ROLE OF LOCAL FIBER DISTRIBUTION AT NOTCH TIP IN THE FRACTURE TOUGHNESS OF FRP

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ABSTRACT

The results of the evaluation of fracture toughness and observations of the fracture process are described with regard to continuous fiber reinforced plastics with the local state of fiber distribution changed artificially, particularly paying attention to its low fiber volume fraction. Also, a description is made of the results of studies not only on the strengthening mechanism due to fiber against the fracture toughness but also on the cause of scattering of fracture toughness values.

KEYWORDS

FRP, Fracture toughness, Fracture process, Scattering of G_c values, Strengthening mechanism and Critical fiber volume fraction V_{fc}.

INTRODUCTION

Discussions regarding the strengthening effect due to fibers in the fiber reinforced plastics (FRP) have so far been mainly made on the basis of the linearly additive law, or the law of mixtures concerning the strengthening effect due to individual fiber (Broutman and Krock, 1967; Zweben, 1969; Mullin, 1973). There is, however, a limit in applying such an approach to the whole range of fracture problems. Particularly, in order to investigate the strengthening mechanism due to fibers as well as the scatter of fracture strength (Mill, Brown and Waterman, 1976; Uenura, 1979), another approach is required with consideration given to the detailed structure of materials. In the previous report (Kunio, Shimizu and Sohmiya, 1980), therefore, authors attempted to make clear the strengthening effect due to fibers which governs the fracture toughness of FRP through discussions on the role of the dispersed state of fiber in the discontinuous fiber reinforced plastics in the crack propagation process. However, because of a limit in controlling the dispersed state of fibers in the discontinuous fiber reinforced plastics, it was impossible to change the dispersed state over a wide range and systematically as well, leading to a failure in obtaining sufficiently desired information. In the present study, therefore, the continuous fiber reinforced plastics in which it is much easier to control the dispersed state of fibers, was used as a specimen; particularly in its low fiber volume fraction range, model material in which the local dispersed state of fiber at a crack front had been artificially changed was prepared, to make studies of not only the strengthening mechanism due to fibers against fracture toughness but also the cause of scattering of G_c values through evaluation of these G_c values and observation of the fracture process.

MATERIAL AND TESTING PROCEDURE

The continuous fiber reinforced plastics was prepared for test material by laminating two kinds of layers alternatively; one layer had a rich density of unidirectional E-glass roving fiber in the matrix of epoxy resin (Epikote-828) and another one had very poor density of the fiber. As was the case with the discontinuous fiber reinforced plastics described in the previous paper (Kunio, Shimizu and Sohmiya, 1980), 7 volume fractions of fiber V_f were employed within the range of $V_f = 0.026 - 0.11$, including $V_f = 0$ (pure resin).

The specimen for fracture toughness test was machined into the shape as shown in Fig. 1, then a razor edge was pressed into the notch root at a temperature of 130°C to cause a sharp pre-crack at the tip by a wedge effect. The fracture toughness value Gc was determined by substituting the load $P = P_c$ at the initial point of suddenly decreasing load (the starting point of crack propagation) on the $P - \delta$ curve at the time when an in-plane 3-point bending load was applied to the specimen, into the following equation:

$$G_c = \frac{P^2}{2t} \cdot \frac{dc}{da}$$

where,

c : compliance
a : pre-crack length
t : specimen thickness

Furthermore, studies were made on the fracture process by observing the process of crack growth with a stereoscope directly from the side of the specimen, as well as by means of the fractography.

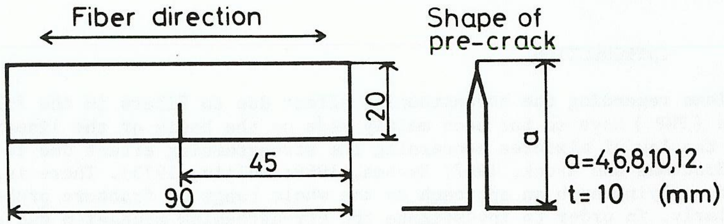

Fig. 1. Dimensions of specimen.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Dependence of G_c on V_f value

Figure 2 shows the experimental results on dependence of G_c on V_f value. With regard to the behavior of G_c in this figure, the following two points are noted in particular.

