Notch Sensitivity of Polymers

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Synopsis

The influence of notches on the static tensile strenght, low-cycle fatigue strength and creep rupture strength was investigated for selected polymeric materials. This investigation was prompted by the unusual phenomena of necking and notch strengthening observed in some glass fiber reinforced plastic materials. Two types of epoxy resin, polymethyl methacrylate and polycarbonate, were studied under static tensile loading. Three sizes of semicircular symmetrical side notch on flat specimens were investigated. It was observed that one of the epoxies was very notch sensitive, while the other exhibited significant (and maximum, out of all the polymers tested) notch strengthening in tensile loading. Perspex and polycarbonate showed a small notch sensitivity for the smallest and intermediate notches but notch strengthening for the biggest notch. The epoxy resin which exhibited notch strengthening was also tested with different percentages of hardener; for the biggest and the intermediate notches, there was a notch strengthening effect and unnotched as well as notched tensile strength showed a peak around 14% hardener. The epoxy which exhibited notch strengthening in tensile loading was next tested in low-cycle fatigue and creep loading. The behavior in low-cycle fatigue and creep loading was remarkably similar: it was found that for this polymer, the notch sensitivity was small in the case of the smallest and intermediate notches, whereas there was a significant notch strengthening effect in the case of the biggest notch. It is recommended that notch-strengthening behavior be added to the other criteria for the selection of matrices for composite materials.

INTRODUCTION

It has been generally concluded that a notch is fully effective in initiating damage in glass fiber reinforced plastics but that its effect on ultimate failure is small due to the progressive damage at the root of the notch and the consequent change in the notch geometry.[1–4] However, recently, notch strengthening in static tensile and low-cycle fatigue loading, with and without necking, has been reported.[5,6] The notch strengthening effect has been found to be a maximum, in the case of bidirectionally reinforced composites, for the 45° orientation when the role of the matrix becomes significant. Another extreme in behavior, namely, almost full notch sensitivity, has also been observed in some composites utilising brittle matrices.[5] This clearly indicates the need to study the notch sensitivity of polymers which may be likely candidates for matrices in composites.

The available literature on notch sensitivity of polymers is very limited. Most of the literature on this topic is for impact tests.[7,8] Recently, the stress-strain behavior of a number of polymers, with and without notches, in static loading has been reported.[9] Little information is available regarding the notch sensitivity of polymeric materials in fatigue and creep loading.

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The purpose of this investigation was to study the notch sensitivity of a few polymers in low-cycle fatigue and in creep. Two thermoplastic and two thermosetting materials, giving a total of about 500 specimens, were tested, and the results are summarized in this paper.

MATERIALS AND TECHNIQUES

Two thermoplastics and two thermosets were investigated. Since the range in notch sensitivity was of interest, a comparison between the behavior of ductile polymers and that of brittle polymers was desired. Therefore, a brittle thermoplastic, poly(methyl methacrylate), a ductile thermoplastic, polycarbonate, a brittle epoxy (Araldite* LY-556) and a ductile epoxy (Araldite* CY-230) were selected. As the properties of the ductile epoxy were found to be sensitive to the percentage of hardener (HY-951*) added, compositions with 9%, 10%, 12%, 14%, 18%, and 25% hardener were tested.

All unnotched and notched specimens were machined by routing with suitable aluminium templates and were 6 in. long and 1/8 in. thick. The unnotched specimens were 3/4 in. wide, with a reduced section 1/2 in. wide and a gauge length of 2 in. The notched specimens were 1 in. wide and had symmetrical semicircular side notches. Three sizes of notches were chosen for investigation and the stress concentration factors associated with these are given in Table I. The thermoplastic materials were available commercially but the epoxies were cast in perspex moulds. The two thermoplastics, brittle epoxy and the various compositions of the ductile epoxy were tested only in static loading. Low-cycle fatigue and creep tests were performed on the ductile epoxy cured with 12% hardener.

