CRITERION OF ADHESION STRENGTH IN THE PRESENCE OF NORMAL AND SHEAR STRESSES

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A criterion of the short-time adhesion strength is proposed for the case where the interphase surface is subjected to the combined action of normal and shear stresses. The proposed criterion is based on the assumption that at the moment of adhesion failure a definite relation exists between τ_{oct} and σ_{oct}. The proposed criterion has been experimentally confirmed.

One of the principal characteristics of reinforced plastics is the fact that their structural elements – reinforcement, matrix and contact layer – do not fail simultaneously, since their strengths are usually very different. In many cases of loading the strength of the reinforced plastic may be determined both by the strength of the matrix and by the matrix-reinforcement bond strength, depending on which is the lower. Thus, for example, in [1, 2] criteria of the strength of reinforced plastics in tension at an angle to the directions of reinforcement are given for the case where the bond strength is greater than the strength of the matrix. At the moment it is difficult to estimate the effect of the adhesion strength of the contact layer on the overall strength of the reinforced plastic owing to the lack of suitable bond strength criteria in which the actual state of stress of the contact layer is taken accurately into account. One of the reasons for the development of phenomenological criteria is the fact that the physicochemical nature of the adhesion forces acting on the internal interphase surfaces is not yet clear. There are several theories which even in the simplest cases give only a qualitative picture of the effect. Thus, for example, the adsorption theory explains adhesion in terms of the interaction between the surface molecules of the contacting phases [3]. Weyl [4], in considering the adhesion of high polymers to glass, assumes that all the molecular forces – orientation, induction and dispersion – may participate in the interaction processes. Hamaker [5] determined the force of attraction of two condensed systems starting from the dispersion interaction of their molecules. In recent years theoretical and experimental studies have been carried out with the object of applying Hamaker's theory to simple systems [6-8].

In [9-11], in order to account for effects that do not satisfy the adsorption theory, the electric theory of adhesion was worked out. This theory is based on the assumption that the system of contacting phases forms a capacitor, and that the electric double layer formed at the contact of two unlike bodies forms the plates of the capacitor. The pros and cons of the electric theory are discussed in [12].

One of the processes taking place at a phase interface is interdiffusion. The principles of the diffusion theory of adhesion are explained in [13, 14]. The effect of diffusion processes on adhesion has been investigated by a number of authors [15-17].

In [18] as a result of an investigation of the strength of glued joints, it was concluded that the strength of the joint is a purely mechanical property and accordingly could be considered from the standpoint of mechanics. It was established that the joint almost never fails precisely along the phase surface. The author of [18] asserts that adhesion as an independent entity does not exist and that the molecular forces acting between phases do not determine the strength of the bond. This assertion is based on the fact that the interphase surface has an uneven microrelief. Accordingly, the probability that failure will occur along the interphase surface is low. This thesis is criticized in [19].

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In some studies [9, 20] adhesion is considered from the standpoint of thermodynamics. Thus, for example, in [20] the temperature dependence of the bond failure activation energy is obtained on the assumption that adhesion at the phase interface is attributable to the intermolecular forces.

Crack theory is also beginning to be used for determining the adhesion strength [21-25].

Many studies have been devoted to the purely experimental investigation of adhesion strength [12, 26-29].

In all these theoretical and experimental studies of the adhesion strength only one normal or tangential stress has been involved. As shown, for example, in [30], in reinforced plastics both normal and tangential stresses act at the phase interface. Physical bond strength criteria have not yet been developed for this combined state of stress. Accordingly, we will adopt a phenomenological approach. In order to simplify the problem we will consider the case where both contacting surfaces are flat. In practice this case occurs in plastics reinforced with films. The contact layer in such materials may be disturbed by the action of either tensile or shear stresses. In order to determine the strength of the contact layer we employ a strength criterion according to which at the moment of failure a certain relation exists between the octahedral stresses:

$$\tau_{oct}=F(\sigma_{oct}). \tag{1}$$

In the first approximation we may assume a linear relation between σ_{oct} and τ_{oct}, and in this case criterion (1) takes the form:

$$\tau_{oct}=a-k\sigma_{oct}, \tag{2}$$

where a and k are characteristics of the adhesion strength of the contact layer. In the case of combined shear and tension or compression the octahedral stresses are given by

$$\tau_{oct}=\frac{\sqrt{2}}{3}\sqrt{\sigma^2+3\tau^2}\,;\quad \sigma_{oct}=\frac{\sigma}{3}. \tag{3}$$

