MATTER: International Journal of Science and Technology
ISSN 2454-5880

Mahmoud Nadim Nahas, 2018

Volume 4 Issue 2, pp. 63-73

Date of Publication: 23rd August 2018

DOI-https://dx.doi.org/10.20319/mijst.2018.42.6373

This paper can be cited as: Nahas, M. N. (2018). The Fracture Behavior of Random Fiber-Reinforced Composite Specimens. MATTER: International Journal of Science and Technology, 4(2),63-73.

THE FRACTURE BEHAVIOR OF RANDOM FIBER-REINFORCED COMPOSITE SPECIMENS

Mahmoud Nadim Nahas
Professor, Mechanical Engineering Department, King Abdulaziz University, Jeddah, Saudi Arabia
mnahas@kau.edu.sa

Abstract

An experimental investigation of the fracture behavior of random fiber-reinforced composites has been carried out using tension tests. The crack opening displacement (COD) was measured continuously with the applied load. The load-COD curves were used to draw the R-curves (crack growth resistance curves). Using the resulted R-curves, few analytical relationships have been obtained. From these relationships, the fracture toughness has been predicted. The present work gives a better understanding of the crack resistance characteristics of randomly distributed fiber composites.

Keywords

Composites; Fracture; R-Curve; Toughness; Crack Opening Displacement; COD

1. Introduction

In the design of mechanical parts it is not enough to take into account the conventional requirements of static strength, static stiffness and the buckling stability of the undamaged parts, but it is necessary to consider also the effect of cracks and other damage.

The latter requirement has lead to the known design philosophy of “fail-safe” or “damage tolerance” concept. This concept allows for “damaged” parts, but the safety of the part is guaranteed by designing the part by such a way that slow crack growth is tolerated. It has to be demonstrated, however, that the crack growth rate remains sufficiently low for the part to be safe until the next scheduled inspection, during which the damage can be detected and repaired. It is, therefore, of a prime importance to study the crack propagation characteristics of materials.

The fiber-reinforced composite materials have been used extensively in mechanical parts. This has led to many investigations to study the fracture behavior of composite materials in order to provide designers with better insight into the fracture resistance and crack growth mechanism of these materials to arrive at "fail safe" design of parts.

There have been many recent papers addressing different problems in fracture of composite materials. Abdel-Wahab et al. (2004), for instance, applied the finite element method to predict the fatigue crack propagation lifetime in composite bonded joints. Van den Heuvel et al. (2004) studied the failure phenomena in fiber-reinforced composites. Fracture behavior of glass fiber reinforced polymer composite was studied by Avci et al. (2004). Interlaminar fracture was studied by Pereira et al. (2004), Li et al. (2004) and Pereira and de Morais (2004). Fox et al. (2004) investigated the failure mechanism in aged composites. Unstable crack advance across a regular array of short fibers in brittle matrix was studied by Qiao and Kong (2004), while Belmonte et al. (2004) studied physically-based model for the notched strength of woven laminates. Other studies also discussed different problems related to fracture of composites (Whitney et al. 2004; Yukalov et al. 2004; Ge et al. 2004; van Mier et al. 2002; Baxter et al. 2001; Rodriguez et al. 2000). Benrahou et al. (2007) used finite element method to estimate the plastic zone under mixed mode loading. Delamination was Investigated by Choupani (2008), and Zemcik and Las (2008), while Naghipour and Bartsch (2009) studied the effect of fiber angle orientation and stacking sequence on fracture toughness of carbon fiber reinforced plastics. Mixed mode fracture behaviour of woven laminated composites was investigated by Nikbakht and Choupani (2009), while Gouda et al. (2011) studied fracture toughness of glass-carbon (0/90)s fiber reinforced polymer composite. Lately, Shameli and Choupani (2016) investigated the fracture criterion of woven glass-epoxy composites. An overview of the subject is given by Rizov (2012).

This paper is a contribution to the understanding of the crack resistance characteristics of randomly distributed fiber composites. The paper starts by describing the experimental procedure used. It, then, presents the experimental results, and finally discusses the results fairly deeply.

