FAILURE MECHANISMS OF COMPOSITE MATERIALS

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ABSTRACT

The approach is proposed allows to describe the nonmonotonous dependences of strength on loading rate and temperature. The three ranges of these dependences are connected with a possible change of failure modes. The special experiments on organoplastics have been carried out to affirme the proposed model.

KEYWORDS

Composite material; failure mode; damadge accumulation, macrocrack propagation; agglomerated failure.

INTRODUCTION

Nowdays quite an extensive literature material is available, identifying mechanisms of failure of composites, but how they depend on the character of loading, as well as their natural limits, still remain vague. But since mechanical models should be of use for evaluation strength of construction and crack resistance problem the information is obviously necessary.

It is clear that the increasing of loading rate (the temperature decreasing as well) applied to composites with polymer matrix is to result in gradual "freezing" of matrix, i.e. in lowering matrix viscosity. The effect is that the rigidity of the whole composite system rises and the comparatively high strength of fibres fails to be utilized.

It has been shown /1,2/ that the same material may fail in different ways depending on the rate of loading, complete fracture being either caused by the process of accumulation of damage, or macrocrack propagation. There may also appear some other forms of failure resulting from changing thermo or loading re-

gimes. For instance, the strength-loading rate diagram, as it has been noticed in /1/, comprises three areas due to different types of failure. In /2/ the first and the second of these areas have been described.

The aim of this paper is to further develop the ideas previously represented and to put forward an approach to analysis of the mechanisms of failure.

As previously the analysis is being carried out in terms of the hereditary type of deformation and failure processes. The constitutive equation for behaviour of a material being subjected to loading and representing viscousity as well as damage accumulation can be written as follows

$$E\varepsilon = \sigma + \mathcal{L}^*\sigma + M^*\sigma \qquad (1)$$

where two operators are present, $\mathcal{L}^*\sigma$ accounting for reversible deformation, $M^*\sigma$ - for irreversible deformation; E - being Youngs modulus.

$$\mathcal{L}^*\sigma = \int_0^t \mathcal{L}(t-\tau) f_\ell(T) \sigma(\tau) d\tau$$

$$M^*\sigma = \int_0^t M(t-\tau) f_m(T) \sigma(\tau) d\tau$$

$\mathcal{L}(t-\tau)$, $M(t-\tau)$ are kernels which one to be chosen, as well as temperature effects functions f_ℓ , f_m , from the macroexperiments data.

I. Failure due to damage accumulation

The irreversible deformation, as it is, is the result of damage accumulation process, i.e. the process of gradual material degradation. If the final fracture results from this particular process, the strength criterion, as it follows from (1), may be constructed as

$$\sigma + M^*\sigma = \sigma_0 \qquad (2)$$

Here σ_0 is a constant, determined from macroexperiment. The constant may be taken as the strength value of a defectless "ideal" material. It should be underlined that operator M^* in the equation (2) is the same as in the equation (1), permitting to determine all the strength criterion parameters, save σ_0 , from the stress-strain diagrams.

II. Failure due to macrocrack propagation.

With the increase of loading rate (or temperature decrease)

the resin is embrittling gradually and the initial matrix defects, as well as localized fibre breakages, become stress concentrators, the most dangerous of which developing into a macrocrack. In the case of a sufficiently viscous resin all defects become elongated, stress concentration decreasing to the out-of-danger values, failure then being of the 1-st type.

In /3/ the analysis of size defects changing has been made, showing the dependence on material macrocharacteristics . The following criterion has been obtained

$$\sigma\left(1 + \delta \frac{\sigma}{\sigma + M^*\sigma}\right) = \sigma_0 \qquad (3)$$

Here M^* and σ_0 are the same as in the equation (2), while δ is a constant, accounting for the initially induced defects state of the material and fibre-matrix bond, the latter exposing transition of loading to the fibres. As it follows from (3), the higher the rate of loading or the lower the σ temperature, the lower the value of $M^*\sigma$, hence, the lower the value of σ . This accounts for lowering strength with the increasing of loading rate if fracture is caused by crack propagation.