All the specimens were conditioned at about 25°C and 50% relative humidity for several days prior to testing. The tensile tests and the low-cycle fatigue tests were conducted on an Instron machine. The creep tests were performed on the three stations of a creep testing rig specially designed for this study.[10] A crosshead speed of about 0.2 in./min was used for the tensile tests and the frequency for the low-cycle fatigue tests was kept low (1–6 cycles/min) so as to minimize hysteresis heating.

RESULTS AND DISCUSSION

The tensile stress-extension curves for poly(methyl methacrylate), polycarbonate, and the two epoxies (unnotched specimens) are shown in Figure 1. These curves clearly show the ductile behavior of Araldite CY-230 and polycarbonate as well as the relative brittle nature of poly(methyl methacrylate) and Araldite LY-556. In the case of Araldite CY-230, the mechanical properties were found

TABLE I
Type of Notches

Notch No.	Notch radius, in.	Theoretical stress concentration factor, K_t
1	0.065	2.68
2	0.188	1.78
3	0.370	1.20

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* Marketed by CIBA of India.

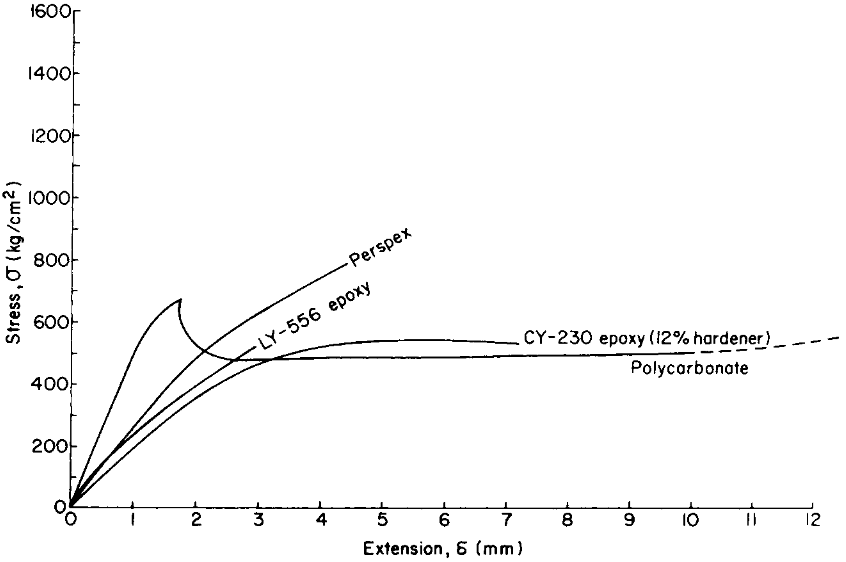

Fig. 1. Stress-extension curves for Araldite LY-556, Araldite CY-230, perspex, and polycarbonate.

to be sensitive to the percentage of hardener HY-951 and so a series of experiments was conducted with different hardener percentages. The results are summarized in Figure 2. As the hardener proportion is increased from 8% (by weight), there is an increase in the yield stress (stress calculated from the point of maximum load of ductile plastic) and the fracture strength (based on the load at which specimen breaks) upto 14%, beyond which both these properties decrease appreciably. The data available was not sufficient to draw similar conclusions regarding the extension upto fracture.

The notch sensitivity factor q is defined as

$$q = (K - 1)/(K_t - 1) \tag{1}$$

where K_t is the theoretical or elastic stress concentration factor and K is the

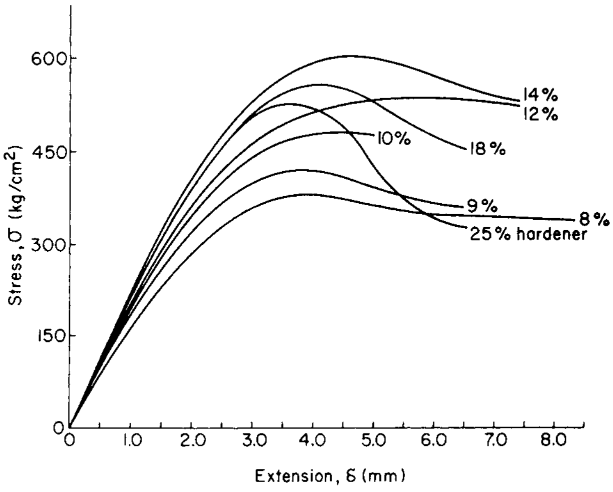

Fig. 2. Stress-extension curves for various compositions of Araldite CY-230.

