

# DYNAMIC FRACTURE OF NOTCHED COMPOSITE LAMINATES

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**SUMMARY:** Dynamic loading including impact are of great importance in manufacturing and exploitation of composite materials. Hence, the development of methods for crack resistance estimation is the keynote problem for reinforced plastics. The impact behavior of composites depend on such factors as the material structure (physical-mechanical properties of material, volume of the components, specific conditions of manufacturing), environmental and exploitation conditions (temperature, moisture, loading parameters, etc.) [1-3]. As a result, development of methods for fracture analysis including appropriate model for crack origin, its start and moving, is of great difficulty. The theoretical-experimental method is proposed for determining the parameters of impact fracture of composite materials.

**KEYWORDS:** fracture resistance, composite laminates, impact loading, stress intensity factor.

## ANALYTICAL-EXPERIMENTAL METHOD FOR DETERMINING THE CRACK RESISTANCE PARAMETERS OF COMPOSITES UNDER IMPACT BENDING

Let us consider three point bending of a composite bar subjected to impact loading. Multilayered material of a bar has a symmetrical structure with respect to the middle reference surface.

The principal scheme of impact loading in the case of dynamic bending is as follows. Consider the composite bar of length  $h$  and width  $t$ , which is rested on two supports. The distance between supports is equal to  $L$ . In the case under consideration, the length of a bar is slightly exceeds the distance between the supports; the value of this overlap is of no matter. The bar in its bottom part has a cross notch, which is located symmetrically with respect to the supports. The initial length of the notch before loading is equal to  $a$  and the initial width of the notch is equal to  $\delta$ . The shape of the notch is considered to be ellipse. Hence the radius of curvature in the top of the crack can be presented by the formula

$$\rho = \left( \frac{\delta}{2} \right)^2 \cdot \frac{1}{a}, \quad (1)$$

where  $a$  and  $\delta$  are the principal and minor axes of the ellipse.

The local impact loading  $P$  is applied vertically to the plane surface of the bar.

The stress intensity factor  $K_I$  is related to the coefficient of stress intensity  $K_t$  for the notch with rounded edges of the radius  $\rho$ , by the following formula [1]

$$K_I = \frac{1}{2} K_t \sigma \cdot \sqrt{\pi \rho} . \quad (2)$$

In the case of bending, we have

$$K_I = \sigma \cdot \sqrt{a} \cdot Y(\bar{a}) , \quad (3)$$

where  $\bar{a} = a/h$  and  $Y = Y(\bar{a})$  is some function to be determined.

On substituting (3) into (2), we can represent the curvature radius as follows

$$\rho = \frac{4a \cdot Y^2(\bar{a})}{K_t^2 \cdot \pi} . \quad (4)$$

The coefficient of concentration  $K_t$  is determined by the ratio of the stress in the top of the crack  $\sigma_A$  and the nominal stress  $\sigma$ . In the case of loading under consideration,  $\sigma_A$  can be expressed as follows [4]

$$\sigma_A = \frac{PL}{4I} \left[ (a+d) + k \frac{a+2d}{2} (\beta_1 + \beta_2) \right] , \quad (5)$$

where  $I$  is the moment of inertia of the cross-section of the bar,  $d$  is the distance from the neutral axis,  $\beta_1$  and  $\beta_2$  are imaginary parts of the roots  $\mu_1$  and  $\mu_2$  of the characteristic equation for the composite material, respectively, and  $k = 2a/\delta$ .

The nominal bending stress can be calculated by well-known formula

$$\sigma = \frac{3PL}{2t \cdot h^2} . \quad (6)$$

As a result, we can write the following formula for the stress intensity factor

$$K_t = \frac{\sigma_A}{\sigma} = \frac{2}{h} \left[ (a+d) + k \frac{a+2d}{2} (\beta_1 + \beta_2) \right] . \quad (7)$$

Equating the expression (1) and (4), we get

$$a = \frac{\delta \cdot K_t}{4Y(\bar{a})} \cdot \sqrt{\pi} . \quad (8)$$

Substituting (8) into (3) and taking into account (7), we arrive at

$$K_I = \sigma \frac{\sqrt{\delta \cdot Y(\bar{a})}}{\sqrt{2h}} \cdot \sqrt[4]{\pi} \cdot \sqrt{\left[ (a+d) + k \frac{a+2d}{2} (\beta_1 + \beta_2) \right]} . \quad (9)$$