2. Experimental Procedure

A total of eight different tensile-strip specimens were tested in this investigation under dry conditions. The specimens are all of length L = 400 mm, width w = 40 mm, and thickness t = 4 mm. The specimens were prepared using four layers of glass-fiber in chopped strand mat form and polyester resin. Glass fiber end tabs were bonded to the specimens to provide stronger sections for the grips of the testing machine. The remaining un-reinforced length is 280 mm. A single edge notch (or crack-like slit) of length a_o was made at mid-span of each specimen using a thin-blade saw. Figure 1 shows the test specimen.

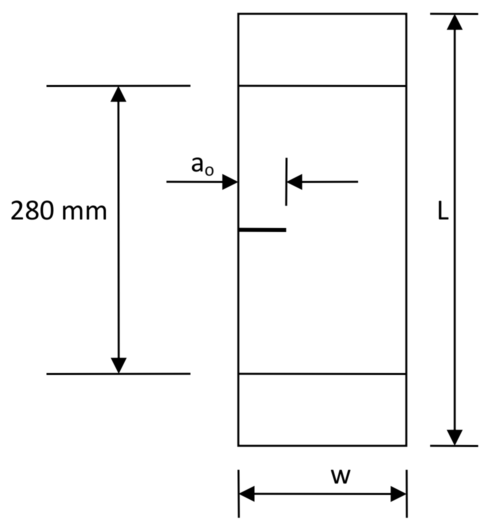

Figure 1: *Test specimen*

The relative crack length, or as called the aspect ratio (notch length to specimen width, a_o/w) ranged from 0.2 to 0.55, in increment of 0.05.

A double-cantilever-beam clip gauge was used to measure the crack opening displacement (COD) as recommended by the American Society for Testing and Materials (ASTM) for fracture testing. The clip was mounted across the mouth of the notch on one face of the specimen. The linear range of the clip gauge was far greater than the largest displacement recorded in the experiments (see Liu and Wu, 1997).

The specimens were tested in tension to failure in a standard hydraulic testing machine. To minimize any dynamic effect the load was applied slowly at a constant cross-head movement rate of 1 mm/min. The applied load and COD were continuously recorded during the test of each specimen using an X-Y recorder.

3. Experimental Results

The load-COD traces obtained for the specimens are shown in Figure 2. In general, the specimens exhibited nearly linear response to a certain load level after which the response became non-linear where the crack growth became faster prior to catastrophic fracture.

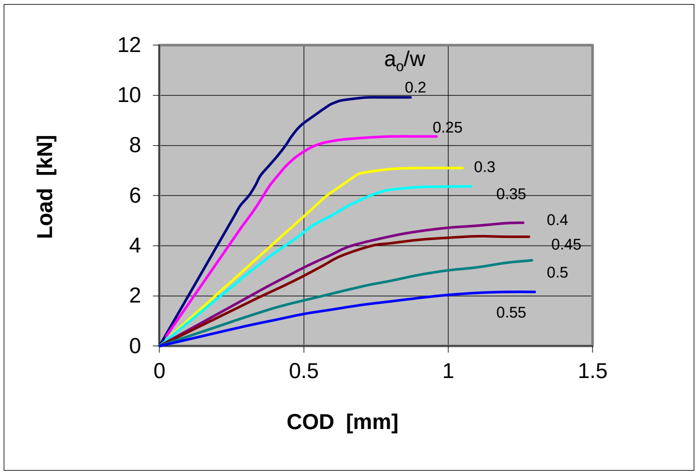

Figure 2: *Load-COD curves*

The specimens under consideration did not show obvious crack growth that usually seen in metals. Hence, a compliance matching technique to get the effective crack length at an arbitrary load was used.

The compliance, c, for the linear portion of the load-COD response is the inverse of the slope of the straight line, while at any other point in the load-COD response is the inverse of the slope of the secant line (i.e. the line between the origin and the concerned point). However, the values obtained are multiplied by the specimen thickness to eliminate any variation due to this parameter. Figure 3 shows the results of the initial and final compliance versus a_o/w.

