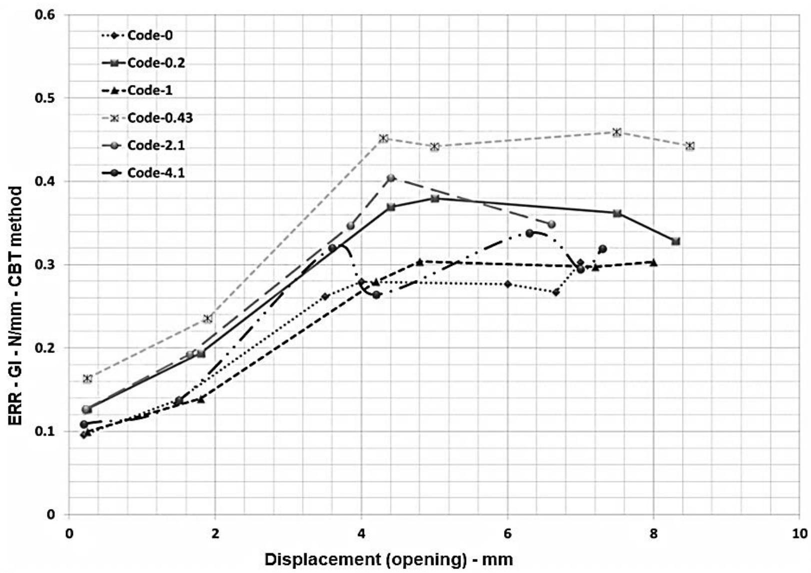


Figure 4: ERR Vs. δ* for CBT Method.

5. Discussion and Conclusion

In this paper effect of adding nanoparticles to epoxy composite laminates is evaluated in terms of mode I fracture resistance. A glance at the Figure 5 reveals that the calculated initial slope of the GI curves (GI,0) by CBT method for the sample with 0.43% nano-alumina particle has highest value, somewhere n the vicinity of 0.13 N/mm, whereas the code-0 presents the minimum initial energy release rate, just above 0.06 N/mm. In general, adding nanoparticle to composite materials soars GI,0 up to a certain value and then gives rise to a decrease in this feature. Given the right column chart in figure 5, the samples with 0.2%, 1%, 2.1% and 4.1% wt approximately present the same value for steady energy release rate, GI,SS, calculated by CBT method (0.5 N/mm), while the code-0.43sample has the highest value (about 0.65 N/mm).

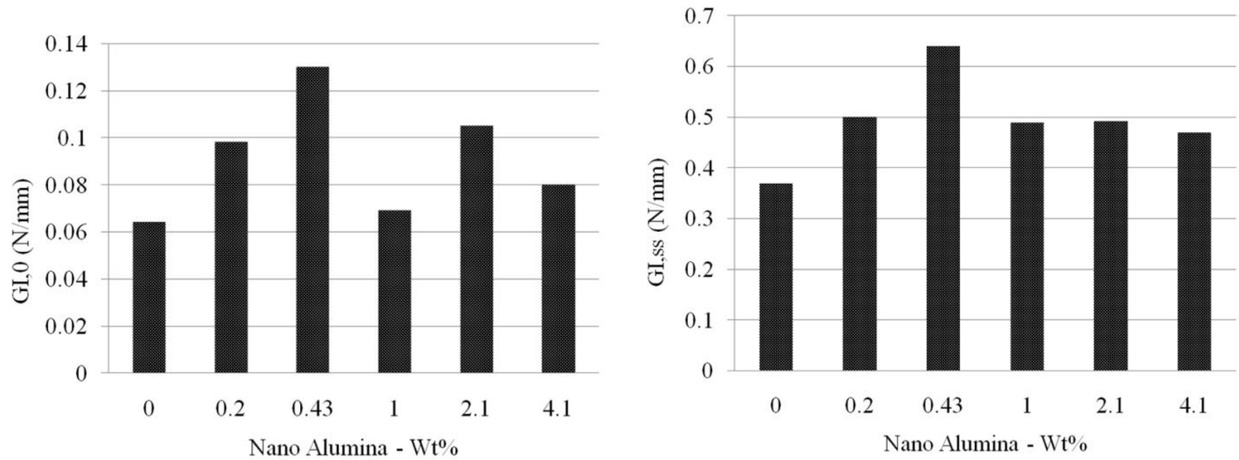


Figure 5: Energy release rate parameters.

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