AN EXAMINATION OF CRACK LENGTH ESTIMATION PROCEDURE FOR SHORT FIBRE COMPOSITES

B. S. Patro, B. D. Agarwal and P. Kumar

Department of Mechanical Engineering, Indian Institute of Technology, Kanpur, India

ABSTRACT

Validity of the compliance matching procedure has been examined for short fibre composites experimentally by studying the behaviour of damaged specimens. The load - COD curve and fracture load of a damaged specimen are different from that of a fresh specimen. However, it has been clearly established that the secondary compliance of the damaged specimen can be used to accurately estimate the extent of damage to the specimen by earlier loading.

KEYWORDS

Short fibre composite, crack growth resistance, crack length, crack mouth opening displacement, fracture toughness.

INTRODUCTION

Fracture mechanics of composite materials has received considerable attention in last 10-15 years. The concepts of fracture mechanics of homogeneous, isotropic materials have generally been extended to composite materials. Fracture toughness tests on them are also carried out and data analysed through the procedures developed for homogeneous materials. Some times the data are obtained in a form different from that for homogeneous materials. In such cases, it becomes necessary to develop auxiliary procedures to transform the data before a particular analysis procedure is applied. The validity of analysis, then, largely depends upon the validity of the transformation procedure which must, therefore, be carefully examined.

The crack growth resistance (R curve) approach (Hayer, 1973) has been very widely used to analyse fracture test results on composite materials (Agarwal, 1981; Awerbuch, 1978; Gaggar, 1975; Yanada, 1983). Analysis using this approach requires measurement of instantaneous crack length with increasing load in a fracture test. In case of homogeneous materials the crack is visible and well defined and can be easily measured at any instant. However, fracture process in composite materials does not proceed by a simple enlargement of the original crack. Damage progresses by formation of a large number of microcracks due to debonding, matrix cracking and fibre breaks. An instantaneous crack length is difficult to define or measure. Consequently, a procedure for estimating instantaneous crack length must be adopted. A procedure involving matching of compliance of a damaged specimen to that of a fresh specimen, generally referred to as the compliance matching procedure (Gaggar, 1975, 1976), has been extensively used by the researchers to transform the test data (e.g., the crack opening displacement) into estimated crack length (Agarwal, 1981; Awerbuch, 1978; Yanada, 1983). Appropriateness of the procedure does not appear to have been examined systematically. This paper explains the procedure and implications of various steps involved and examines their validity.

EXPERIMENTAL PROCEDURE

The present studies are performed on randomly oriented short glass fibre reinforced epoxy resin. A chopped strand mat of glass fibres having a mass of 0.6 Kg/m^2 and an average fibre length of 50 mm is used as the reinforcement. The matrix material is an epoxy resin (Araldite CY 230 cured with hardener HY 951). The composite plates (3 mm thick) are cast in the laboratory and cured at room temperature for atleast 10 days. The cured plates exhibit a fibre volume fraction of about 36%. Single edge notched specimens are 25 and 30 mm wide and length between grips is atleast three times the width. Notches are machined using a 0.2 mm thick slit cutter with their length varying between 0.1 and 0.7 of specimen width. The fracture toughness tests are performed on a 10 Ton MTS machine. The load is measured by the load cell and the crack mouth opening displacement (COD) by a home made clip gauge (Patro, 1983).

CONCEPT OF COMPLIANCE MATCHING PROCEDURE

Typical load - COD curves for single edge notched specimens in tension are shown in Fig. 1 for different initial crack lengths. Initial compliance (based on crack mouth opening displacement) of specimens changes with length of initial machined crack. Compliance also changes with load since the load - COD curves are nonlinear. The damage to the specimen during loading has the effect of enlargement of initial crack in changing compliance. The compliance matching procedure is based on the assumption that the compliance may be taken as a measure of crack length and, hence, effective crack length in a damaged specimen may be estimated by matching its compliance with the compliance of a fresh specimen having machined notch. In the compliance matching procedure, initial compliance (obtained from the curves in Fig. 1) is first plotted against crack length. This plot (Fig. 2) is referred to as the compliance curve or the crack length estimation curve. To estimate instantaneous crack lengths at points P_1 , P_2 and P_3 on load-COD curve, compliances, C_1 , C_2 and C_3 of the lines joining P_1 , P_2 and P_3 to the origin are obtained (Fig. 3). The crack lengths a_{e_1}, a_{e_2} and a_{e_3} at points P_1 , P_2 and P_3 are then estimated from the crack length estimation curve (Fig. 2) corresponding to compliances C_1 , C_2 and C_3 respectively. Thus, this method assumes that the damaged specimen behaves like an undamaged specimen with a machined crack of length equal to the estimated crack length. This underlying assumption is examined in this paper through studying the behaviour of notched specimens in which additional damage had been produced by loading them in tension and comparing it with the initial behaviour of fresh specimens as shown in Figs. 1 and 2.