strength reduction factor. The strength reduction factor K is given by the following ratio:

$$K = \frac{\text{strength of unnotched specimen}}{\text{strength of notched specimen}} \tag{2}$$

It should be noted that by using the tensile strength, fatigue strength (for a given number of cycles) or creep rupture strength (for a given time) in eq. (2), the corresponding strength reduction factor is obtained; thus the proper value of K in eq. (1) leads to the required notch-sensitivity factor for tensile, fatigue, or creep loading. A high positive value of q indicates full notch sensitivity (weakening effect) and a negative value of q indicates a notch-strengthening effect.

The variation of notch sensitivity with notch parameter of the two thermoplastics and the two thermosets in static tensile loading is shown in Figure 3. The notch parameter is defined as $2r/w$, where r and w are the notch radius and the width of the specimen, respectively. In all cases, the notch sensitivity for the intermediate notch is smaller than that for the sharpest notch, while the notch sensitivity for the biggest notch is much less. The ductile polymers, polycarbonate, and Araldite CY-230 exhibited a yield stress and hence curves based on yield stress and fracture strength are shown for these two materials. The yield stress of polycarbonate appears to be notch insensitive but there is a small reinforcing effect due to the biggest notch, based on the fracture strength. Poly(methyl methacrylate) is more notch sensitive than polycarbonate for the smallest and intermediate notches but for the biggest notch the notch-strengthening effect is surprisingly much larger for perspex. Araldite LY-556

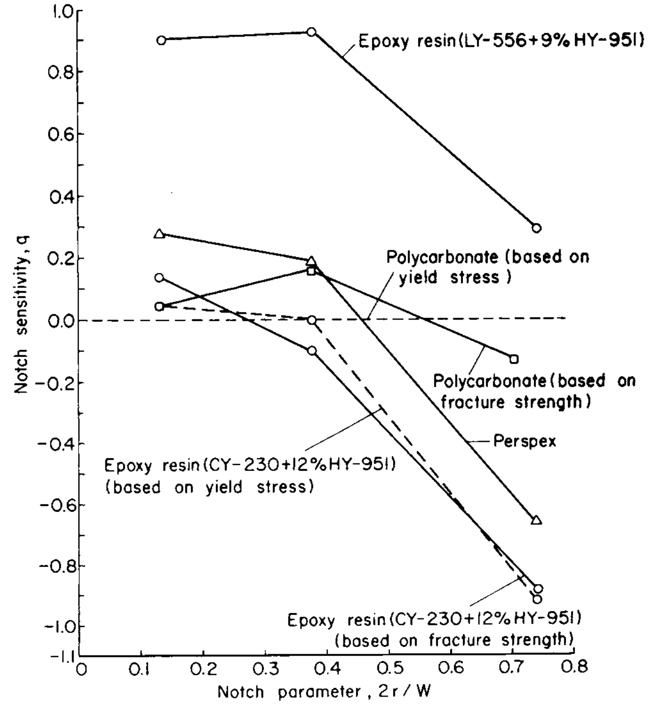

Fig. 3. Notch sensitivity of polymers in tensile loading.

shows a very high notch sensitivity (weakening effect) for the sharpest and intermediate notches but for the biggest notch the notch sensitivity decreases sharply. While Araldite CY-230 exhibits the greatest notch-strengthening effect for the biggest notch, the curve based on yield stress is very close to that based on fracture strength.