(1) In the low fiber volume fraction range, there exists a critical fiber volume fraction V_{fc}, below which the strengthening effect due to fibers against the G_c value does not take place.

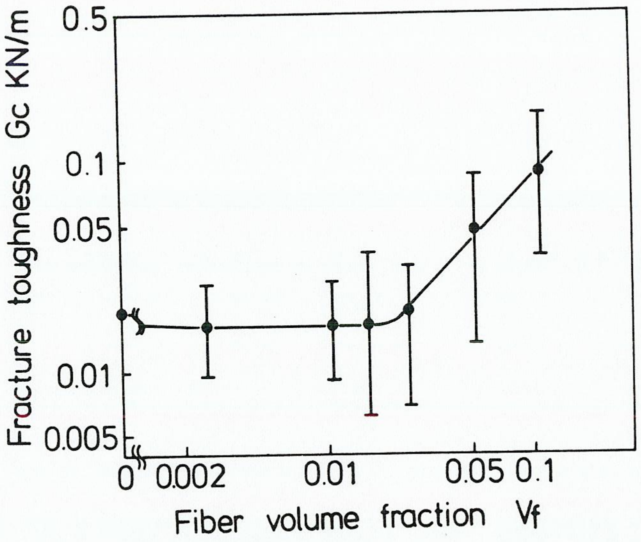

Fig. 2. Dependence of G_c on V_f.

(2) Even with the specimen having constant V_f, large scattering is still apparent in the G_c values.

The fact that there exists V_{fc} in the dependence of G_c on V_f was also recognized in the chopped strand fiber reinforced plastics (Kunio, Shimizu and Sohmiya, 1980). In the case of the present specimen, the G_c value is nearly equal to that of the matrix resin and does not depend on V_f in the range of $V_f < V_{fc}$ with $V_{fc} = 0.02$ as a boundary. On the other hand, the G_c value increases almost linearly with V_f on the log-log plot in the range of $V_f > V_{fc}$.

Also, the fact that there appears considerable scattering in the G_c values of FRP has been widely recognized in general (Hardy, 1971; Sih and co-wokers, 1973; Owen and Bishop, 1974; Beaumont, 1974; Owen and Cann, 1979). The present experimental results show that scattering of the G_c values of FRP is particularly large in the range of $V_f > V_{fc}$, as compared with scattering of the G_c values of the resin itself.

Now, on the basis of the results of observations made on the fracture process, consideration will be given to the cause of phenomena described in (1) and (2) above.

Observation of Fracture Process

As was the case with the chopped strand fiber reinforced plastics described in the previous papers (Kunio, Shimizu and Sohmiya, 1980), the semi-cicular pattern (Fig. 3) was recognized at the pre-crack front on the fractured surface of the specimen. This pattern is caused when a rapid fracture develops locally in part of resin at the pre-crack front and when its further development is supressed by fibers. Such a local rapid fracture phenomenon is called "micro-pop in".

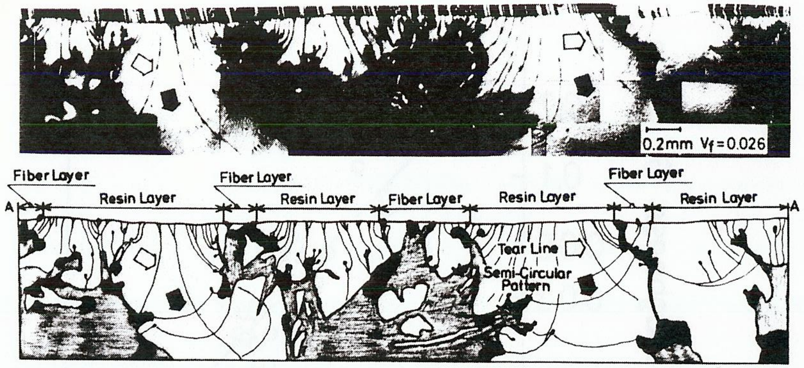

Fig. 3. Appearance of fracture surface at pre-crack front.