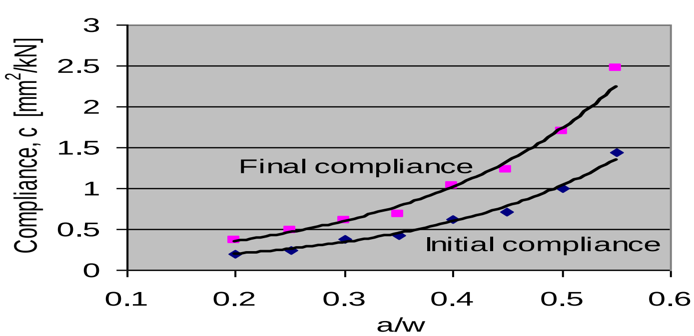

Figure 3: *Initial and final compliance*

Using the initial and final compliance curves the effective crack length was obtained. This was done by measuring the horizontal distance between the final and initial compliance curves corresponding to the concerned value of the aspect ratio (a/w) by locating it on the final compliance curve.

4. Discussion

The load-COD curves shows that the increase in the crack length leads to reduction in the maximum load achieved before to the beginning of crack propagation. The load firstly rises linearly with the displacement in all the specimens. This belongs to the phase in which the specimens largely have elastic stresses. Followed by this period, the crack propagation takes place. This is echoed in the nonlinear increase in the load with COD. The specimens show a sharp, but constant fall in the load with increase in the COD. Such performance is realized in specimens with lesser crack lengths. This obviously indicates steady propagation of the crack front. However, specimens of higher crack dimension do not show such sharp load decrease. Instead, these specimens show almost saturation in the variation of load with displacement.

To describe the resistance to fracture, R-curves were drawn (see Xi and Bazant, 1997). An R-curve is a graph of crack-growth resistance, K_R, as it varies with the effective crack length.

The crack growth resistance, K_R, is computed from the typical stress-intensity factor formula, i.e. Eq. (1) that follows:

$$K_I = \frac{P}{wt} a^{1/2} f(a/w) \tag{1}$$

with P being the load, a is the effective crack length at the load P, and f(a/w) is called the shape factor of the geometry of crack, which is a specific function of the relative crack length. For the present specimens, which are single-edge-cracked plates in tension f(a/w) is specified by Eq. (2) (see Brown and Srawley, 1969):

$$f(a/w) = 1.99 - 0.41(a/w) + 18.70(a/w)^2 - 38.48(a/w)^3 + 53.85(a/w)^4 \tag{2}$$

Figure 4 shows the R-curves, which indicates that the first slopes of the R-curves are huge. However, later, the composite fracture shape appears to be matrix cracking only, seemingly due to weak bonding, where merely a small maximum resistance is attained. Near the end, however, fiber failure happens.

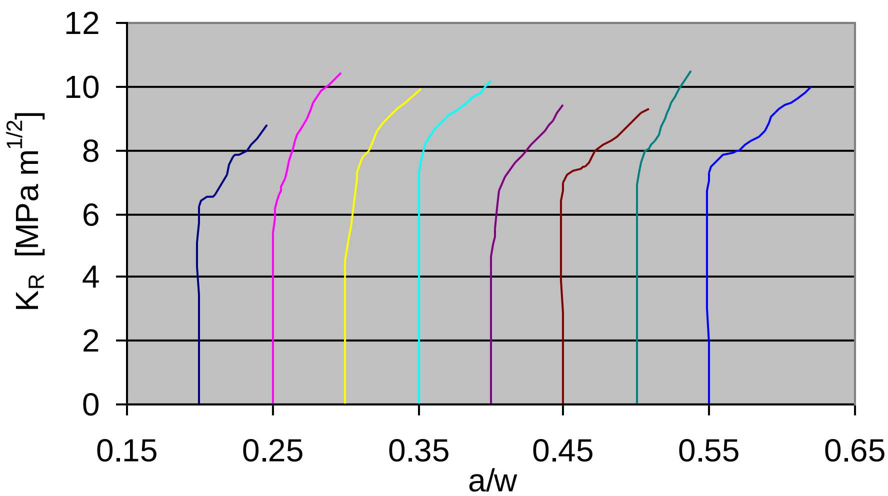

Figure 4: *R-curves*

Figure 4 gives the observed crack resistance as functions to the relative crack length. In this figure, the data of each line shows the results obtained from a single crack, from which it can be seen that the crack resistance of each increases progressively with the propagation of crack, with some deviations between the forms and the positions of the measured R-curves. Other authors have also noticed these scatters in the crack resistance. Obviously, this makes it difficult and irrational to fit the data of Figure 4 to one curve.