The influence of hardener percentage on the yield stress of Araldite CY-230 is shown in Figure 4. Only the sharpest notch shows a weakening effect and upto about 18% of hardener addition. The notch sensitivity for the various compositions is shown in Figure 5. For each notch size, while the curves based on yield stress and fracture strength are not identical, the differences are not very significant and the trends are the same. From this figure it is clearly seen that for all resin compositions there is a significant reinforcing effect in the case of the biggest notch.

The results of the low-cycle fatigue tests are shown in Figure 6. Only the ductile epoxy (Araldite CY-230) was tested in fatigue as this polymer exhibited the maximum notch-strengthening effect under static tensile loading. The actual fatigue test results are shown in the figure, illustrating scatter. The straight lines are the best-fitting lines obtained on the basis of regression analysis. The line for the biggest notch is seen to lie above that for unnotched specimens. The intermediate notch, which showed a strengthening effect in tensile tests now shows a weakening effect. The notch-sensitivity factor for fatigue, computed from eqs. (1) and (2) and Figure 6, is shown in Figure 7. As the cyclic life increases, there is a general tendency for the notch sensitivity to increase. It is also interesting to note that the intermediate notch shows the maximum notch sensitivity for large fatigue lives.

The influence of notches on the room-temperature creep rupture strength of Araldite CY-230 (cured with 12% hardener) is shown in Figure 8. The similarity between the low-cycle fatigue results (Fig. 6) and the creep results (Fig. 8) is remarkable. There is a notch-strengthening effect in the case of the biggest notch and the curves for the smallest and intermediate notches come close together as time (or the number of cycles, in fatigue) increases.

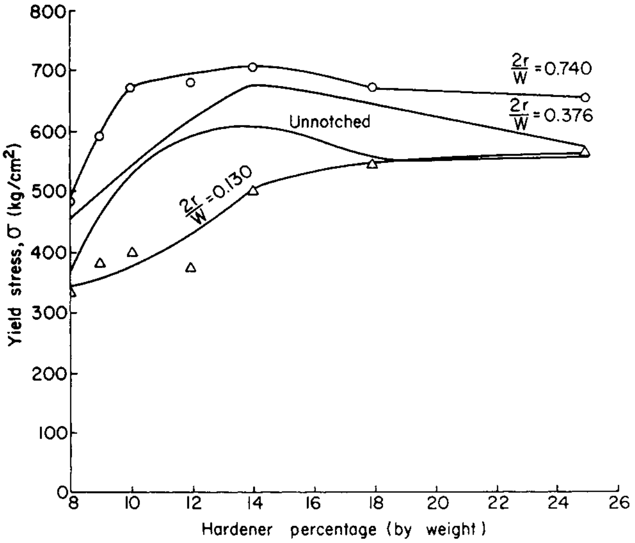

Fig. 4. Dependence of yield stress of Araldite CY-230 on composition.

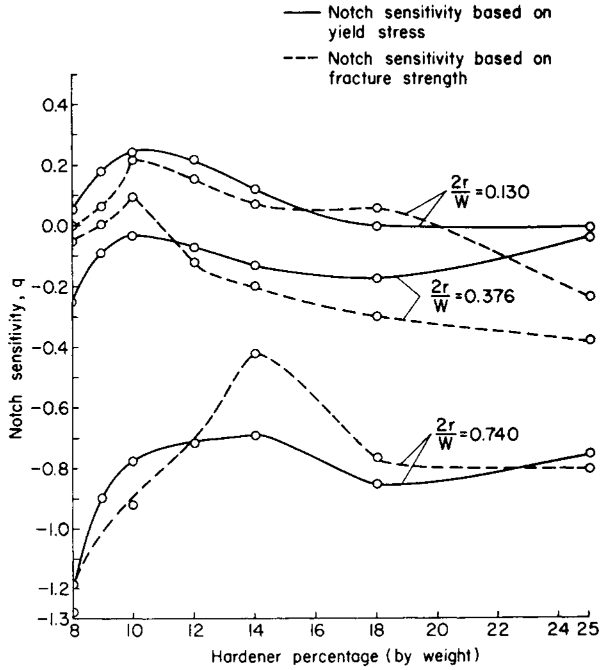

Fig. 5. Dependence of notch sensitivity of Araldite CY-230 on composition.