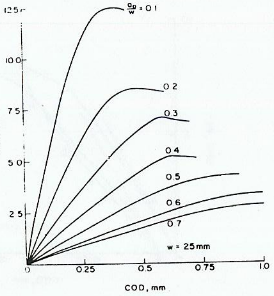

Fig. 1. Load-COD curves.

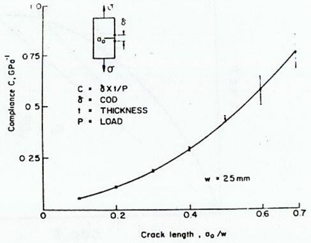

Fig. 2. Crack length estimation curve

RESULTS AND DISCUSSION

The results shown in Figs. 1 and 2 are obtained by conducting fracture toughness tests on atleast six identical fresh specimens at each crack length. These results serve as the standard for comparison with the behaviour of damaged specimens. Fracture behaviour of damaged specimens was studied in two ways. First, 12 single edge notched specimens (3 specimens each at 4 different initial crack lengths namely, 5, 10, 12.5 and 15 mm) were loaded in tension to produce damage ahead of the machined notch. The maximum load on the specimens before unloading them was varied to different fractions of their expected fracture loads so that the extent of damage to the specimens was different in each case. These damaged specimens were then reloaded to fracture and their behaviour studied. The second approach involved producing damage, in the same manner to wider specimens. After unloading, the specimens were reduced in width by cutting off the notched edge so that a major part of the machined crack was removed. These reduced width specimens with machined crack and additional damage were also loaded to fracture and their behaviour studied.

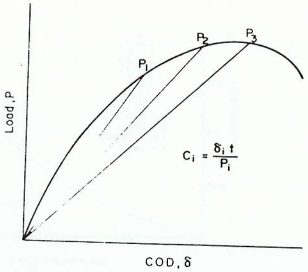

Fig. 3. Evaluating instantaneous compliance.

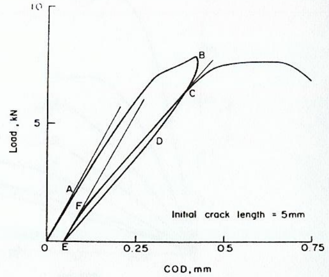

Fig. 4. Loading, unloading and reloading paths.

Results of the investigations using both the approaches are described as follows.

Behaviour of Damaged Specimens without Changing Width

Typical behaviour of a fresh notched specimen is illustrated in Fig. 4 through loading and unloading paths for a 25 mm wide specimen having a 5 mm long initial crack. The specimen was unloaded after subjecting it to about 95% of the expected fracture load. Typical behaviour of a damaged specimen is also illustrated in Fig. 4 by superimposing on it the reloading path of the same specimen. The loading path of a fresh specimen is linear in the beginning and progressively deviates from linearity due to increasing damage to the material. Reloading path of the damaged specimen is also linear in the beginning but shows a sudden change in slope at a relatively small load. The magnitude of change in slope (sharpness of the knee, F) depends upon the maximum load on the specimen prior to unloading. When the maximum load is small, change in slope is negligible or the knee almost disappears.