Direct observations were made on the behaviors of "micro-pop in" and crack growth at the pre-crack front, in addition to fractographic analysis of fractured surfaces. As the results, the followings were made clear.

(1) A crack growth from the pre-crack front is triggered by "micro-pop in".

(2) "micro-pop in" initially develops at the site where the local fiber interspacing at the pre-crack front is large and occurs successively at the locations where the fiber interspacing is much smaller with the subsequent increase of applied load.

(3) In the FRP having V_f smaller than V_{fc}, the occurrence of single "micro-pop in" immediately leads to a rapid fracture of the entire specimen. On the other hand, in the FRP having V_f larger than V_{fc}, several numbers of "micro-pop in" develop almost simultaneously at pre-crack front, then a stable crack growth takes place subsequently as shown in Fig. 4.

From the above observations, the reason for appearance of V_{fc} in the dependence of G_c values on V_f may be explained in the following manner. That is, once "micro-pop in" develops at the pre-crack front in the range of $V_f<V_{fc}$, it immediately leads to an unstable fracture on the whole. On that occation, the fiber has little effect to block crack propagation. In the range of $V_f>V_{fc}$, on the other hand, the small fiber interspacing makes it difficult for "micro-pop in" to initiate and develop, thus possibly acts as a controlling factor against the onset of crack growth at the pre-crack front.

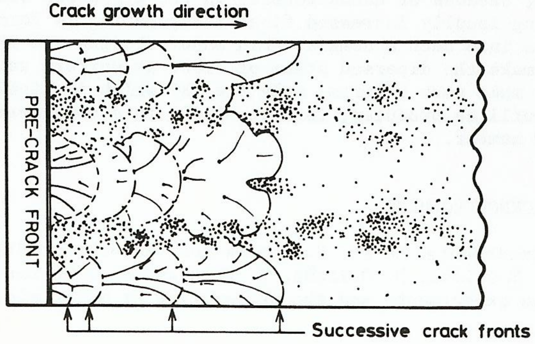

Fig. 4. Schematic representation of crack growth process.

Cause of Scattering of G_c values

From the aforementioned results of observations on the process of crack growth from the pre-crack front, it might be considered that the G_c value characteristics of FRP are greatly affected by the dispersed state of fiber at the pre-crack front.

Figure 5 is a schematic representation that the local state of fiber distribution at the pre-crack front varies with each specimen even if the fiber volume fraction V_f is held constant. V_{fL} in this figure stands for the local fiber volume fraction at the pre-crack front, while D_{ave} is a parameter for representing the interspacing of fibers which takes part in initiating a local fracture at the pre-crack front, as defined hereunder. Quantitatively, the D_{ave} is the average of fiber interspacings measured at the locations where "micro pop in" occurred at the pre-crack front at $P = P_c$. These interspacings are measured on the fractured surface of specimen, after fracturing.

The results of a study on the relation between G_c and this new parameter V_{fL} are illustrated in Fig. 6 with respect to the present specimen. The dependence of G_c on V_{fL} is clealy recognized from the figure. Futhermore, comparing this with Fig. 2, it might be found that the scattering of G_c values is decreased but there still remains considerable scattering.