In the creep tests, the extension of the specimens was monitored continuously upto fracture. The results for unnotched specimens are shown in Figure 9, for various stress levels. The creep strain at the time of rupture clearly increases as the stress level is decreased.

The creep notch sensitivity factor is shown in Figure 10 as a function of time under load. There is an appreciable notch-strengthening effect for the biggest

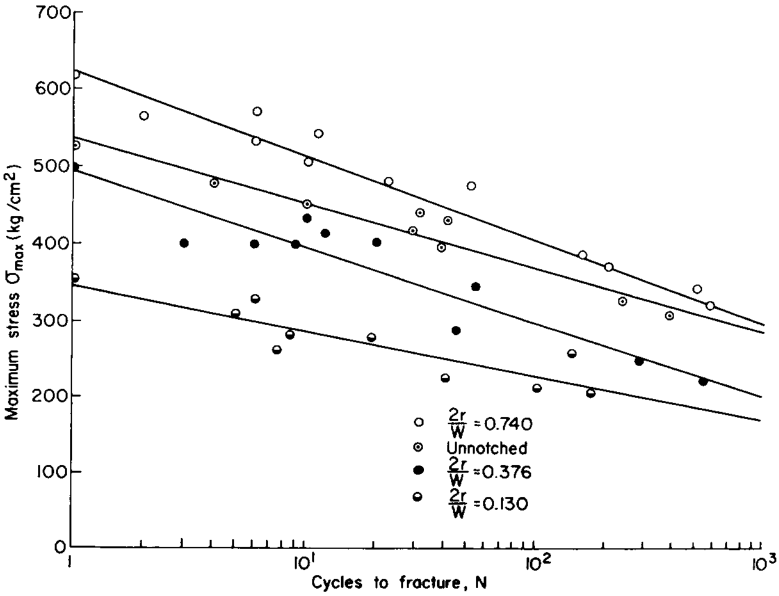

Fig. 6. S-N curves for unnotched and notched specimens of Araldite CY-230 (12% hardener).

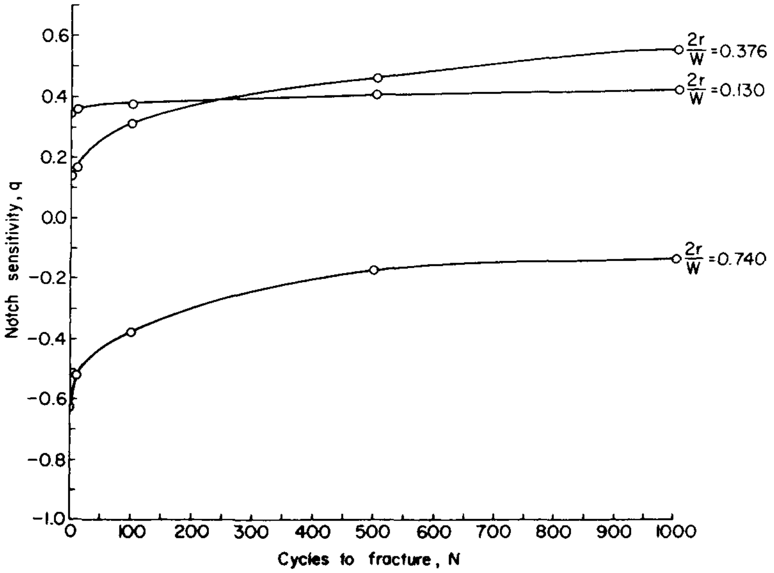

Fig. 7. Notch sensitivity of Araldite CY-230 (12% hardener) in low-cycle fatigue loading.

notch and this strengthening increases as time under load increases (in the case of low-cycle fatigue, the notch-sensitivity factor increased, or the strengthening effect decreased, as the number of cycles of fatigue life increased). The smallest and the intermediate notches show a weakening effect, with the intermediate notch becoming more severe than the smallest notch for longer times (similar to the low-cycle fatigue behavior).