The illustration of the above mentioned types of failure as the function of loading rate and temperature is figure 1

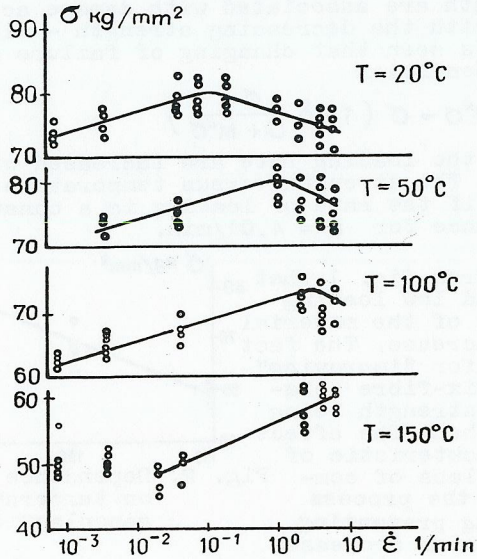

Fig. 1
Dependences of strength on loading rate and temperature for organoplastic.

exhibiting the strength charackteristics of a woven organoplastic. It has been experimentally proved, that for this material the governing equation can be chosen according to (1), kernels of creep and failure being as follows

$$\mathcal{L}(t-\tau)=\frac{\ell}{(t-\tau)^{\alpha}} \quad , \quad M(t-\tau)=\frac{m}{(t-\tau)^{\alpha}} \quad ,$$

and temperature effects functions being as follows

$$f_{\ell}(T)=(T/273)^{\gamma} \quad , \quad f_{m}(T)=(T/273)^{\gamma}$$

Kernels parameters values are shown below.

T°C	20	50	100	150
$m\, f_m\ (T)$	0,017	0,021	0,032	0,069
$\ell\, f_\ell\ (T)$	0,056	0,061	0,078	0,141
δ	0,23	0,25	0,41	-

$\alpha = 0{,}93$; $E = 4570$ kg/mm^2

The numerical results according to the equations (2),(3) are plotted in the diagrams (solid lines). Here the areas with the increasing strength are associated with damage accumulation, while the areas with the decreasing strength - with macrocrack propagation. It is seen that changing of failure mechanisms determined by the condition

$$\sigma + M^{*}\sigma = \sigma\left(1+\delta\frac{\sigma}{\sigma+M^{*}\sigma}\right)$$

takes place when the loading rate are increased with the increasing temperature. The strength versus temperature dependence is of the same kind if the rate of loading is a constant. Fig. 2 shows the dependence for $\dot{\varepsilon} = 4{,}01$/min.

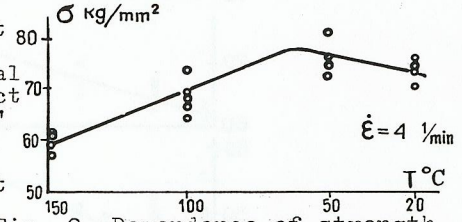

Fig. 2. Dependence of strength on temperature for organoplastic.

It can be taken from fig. 1 that with T = 150°C and low loading rate the strength of the material again tends to increase. The fact can be accounted for "improving" the combined matrix-fibre behaviour, the fibre strength being better utilized then. The effect seems to be charackteristic of this particular class of composites **in which the process** of resin crumbl**ing preventing** stress redistribution decreases their strength. As a matter of fact the temperature increasing and the loading rate decreasing improves the combined behaviour of the composite components.

The dependence of failure strain on loading rate and temperature can also be determined from the equations (1),(2). Obviously the stress-strain relationship for the failure moment is as follows

$$E\varepsilon = \sigma_0 + \mathcal{L}^{*}\sigma \qquad (4)$$

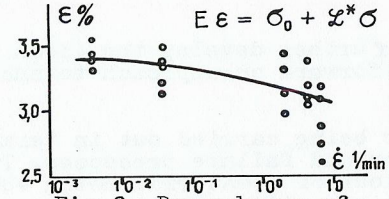

Fig. 3. Dependence of strain on loading rate for organoplastic.

Fig. 3 represents the corresponding curve for T=50°. It is seen that with the increasing loading rate the strain value decreases, which is usually associated with the viscous material behaviour.