Then, paying attention to the second parameter D_{ave}, a study will be made of the relation between the D_{ave} and the G_c values. For this study, however, it is necessary to carry out an experiment in such a way that only the effect of D_{ave} on G_c will be taken at a state in which no effects of V_f and V_{fL} are caused on the G_c values. For this purpose, the conventional test specimen is not clearly suitable. Using a special processing, therefore, model materials in which the D_{ave} alone was changed over a considerably wide range with V_f and V_{fL} held almost constant were prepared, and the dependece of G_c on D_{ave} was examined with respect to these materials. Fig. 7 shows the measured results on the dispersed state of fiber at the pre-crack front in such model materials. It is found from the figure that in these model materials, the D_{ave} alone is changing over a range of 0.27 - 8mm with V_{fL}

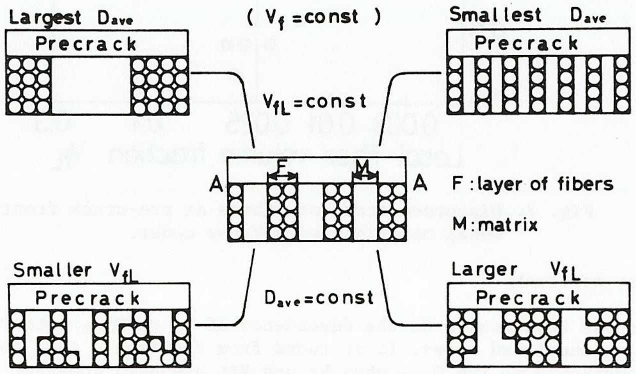

Fig. 5. Illustration of possible local fiber arrangement at the pre-crack front for FRP having V_f =const. (A-A, pre-crack front.)

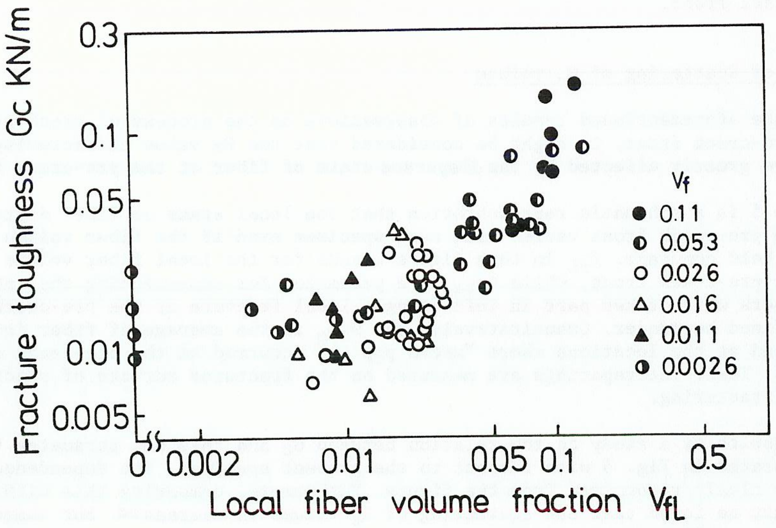

Fig. 6. Dependence of G_c on V_{fL}.

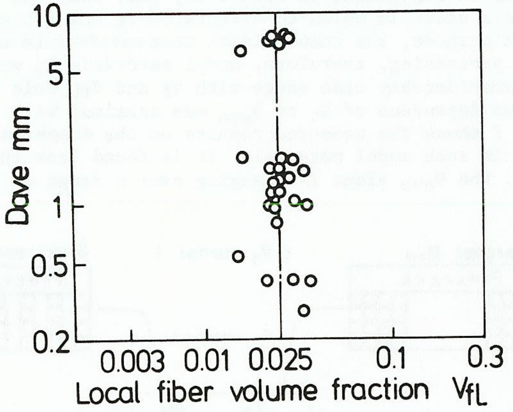

Fig. 7. Dispersed state of fibers at pre-crack front in model materials with $V_{fL} \approx$ const.

kept almost constant.

Figure 8 shows the results on the dependence of G_c on D_{ave} with respect to the model materials as mentioned above. It is found from the figure that the G_c shows as obvious dependence on the D_{ave} when V_f and V_{fL} are held constant and also that the G_c value is decreasing sharply with increase of the D_{ave}.

Consequently, it can be pointed out that the two parameters, V_{fL} and D_{ave}, regarding the local state of fiber distribution at the pre-crack front are primarily responsible for causing considerable scattering of the G_c values of FRP. Particularly, it might be said that the effect of the D_{ave} is significantly large.