Only Araldite CY-230 cured with 12% hardener was tested under the three types of loading (static tensile, fatigue, and creep). For this material the notch sensitivity results are summarized in Figure 11 for all three types of loading.

Results for a wide variety of polymers indicating their notch sensitivity in static tensile loading have been recently reported.[9] The notch sensitivity was defined

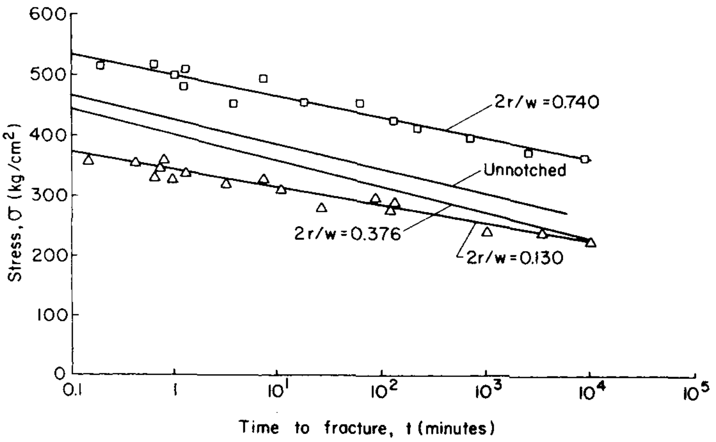

Fig. 8. Stress vs time to rupture curves for unnotched and notched specimens of Araldite CY-230 (12% hardener).

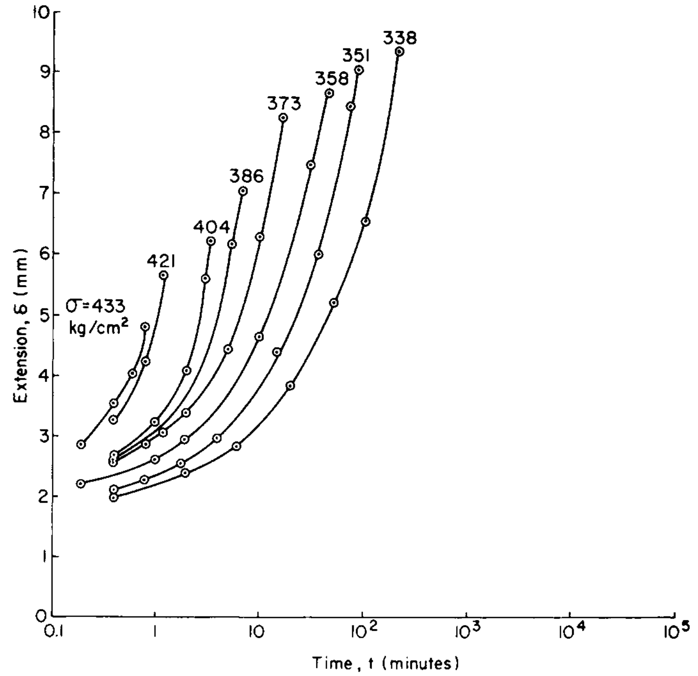

Fig. 9. Creep extension vs time for unnotched specimens of Araldite CY-230 (12% hardener).