Therefore, it is proposed here to fit the non-linear part of the experimental data of each separate crack using an exponential function as in Eq. (3):

$$K_R = A - Be^{(-a/C)} \quad (3)$$

where A, B and C are modifiable factors.

The best-fit values of the modifiable factors included in Eq. (3) are calculated by iterative regression while minimizing the total variance. Although Eq. (3) represents good fits to the measured data (for each crack), however, the best-fit values of the factors, A, B and C in Eq. (3) are not the same for all the cracks. This illustrates that the measured R-curve behavior depends on the crack location.

The R-curve performance for a specific material can be established merely by the following three parameters:

a) the stress intensity for the crack initiation (i.e. the beginning of crack resistance), K_{th},

b) the stress intensity of the critical crack resistance, K_C, and

c) the tolerance of the crack, Δa*, which is the difference between the length of the crack at the critical stage and the initial status.

These three parameters were established as follows.

Rewriting Eq. (3) as follows:

$$K_R = A - Be^{(-ao/C)}e^{(-\Delta a/C)} \quad (4)$$

Here, $\Delta a = a - a_0$, where a is the length of the crack measured after any loading–unloading cycle. The K_{th}, also called the threshold crack resistance, is obtained when Δa = 0 in Eq. (4). The average value for K_{th} for the present specimens is calculated as 5.98 MPa $m^{1/2}$ with a standard deviation of 1.32 MPa $m^{1/2}$.

The fracture mechanics analysis is then used to determine the crack tolerance, Δa*. The unstable crack growth occurs by satisfying the following two conditions, Eq. (5) and Eq. (6):

$$K_I = K_R \quad (5)$$

$$\frac{dk_I}{da} \geq \frac{dK_R}{da} \quad (6)$$

Using Eq. (1) and Eq. (3) into Eq. (5) and Eq. (6), the following equations are obtained:

$$\frac{P}{wt}\sqrt{a*}\,f(a/w) = A - Be^{(-a*/C)} \quad (7)$$

$$\frac{1}{2}\frac{P}{wt}\sqrt{\frac{1}{a*}}\,f(a/w) = \frac{B}{C}e^{(-a*/C)} \quad (8)$$

where a* is the crack length of the critical state.

After calculating a* for each crack, the crack tolerance, $\Delta a^* = a^* - a_0$ is calculated. The results showed that Δa* varies from one specimen to another, indicating dependency of Δa* on the crack position.

This dependency of crack tolerance is understood from the effect of inhomogeneity of the microstructure on crack resistance. This was also reported by Gong and Guan (2000) who studied crack of hot pressed Si3N4.

The K_C, intensity of the critical crack resistance, can be determined by putting a=a* in Eq. (1) or Eq. (3). The average value for K_C is found to be 9.81 MPa $m^{1/2}$ with a standard deviation of 0.59 MPa $m^{1/2}$.

5. Conclusions

Crack propagation can be simulated and expressed in terms of R-curve. The influences of the stress intensity for the crack initiation, K_{th}, critical crack resistance K_C, and tolerance of the crack, Δa*, on R-curve were studied and found to be dependent on the crack position. The behavior of the measured R-curve with crack growth shows dependency on crack locality. The main cause of this dependency is the distribution of the fiber within the composite material in consideration, which is randomly distributed. The measured R-curve for each crack is described here by an exponential function.