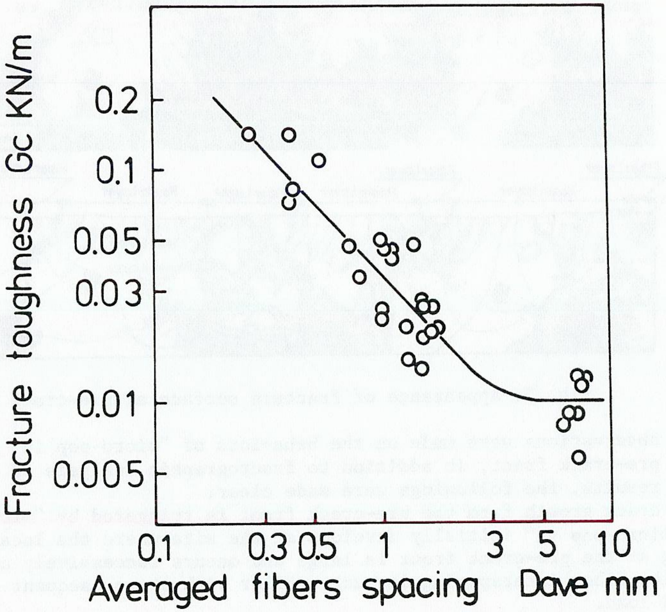

Fig. 8. Dependence of G_c on D_{ave} for model materials with $V_{fL} \approx$ const.

CONCLUDING REMARKS

As the result of these studies, it has been made clear that the fracture toughness characteristics of FRP are greatly affected by the dispersed state of fiber. Generally, in the FRP, large scattering appears in its fracture toughness. It might be, however, considered that such scattering is fundamentally attributable to the fact that, because of nonuniformity in the dispersed state of fiber in the FRP, a domain having locally increased fiber interspacing is formed and a crack preferentially grows into such a domain. When manufacturing the FRP, therefore, it is important to make the dipersed state of fiber as uniform as possible. In the event of failure to make such efforts, only the FRP which is liable to cause scattering in G_c values will be produced, thus resulting in a considerable loss of reliability as a strength member.

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REFERENCE

Beaumont, P. W. R. (1974). A Fracture Mechanics Approach to failure in Fibrous Composite. J. Adhesion, 6.107.

Broutman, L. J. and R. H. Krock (1967). Modern Composite Material. Addison- Wesley. Massachusetts. 3-119.

Hardy, G. F. (1971). Fracture toughness of Glass Fiber Reinforced Acetal Polymer. J. Appl. Polymer.Sci.,15 853-866.

Kunio, T ., M. Shimizu and S. Sohmiya (1980). Effect of local fiber distribution ahead of crack on the fracture toughness of FRP. To be published in 4NATIONAL 1 INTERNATIONAL MEETING on COMPOSITE MATERIALS, Milano, Italy.

Mill, G. J., C. Brown, and D. Waterman (1976). Prestressing of fiber/resin prepared systems for laminate property improvement. Proc. ICCM. 2 . AIME, 222-246

Millin, J. V (1973) Imfluemce of Fiber Property Variation on Composite Falure Mechanisms. ASTM.STP.521 . 349-366

Owen, M. J. and P. T. Bishop (1974). Critical stress intensity factors applied to Glass fiber reinforced Polyester resin. in C. J. Hilado (Ed.), Materials Technology Series, 5 74-87

Owen, M. J. and R. J. Cann, (1979). Fracture toughness and crack-growth measurement in GRP. J. Material, Sci. 14. 8. 1982- 1996

Sih, G. C., P. D. Hilton and Co-workers. (1973) Fracture Mechanics for Fibrous Composite. ASTM STP 521, 98-132

Uenura, Mand Co-workers(1979) FRP Desin Manuals.Japan reinforced plastics Society, Tokyo, 52-122

Zweben, C. (1969). Tensile strength of Fiber reinforced composite, ASTM.STP.460 . 528-539