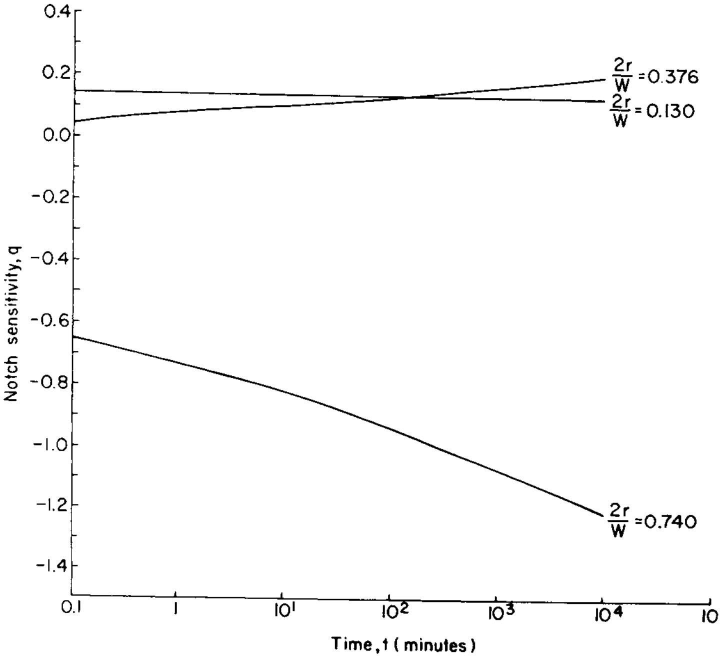

Fig. 10. Notch sensitivity of Araldite CY-230 (12% hardener) in creep loading.

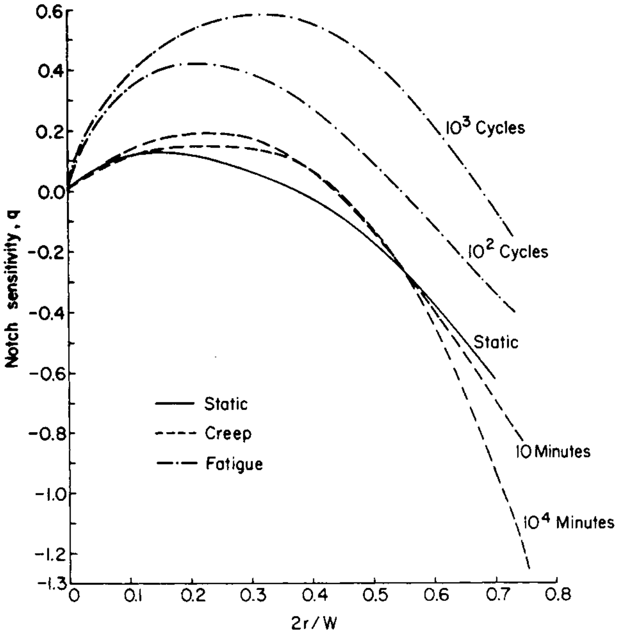

Fig. 11. Comparison of notch sensitivity of Araldite CY-230 (12% hardener) in tensile, fatigue, and creep loading.

in that study by the ratio

$$Ks = \frac{(\text{strength of unnotched specimen}) \times \dfrac{\text{residual cross-sectional}}{\text{area at the notch site}}}{(\text{strength of notched specimen}) \times \dfrac{\text{original cross-sectional}}{\text{area of unnotched specimen}}}$$

Values of Ks less than unity were reported for some polymers, such as polycarbonate, for some notches. However, this does not explicitly indicate a notch-strengthening effect as the ratio of the residual cross-sectional area at the notch site to the original cross-sectional area of unnotched specimen is included in Ks. The definition of notch sensitivity factor employed in the present investigation is quite commonly used in fatigue studies and clearly differentiates between notch strengthening and weakening.

Although the range in the elastic stress concentration factor K_t covered in this study was not broad, the possibility of some polymeric materials exhibiting a notch-strengthening effect under static tensile, low-cycle fatigue, and creep loading has been established. It has also been shown that it is possible for some polymers (such as Araldite LY-556) to show almost full notch sensitivity.

In a composite utilising a polymeric material as the matrix, the role of the matrix is greatest when the applied stress makes an angle of 45° with the reinforcement. The basic (unnotched) strength of the composite in this direction under tensile, fatigue and creep loading is a minimum (compared to other orientations). Therefore, if a notch strengthening effect can be introduced by employing a suitable matrix, the composite properties can be improved significantly.

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