Nomenclature

a	effective crack length at load P
a_o	notch length
a*	crack length corresponding to critical state
a/w	relative crack length
a_o/w	aspect ratio
A	adjustable parameter (Eq. 3)
B	adjustable parameter (Eq. 3)
c	compliance
C	adjustable parameter (Eq. 3)
COD	crack opening displacement
f(a/w)	shape factor of crack geometry
K_C	critical crack resistance
K_I	stress intensity factor
K_R	crack growth resistance
K_{th}	threshold crack resistance
L	specimen length
P	load
t	specimen thickness

w specimen width

References

Abdel-Wahab, M. M., I. A. Ashcroft, A. D. Crocombe, and P. A. Smith. 2004. "Finite Element Prediction of Fatigue Crack Propagation Lifetime in Composite Bonded Joints," Composites Part A: Applied Science and Manufacturing, 35 (2): 213-222. https://doi.org/10.1016/j.compositesa.2003.10.002

Avci, A., H. Arikan, and A. Akdemir. 2004. "Fracture Behavior of Glass Fiber Reinforced Polymer Composite." Cement and Concrete Research, 34 (3): 429-434. https://doi.org/10.1016/j.cemconres.2003.08.027

Baxter, S. C., M. I. Hossain, and L. L. Graham. 2001. "Micromechanics Based Random Material Property Fields for Particulate Reinforced Composites." International Journal of Solids and Structures, 38(50-51): 9209-9220. https://doi.org/10.1016/S0020-7683(01)00076-2

Belmonte, H. M. S., S. L. Ogin, P. A. Smith, and R. Lewin. 2004. "A Physically-Based Model for the Notched Strength of Woven Quasi-isotropic CFRP Laminates." Composites Part A: Applied Science and Manufacturing, 35(7-8): 763-778. https://doi.org/10.1016/j.compositesa.2004.01.006

Benrahou, K.H. M. Benguediab, M. Belhouri, Nait-Abdelaziz and A. Imad. 2007. "Estimation of Plastic Zone by Finite Element Method under Mixed Mode (I&II) Loading." Computational Material Sciences, 38(4): 595-601. https://doi.org/10.1016/j.commatsci.2006.04.001

Brown, W. F., and J. E. Strawley. 1969. "Plane Strain Crack Toughness Testing of High Strength Metallic Materials." American Society for Testing Materials (ASTM), Report No. STP 410. Washington, DC.

Choupani, N. 2008. "Experimental and Numerical Investigation of the Mixed-Mode Delamination in Arcan Laminated Specimens." Journal of Materials Science and Engineering A, 478(1-2): 229-242. https://doi.org/10.1016/j.msea.2007.05.103

Fox, B., A. Lowe, and J. Hodgkin. 2004. "Investigation of Failure Mechanisms in Aged Aerospace Composites." Engineering Failure Analysis, 11(2): 235-241. https://doi.org/10.1016/j.engfailanal.2003.05.010

Ge, D., F. Liu, and M. Lu. 2004. "Effect of Mode III Fracture on Composite Laminates." Composite Structures, 63(3-4): 469-480. https://doi.org/10.1016/S0263-8223(03)00209-5

Gong, J., and Z. Guan. 2000. "Crack-location-dependent R-curve behavior in Si3N4." Journal of the European Ceramic Society, 20(9): 1339–1344. https://doi.org/10.1016/S0955-2219(00)00019-4

Gouda, P. S. S., S.K. Kudari, S. Prabhuswamy and D. Jawali, "Fracture Toughness of Glass-Carbon (0/90)s Fiber Reinforced Polymer Composite – An Experimental and Numerical Study." Journal of Minerals & Materials Characterization & Engineering, 10(8), 2011, 671-682. https://doi.org/10.4236/jmmce.2011.108052

Li, X., L. A. Carlsson, and P. Davies. 2004. "Influence of Fiber Volume Fraction on Mode III Interlaminar Fracture Toughness of Glass/Epoxy Composites." Composites Science and Technology, 64 (9): 1279-1286. https://doi.org/10.1016/j.compscitech.2003.10.008

Liu, J. Z., and X. R. Wu. 1997. "Study on Fatigue Crack Closure Behavior for Various Cracked Geometries." Engineering Fracture Mechanics, 57(5): 475-491. https://doi.org/10.1016/S0013-7944(97)00052-0