If the contact layer is loaded only by a tensile load acting at right angles to the contact surface, then $\tau=0$ and at failure $\sigma=R_b$. In this case the breaking octahedral stresses are given by

$$\tau_{oct}=\frac{\sqrt{2}}{3}R_b\,;\quad \sigma_{oct}=\frac{R_b}{3}. \tag{4}$$

In the case of pure shear $\sigma=0$ and at failure $\tau=T_b$. Then

$$\tau_{oct}=\frac{\sqrt{6}}{3}T_b=a;\quad \sigma_{oct}=0. \tag{5}$$

From Eq. (2) there follows

$$k=\frac{a-\tau_{oct}}{\sigma_{oct}}. \tag{6}$$

Substituting a from (5) and (6) and using relations (4), we obtain

$$k=\frac{\sqrt{2}\sqrt{3}T_b-\sqrt{2}R_b}{R_b}, \tag{7}$$

where R_b is the bond strength of the contact layer in normal tension; T_b is the shear strength of the contact layer.

Using relations (5) and (7), we can rewrite Eq. (2) in the following form:

$$\tau_{oct}=\frac{\sqrt{2}\sqrt{3}}{3}T_b-\frac{\sqrt{2}\sqrt{3}T_b-\sqrt{2}R_b}{R_b}\sigma_{oct}. \tag{8}$$

Substituting σ_{oct} and τ_{oct} from (3) in (8), after suitable algebra we obtain the following criteria for the strength of the contact layer:

a) if the contact layer is acted upon by shear stresses τ and normal tensile stresses σ,

$$\tau\leqslant\frac{\sqrt{3}}{3}\sqrt{\left[\left(\sqrt{3}\frac{T_b}{R_b}-1\right)^2-1\right]\sigma^2-2\sqrt{3}T_b\left(\sqrt{3}\frac{T_b}{R_b}-1\right)\sigma+3T_b^2} \tag{9}$$

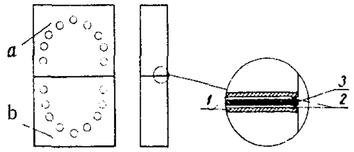

Fig. 1. Device for the experimental investigation of adhesion strength: a, b) metal parts; 1) epoxy resion; 2) glass film; 3) polyester resin.

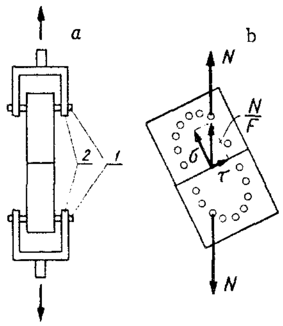

Fig. 2. Application of the load to the interphase surface: 1) pins; 2) shackles.

or

$$\sigma \leqslant \frac{\sqrt{3}T_b\left[\sqrt{3}\frac{T_b}{R_b}-1\right]}{\left[\sqrt{3}\frac{T_b}{R_b}-1\right]^2-1}\left[1-\sqrt{\frac{\left[\left(\sqrt{3}\frac{T_b}{R_b}-1\right)^2-1\right](T_b^{\,2}-\tau^2)}{T_b^{\,2}\left[\sqrt{3}\frac{T_b}{R_b}-1\right]^2}}\right]; \quad (10)$$

b) if the contact layer is acted upon by shear stresses τ and normal compressive stresses σ, then instead of (9) we have

$$\tau \leqslant \frac{\sqrt{3}}{3}\sqrt{\left[\left(\sqrt{3}\frac{T_b}{R_b}-1\right)^2-1\right]\sigma^2+2\sqrt{3}T_b\left(\sqrt{3}\frac{T_b}{R_b}-1\right)\sigma+3T_b^{\,2}}. \quad (11)$$

We note that in criteria (9) and (11) σ denotes the normal stresses acting at right angles to the contact surface and τ the shear stresses acting in the contact plane.

The methods and results of experimental research on the bond strengths R_b and T_b are reviewed in [26, 31].

Special experiments were conducted in order to verify criterion (9). The normal and shear stresses were applied to the interphase surface in a given ratio by means of the special device shown in Fig. 1. This device consisted of two identical steel parallelepipeds a and b, to which a glass film 40 μ thick was bonded with epoxy resin. Then the surface of the glass was rinsed with ethanol, dried and coated with a film of polyester resin. The parallelepipeds were clamped together in pairs and placed in an oven where the polyester resin was polymerized for 48 h at 70°C.