To compare the behaviour of damaged and fresh specimens quantitatively, initial compliance of a fresh specimen (C_o), its compliance at maximum load before unloading (C_d), initial compliance of the damaged specimen during reloading (C_{or}) and its compliance corresponding to the straight line portion of load-COD curve beyond the knee (C_{dr}) have been obtained for all 12 specimens. Corresponding to these four compliances, crack lengths have been estimated from the crack length estimation curve (Fig. 2) as a_o, a_d, a_{or} and a_{dr} respectively. The estimated crack lengths a_d and a_{or} normalized with respect to initial machined crack a_o are plotted (Fig. 5) against estimated crack extension, $(a_d-a_o)/a_o$. The two crack lengths are clearly different and the difference between them increases with crack extension. The estimated initial crack length during reloading is independent of the crack extension and is equal to the initial machined crack in the fresh specimen. Thus, the initial behaviour of a damaged specimen does not reflect the extent of damage to the specimen during initial loading. On the other hand the initial behaviour during reloading and the initial loading are the same irrespective of the extent of damage to the specimen. This will be further explained subsequently.

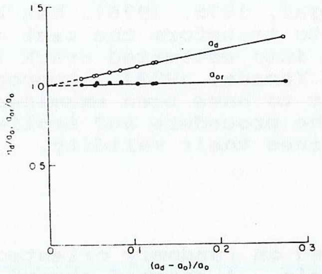

Fig. 5. Normalised crack lengths (a_d/a_o, a_{or}/a_o)

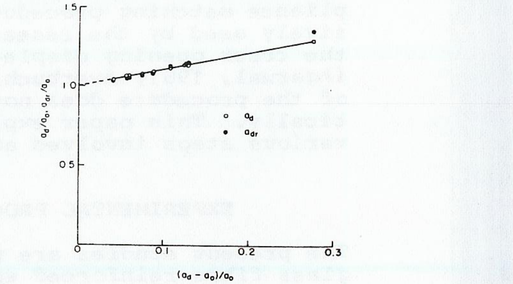

Fig. 6. Normalised crack lengths (a_d/a_o, a_{dr}/a_o)

The estimated crack lengths a_d and a_{dr} are plotted in Fig. 6. The two crack lengths are overlapping in the range investigated here. This indicates that the extent of damage to the specimen during initial loading is truly reflected during reloading only after the knee on the load-COD curve which appears very early. It demonstrates that no additional damage occurs during unloading and reloading. The presence of a sharp knee in the reloading path does not signify occurrence of any sudden damage to the material. At small loads prior damage to the specimen does not influence COD. The load-COD curve beyond the knee is, therefore, representative of the damaged specimen.

Fracture load of the damaged specimens, P_f, normalised with respect to the fracture load expected, P_e, for a fresh specimen having the same initial machined crack length, is plotted in Figs. 7 and 8 against initial crack length and the estimated crack extension prior to unloading respectively. Both the figures show that the fracture load of a damaged specimen is same as the fracture load of a fresh specimen. This observation is independent of initial crack length and the extent of damage to the specimen before unloading. That is, unloading a specimen at any stage of loading does not affect the fracture load.

The above observations clearly show that the load-COD behaviour of a damaged specimen is different from that of a fresh specimen having a machined crack of length equal to the estimated length of crack in the damaged specimen. Further, the fracture loads of two such specimens are also different. In fact, fracture load depends only on the length of initial machined crack and is

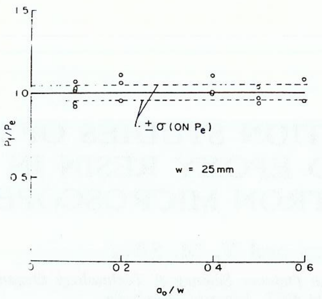

Fig. 7. Ratio of fracture loads vs. crack length

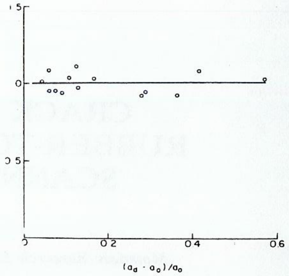

Fig. 8. Ratio of fracture loads vs. crack extension

not influenced by additional damage that may be caused to the specimen during loading or unloading. However, it has been demonstrated that the load-COD curve of a damaged specimen can be used to accurately estimate the extent of damage to the specimen caused by earlier loading. Therefore, the use of compliance matching procedure to estimate the instantaneous crack length appears to be justified. This proposition is further examined in the next section using a different approach.