III. Agglomerated failure due to fibre-matrix debonding.

Fig. 4

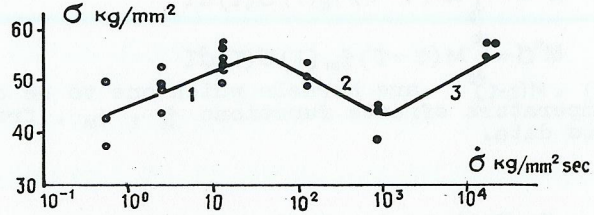

Fig. 4. Dependence of strength on loading rate for carbonplastic.

shows strength-loading rate dependence for carbonplastic, based on experimental data of /1/. In this plot one can see that, while the loading rates are comparatively high, the strength value increases with the increasing loading rate. The phenomenon may be accounted for as follows. The first two areas of the diagram show the composite system functioning as a "whole one". It is the process of damage accumulation that occurs in the first area. As far as the second area is conserned, the macrocrack is cross cutting the whole sample*. This remains valid if the failure strain value of resin exceeds that of fibres. While the latter is partically independent of the loading rate, the failure strain of resin shows substantial dependence (the higher the loading rate **the** smaller the strain value). So, under sufficiently high loading rates, the above mentioned strain condition results the fibre-matrix debonding. It is clear that the lower the failure strain of resin, the sooner the process starts with the resulting resin crumbling and complete fracture. Now a new type of damage accumulation process takes place which brings about fibre-matrix debonding and giving rise to separate agglomerates.

* It should be noted that in this case the crack propagation description methods used for metals are quite applicable for composite materials as well.

Since damage accumulation process is stress-redistribution dependent, which is associated with the combined fibre-matrix behaviour condition, now the failure criterion should be written as

$$\sigma + \int_0^{t_*} F(t-\tau)\sigma(\tau)d\tau = \sigma_0 \qquad (5)$$

where t_* - is the moment of fibre-matrix debonding initiation

The parameters of $F(t-\tau)$ are no longer equal to those for the first area, and t_*, as it should be noted, will be loading rate dependent. If the failure strain of resin versus loading rate data are available, $t_*(\dot\sigma)$ function can be determined from $\varepsilon_m(\dot\sigma)$ and $\varepsilon_f(\dot\sigma)$ comparison, "m" and "f" stand for matrix and fibre respectively. As long as we were lacking such data, t_* has been determined from macroexperiment (Fig. 4).

The condition of changing the second type of failure to the third one is as follows

$$\sigma\left(1+\delta\frac{\sigma}{\sigma+\int_0^{t_{*0}}M(t-\tau)\sigma(\tau)d\tau}\right)=\sigma+\int_0^{t_{*0}}F(t-\tau)\sigma(\tau)d\tau \qquad (6)$$

Here t_{0*} corresponds both to the moment of the changing and the moment $t_{0*}=t_*=t$, i.e. fibre-matrix debonding starts with the moment of macro failure. Further, with the loading rate increasing t_* will decrease. According to (5), if $t_*=0$, i.e. the resin has been initially crumbled away with the bare bundle of fibres remaining, then $\sigma=\sigma_0$, being theoretical strength. The result agrees with the accepted model lacking any statistic representation. Taking statistics into account will improve the accuracy of the results.

The calculations according to (5),(6) are plotted in fig. 4, the kernel parameters being as follows

$$F(t-\tau)=\frac{f}{(t-\tau)^\alpha}\ ,\quad \alpha=0{,}92\ ,\quad f=0{,}59\ s^{-(1-\alpha)}$$

$t_*(\dot\sigma)$ according to (5) is given below (t being the moment of macroscopic failure).

$\dot\sigma$ kg/mm^{2}sec	8 10	100	1000	10000
t, sec	0,53	0,42	0,048	0,0055
t_*, sec	0,53	0,21	0,004	0,00006
σ kg/mm^2	41,5	42,5	48	55

The changing of types of failure took place when

$\dot\sigma$ = 80 kg/mm^2 sec, $t_* = t_{*0} = t$ = 0,53 sec

It is seen that under very high loading rates the debonding starts rapidly, yet the strength values are comparatively high, if

$\dot\sigma$ = 10^4kg/mm^2 sec, σ = 53 kg/mm^2 which is quite near σ_0.

So, the alternation of loading regime obviously results in changing the type of failure. Thus, the most dangerous area will be the second one, where failure is due to macrocrack, that is why optimization should be directed to preventing macrocrack propagation (e.g. by developing certain fibre-matrix bond charackteristics, that is improving interface properties).

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