The method of securing these devices in the testing machine is illustrated in Fig. 2a. If at the moment of failure of the bond the tensile force is equal to N and the bond surface area to F (Fig. 2b), then the critical values of the normal and shear stresses acting on the contact surface are $\sigma = (N/F)\sin\alpha$; $\tau = (N/F)\cos\alpha$. Here, α is the angle between the direction of the load N and the shear stress τ. The given ratio of the stresses σ and τ is controlled by the angle α, which in our experiments took the values 30, 45, 60, 75, and 90°. At each angle we carried out 32 tests. The results of the tests are given in Fig. 3.

The value of T_b (at $\alpha = 0°$) cannot be determined with the device described. For this purpose we employ the method illustrated in Fig. 4.

It should be noted that the joint does not always fail along the glass–resin interface. In those instances where failure occurred partially in the polyester and partially along the interface a decrease in the failure load N was observed.

Accordingly in Fig. 3 we have plotted only the maximum values of the failure stresses corresponding to failure along the interface. In all the cases the loading rate was 4 kgf/sec.

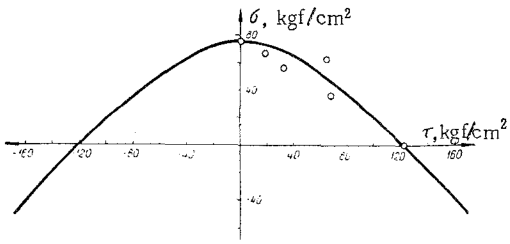

Fig. 3

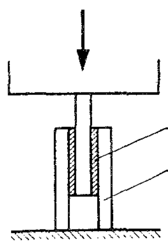

Fig. 4

Fig. 3. Results of an experimental investigation of the adhesion of polyester resin to a glass film under the combined action of the stresses σ and τ. Theoretical curve based on relation (9).

Fig. 4. Loading scheme for determining the bond strength in shear T_b: 1) glass; 2) polyester resin.

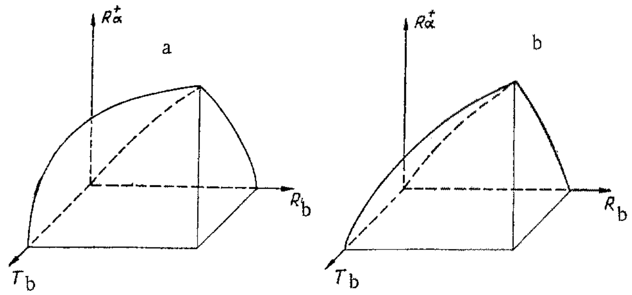

Fig. 5. Dependence of the strength R_α^+ on the orientation of the reinforcement (i.e., the angle α) and the bond strengths R_b and T_b. a) $\alpha = 15°$; b) $60°$.

The theoretical curve in Fig. 3 is based on relation (9) with $R_b = 75$ kgf/cm² and $T_b = 120$ kgf/cm². It is clear from the figure that criterion (9) gives a satisfactory description of the limiting curve for failure along the interface.

For the same combination of reinforcement and resin R_b and T_b depend strongly on the surface treatment of the fibers. The surface treatment is especially important in the case of carbon fibers [32].

Denoting the applied tensile stress at failure by $R_\alpha^+ = N/F$, from criterion (2) we obtain the following expression for determining the strength of the composite as a function of the bond strengths T_b and R_b:

$$R_\alpha^+ = \frac{\sqrt{3}T_b R_b}{R_b \sqrt{\sin^2\alpha + 3\cos^2\alpha} + (\sqrt{3}T_b - R_b)\sin\alpha}. \tag{12}$$

Here it should be noted that Eq. (12) makes it possible to determine the strength of a reinforced plastic under the following conditions: a) the cause of failure of the reinforced plastic is failure of the contact layer, i.e., the strength of the matrix is greater than the bond strength (adhesion); b) the state of stress of the contact layer, i.e., the interphase surface, is homogeneous (this is the case, for example, with plastics reinforced with films).

The dependence of R_α^+ on the bond strengths T_b and R_b and the reinforcement angle α is shown in Fig. 5.

CONCLUSIONS

1. A criterion of the adhesion strength of flat surfaces subjected to the combined action of uniformly distributed normal and shear stresses is proposed and experimentally confirmed.

2. The tensile strength of a film-reinforced plastic is determined for the case when the bond strength is less than the strength of the matrix.

3. The effect of the bond strengths in normal tension and shear on the tensile strength of the reinforced plastic is investigated.

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