Behaviour of Damaged Specimens After Reducing Width

In this approach 10 specimens 30 mm wide each having a 7.5 mm long initial machined crack were loaded in tension to produce damage ahead of the crack. The maximum load on the specimen before unloading them was varied to different fractions of the expected fracture load so that the extent of damage was different in each case. In some cases the commencement of unloading was at a load more than the average fracture load or it was past the peak load. This was done to obtain maximum possible damage to the specimen. This is of particular interest since applicability of the compliance matching procedure in this range may be questionable. At smaller loads the method is expected to yield better results. These 30 mm wide damaged specimens were reduced in width to 25 mm by cutting off a 5 mm wide strip on the notched edge (Fig. 9) so that the 25 mm wide reduced width damaged specimens have a machined crack 2.5 mm long and additional damage due to loading. These specimens were loaded in tension to fracture and their behaviour examined.

The load-COD curve of a reduced width specimen is similar to the reloading curve shown in Fig. 4. As in the earlier case, a major part of the curve can be approximated by two straight lines. The crack lengths estimated by compliance matching procedure corresponding to the two straight lines are denoted by a_{or} and a_{dr}. The crack length estimated at the maximum load during loading of 30 mm wide fresh specimen is denoted by a_d. The estimated crack length in the reduced width damaged specimen is then a_d - 5 which is denoted by a_d'. The crack lengths a_{or} and a_{dr} normalized with respect to a_d' are plotted against estimated crack extension in Fig. 10. It is observed that the ratio a_{dr}/a_d' is independent of the extent of damage and is equal to 1 whereas the ratio a_{or}/a_d' decreases with the increase of damage. These observations indicate that the crack length a_{dr} truly represents the extent of damage. On the other hand a_{or} does not depend upon the extent of damage and its value is 2.5 mm (± 5%).

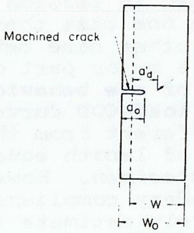

Fig. 9. Two stage specimen.

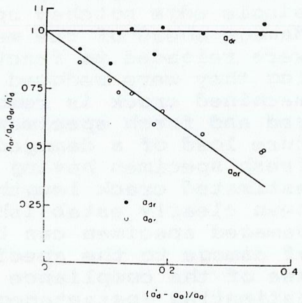

Fig. 10. Crack lengths in reduced specimens.

The fracture load of reduced width specimens has also been found to be independent of the extent of damage to the specimen during initial loading. Its average value agrees very well with the average fracture load of 25 mm wide fresh specimens having 2.5 mm long machined crack.

The fracture toughness of all the reduced width specimens was also obtained using R-curve method. An average fracture toughness was 25.91 MPa $\sqrt{m}$ (S.D. 0.61 MPa $\sqrt{m}$) which compares well with 26.34 MPa $\sqrt{m}$ (S.D. 1.71 MPa $\sqrt{m}$) of 25 mm wide fresh specimens having 2.5 mm long machined crack.

The above observations regarding crack length estimation and fracture load are consistent with the earlier conclusions drawn in the first approach.

CONCLUSIONS

In fracture toughness tests on composite materials, instantaneous crack length is difficult to define or measure. The crack mouth opening displacement is therefore measured and transformed into estimated crack length through the compliance matching procedure. Validity of this compliance matching procedure has been examined for short fibre composites experimentally by studying the behaviour of damaged specimens in two ways. In both cases the single edge notched specimens were loaded in tension to produce damage ahead of the machined notch. In one case these specimens were reloaded to fracture while in the other case before reloading they were reduced in width so that a major part of the machined crack is removed. Comparison of the behaviour of damaged and fresh specimens shows that the load-COD curve and fracture load of a damaged specimen are different from that of a fresh specimen having a machined crack of length equal to the estimated crack length in the damaged specimen. However, it has been clearly established that the secondary compliance of the damaged specimen can be used to accurately estimate the extent of damage to the specimen by earlier loading. Therefore, the use of the compliance matching procedure appears justified for estimating instantaneous crack length in short fibre composites.

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