If the bar is subjected to the impact loading, the corresponding value of the stress intensity factor can be obtained by formula (9). To do this, it is necessary to substitute into (9) the value of the notch opening  $\delta_y$ , which could be determined from the impact experiment. Modern experimental installations for impact loading include electronic devices that allow us to find the displacement  $\Delta$  of the impact load point. Knowing this displacement, we can determine the opening  $\delta$  :

$$\delta = \frac{4\Delta \cdot [a + 2(h-a)]}{L} . \quad (10)$$

Thus, it is possible to calculate the value of  $\Delta$  at any moment on the base of experimental curve  $P-\Delta$  (loading - displacement of the point where the load is applied). Moreover, we can calculate the value of  $\delta$  by relation (10) and, hence, determine the stress intensity factor in the case of impact loading by formula (9).

#### **ANALYTICAL-EXPERIMENTAL METHOD FOR DETERMINING THE CRACK RESISTANCE PARAMETERS OF COMPOSITES UNDER IMPACT TENSION**

Let us consider the tension of composite bar with central notch. In this case, the coefficient of concentration of stresses in the top of the crack can be obtained by formula [4]

$$K_t = 1 + \frac{2l}{\delta} (\beta_1 + \beta_2) . \quad (11)$$

After analysis similar to the case of bending, we can write out the final formula for impact tension as follows

$$K_I = \frac{1}{2} G \cdot \sqrt[4]{\pi} \cdot \sqrt{Y(\bar{l})} \cdot \sqrt{\delta + 2l \cdot (\beta_1 + \beta_2)} , \quad (12)$$

where  $\bar{l} = l/h$  and  $\delta = P/F$ ; here  $F$  is the cross-section area of the bar.

#### **EXPERIMENTS**

For determining the impact crack resistance  $K_I$ , we use composite bars of rectangular cross-sections. The geometrical characteristics of composite specimens are as follows: the height  $h = 12 \dots 13$  mm, the width  $t = 9.2 \dots 9.8$  mm; the distance between supports  $L = 80$  mm; the length of notch  $a = 3 \dots 4$  mm.

The diagrams  $P(\Delta)$  and  $E(\Delta)$  were obtained as a result of tests on impact bending. If we know the geometry of a specimen and the value of  $\Delta$ , we can calculate the notch critical opening  $\delta$  .

It is necessary to determine preliminary the image parts  $\beta_1$  and  $\beta_2$  of the roots of the material characteristic equation and calculate by the correction function  $Y = Y(\bar{a})$  (see [4]). Then we can determine the critical impact stress intensity factor  $K_{Ic}$  by formula (12) (see Table 1).

Table 1: Critical impact stress intensity factor

Material	$K_{Ic}$ , N/mm <sup>3/2</sup>
EF32-301	1840
T-25(VM) $\varphi = 0^\circ$	3430
T-25(VM) $\varphi = 45^\circ$	2070
VMS-6 $\varphi = 0^\circ$	5150
VMS-6 $\varphi = 25^\circ$	3320
LU-3	1990
EDT-10 $\varphi = 5^\circ$	4050

The impact tests for glass-epoxy specimens T-25(VM) with various length of initial notches  $a_1 = 4$  mm and  $a_2 = 3$  mm were conducted to determine the influence of the change of kinetic energy on the value of  $J$ -integral. The values of dynamic  $J$ -integrals calculated by the above-described method are presented in Table 2.

Table 2: Dynamic  $J$ -integral

$\delta$ , mm	$J_I$ , N/mm
0.1	1.10
0.2	4.15
0.3	9.2
0.4	16.3
0.5	25.3
0.6	36.5
0.7	49.3

The final (critical) value of  $J_{Ic}$ -integral, which corresponds to the beginning of fracture, is equal to 49.3 N/mm.

The experimental results are in a good agreement with the theoretical estimations.

The comparisons of the static value  $J_{Ic} = 212.0$  N/mm and dynamic one  $J_{Ic} = 49.3$  N/mm shows that the value of critical  $J$ -integral depends significantly on the velocity of deformation.

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