Naghipour, and M. Bartsch. 2009. "Effect of Fiber Angle Orientation and Stacking Sequence on Mixed Mode Fracture Toughness of Carbon Fiber Reinforced Plastics: Numerical and Experimental Investigations." Journal of Materials Science and Engineering, 527(3): 509-517. https://doi.org/10.1016/j.msea.2009.07.069

Nikbakht, M. and N. Choupani. 2009. "Experimental Investigation of Mixed Mode Fracture Behaviour of Woven Laminated Composites." Journal of Material Science, 44(13): 3428–3437. https://doi.org/10.1007/s10853-009-3456-1

Pereira, A. B., and A. B. de Morais, 2004. "Mode II Interlaminar Fracture of Glass/Epoxy Multidirectional Laminates." Composites Part A: Applied Science and Manufacturing, 35(2): 265-272. https://doi.org/10.1016/j.compositesa.2003.09.028

Pereira, A. B., A. B. de Morais, A. T. Marques, and P. T. de Castro. 2004. "Mode II Interlaminar Fracture of Carbon/Epoxy Multidirectional Laminates." Composites Science and Technology, 64 (10-11): 1653-1659. https://doi.org/10.1016/j.compscitech.2003.12.001

Qiao, Y., and X. Kong. 2004. "Unstable Crack Advance Across a Regular Array of Short Fibers in Brittle Matrix." Composites Science and Technology, 64(5): 711-717. https://doi.org/10.1016/j.compscitech.2003.07.001

Rizov, V. I. 2012. "Fracture In Composites – An Overview (Part I)." Journal of Theoretical and Applied Mechanics, Sofia, 42(2): 3–42. https://doi.org/10.2478/v10254-012-0006-z

Rodriguez, A. A., and E. Medina. 2000. "Analytical Results for Random Line Networks Applications to Fracture Networks and Disordered Fiber Composites." Physics A: Statistical Mechanics and its Applications, 282(1): 35-49. https://doi.org/10.1016/S0378-4371(00)00074-1

Shameli, M. and N. Choupani. 2016. " Fracture Criterion of Woven Glass-Epoxy Composite Using a New Modified Mixed-Mode Loading Fixture." International Journal of Applied Mechanics 8(2): 1650015. https://doi.org/10.1142/S1758825116500150

Van den Heuvel, P. W. J., S. Goutianos, R. J. Young, and T. Peijs, 2004. "Failure Phenomena in Fibre-Reinforced Composites. Part 6: a Finite Element Study of Stress Concentrations in Unidirectional Carbon Fibre-Reinforced Epoxy Composites." Composites Science and Technology, 64 (5): 645-656. https://doi.org/10.1016/j.compscitech.2003.06.003

Van Mier, J. G. M., M. R. A. van Vliet, and T. K. Wang. 2002. "Fracture Mechanisms in Particle Composites: Statistical Aspects in Lattice Type Analysis." Mechanics of Materials, 34(11): 705-724. https://doi.org/10.1016/S0167-6636(02)00170-9

Whitney, T. J., E. V. Iarve, and R. A. Brockman. 2004. "Singular Stress Fields Near Contact Boundaries in a Composite Bolted Joint." International Journal of Solids and Structures, 41(7): 1893-1909. https://doi.org/10.1016/j.ijsolstr.2003.11.013

Xi, Y., and Z. P. Bazant. 1997. "Random Growth of Crack with R-Curve: Markov Process Model." Engineering Fracture Mechanics, 57(6): 593-608. https://doi.org/10.1016/S0013-7944(97)00069-6

Yukalov, V. I., A. Moura, and H. Nechad. 2004. "Self-similar Law of Energy Release before Materials Fracture." Journal of the Mechanics and Physics of Solids, 52(2): 453-465. https://doi.org/10.1016/S0022-5096(03)00088-7

Zemcik, R. and V. Las. 2008. "Numerical and Experimental Analyses of the Delamination of Cross-Ply Laminates." Journal of Materials and Technology, 42(4): 171-174. DOI: 678.6/.7:620.18