Low-Velocity Impact Damage in Graphite-Epoxy Laminates Subjected to Tensile Initial Stresses

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Abstract

LOW-VELOCITY impact tests in the velocity range of 10-40 m/s were conducted with graphite-epoxy laminated beams as targets. In some of the tests the beams were subjected to tensile initial stresses. The delamination area was measured by ultrasonic C-scanning. The damage was characterized by the reduction in tensile strength and by the delamination area. It was found that tensile initial stresses reduce the threshold impact velocity for damage, but beyond certain impact velocity they may help in containing delamination.

Contents

The presence of tensile stresses in beams or plates gives rise to an apparent stiffening effect that reduces the incremental deformation. On the other hand, the initial stress combined with incremental stress may cause more damage in the structures.

In the present experimental study low-velocity impact tests in the velocity range of 10-40 m/s were conducted with SP313 graphite-epoxy laminated beams as targets, and a 12.5 mm diameter steel ball as the impactor. Some of the specimens were under tensile initial stresses during impact. The laminate configuration was $[0_2/90_2/0_2/90_2/0_2]_s$. Specimens of 38 mm width were held between two rigid clamps and the initial stresses were applied by pulling the clamps apart using a pneumatic cylinder. The effective span of a specimen was 180 mm. The impactor was propelled by a sudden release of pressurized air into the delivery tube. The velocity was computed from the travel time of the projectile between two photodetectors mounted on the delivery tube.

We assumed that an impacted specimen has suffered damage if there was any delamination detectable by ultrasonic C-scanning or if there was a reduction in the ultimate tensile strength. The threshold velocity for damage was defined as the minimum impact velocity required to initiate damage in the specimen. Because of the wide scatter in experimental data, precise determination of the threshold velocity may require a larger number of specimens. So, the best estimate of threshold velocity was assumed to be the average of the maximum velocity that did not cause any damage and the minimum velocity that caused some damage. The ultrasonic C-scanning technique measured the damage to the front, middle, and back side of the specimen. The damage levels in a specimen were coded with numbers 0-9. Thus, a 0 in the digital output (Fig. 1) represents an area of 0.75×0.75 mm in the specimen where there is no damage. A 9 indicates maximum damage within that specimen.

There were two types of cracks readily visible after impact. There was always a single longitudinal crack on the back surface symmetric about the impact point. The length of the crack varied 10-50 mm. This splitting of 0 deg layer was assumed to be caused by the σ_{yy} stresses due to platelike behavior of the laminated beam during impact. (Note: The laminate was assumed to be in the *xy* plane with the longitudinal axis of the beam parallel to the *x* axis.) The second set of cracks were on the impact side. Two parallel longitudinal cracks were observed on either side of the impact point. They were separated by about 5 mm. Such splitting occurred only at higher impact velocities.

Another interesting observation was made about the shape of the delamination areas. From the C-scan results, it was found that a damage area on the front side (impact side) was always on either side of the longitudinal axis of symmetry. A representative C-scan output is shown in Fig. 1. On the front side, the damage along the longitudinal centerline was nil or minimal in some cases, whereas on the back side there were two damage areas on either side of the transverse line of symmetry. In the middle layers, there were delaminations in all four quadrants, but the shapes were closer to that in the back

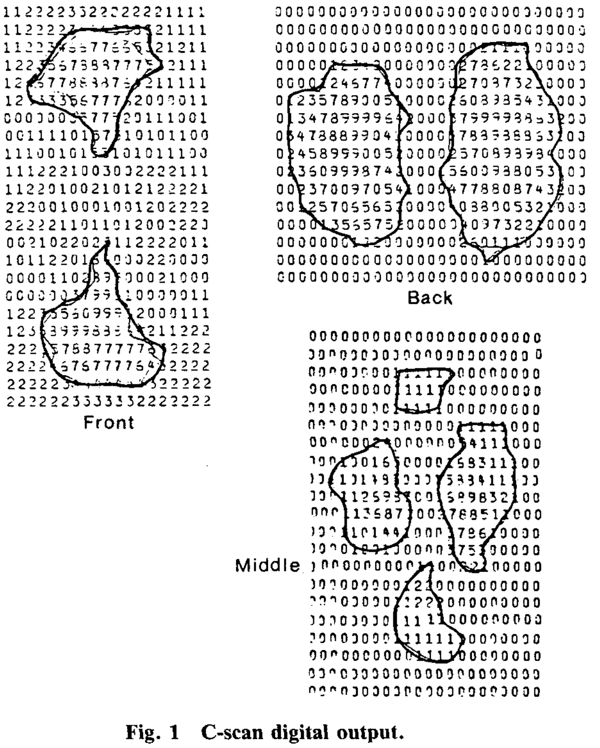

Fig. 1 C-scan digital output.

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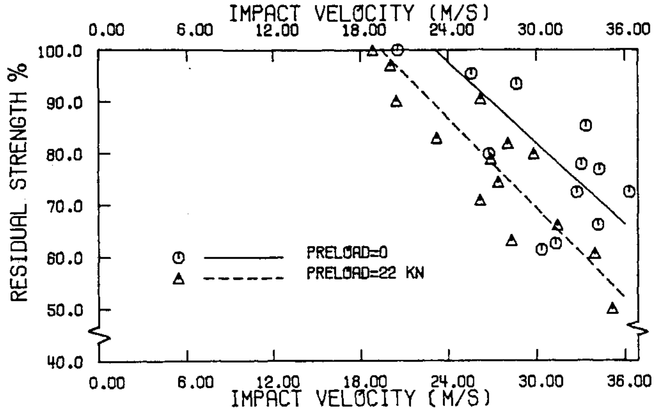

Fig. 2 Effect of initial stresses on the residual strength.

Table 1 Threshold impact velocities for different types of damage

Types of damage	Threshold velocity, m/s Preload = 0 kN	Preload = 22 kN
Delamination in the front portion (i.e., impact side)	22.5	18.8
Delamination in the middle and back portions	22.5	16.2
Reduction in tensile strength	22.5	18.8

side in two out of three cases. The consistency of these shapes in most of the specimens gave us confidence in our ability to map the delaminations at different depths using ultrasonic C-scanning. It should be noted that the shapes shown in Fig. 1 correspond to an impact velocity close to the threshold velocity. At higher velocities, the delaminations spread in all directions.

Two sets of impact tests were conducted, one without any preload and the other with a preload of 22 kN, which was about one-third of the ultimate strength of virgin specimens. Table 1 gives the threshold velocities for different types of damage. The results of C-scanning were as follows. The damage area in the front side was always larger in the presence of initial stresses. However, the damage areas in the middle and back portions showed a different behavior. In the velocity range of 16-30 m/s, the damage areas in the middle and back portions were larger in the initially stressed beam. Beyond 30 m/s, the damage area started decreasing in the presence of initial stresses and the area of damage was less in the prestressed beams.

The residual tensile strength of impacted specimens is given in Table 2. Because the specimens were cut from different panels, there was scatter in the data. So, the residual strength values were expressed as the percentage of tensile strength of virgin specimens cut from the corresponding panel. This is plotted in Fig. 2. It is seen that the initial stresses cause more reduction in strength than in the specimens impacted without initial stresses. This suggests that strength reduction may be due to fiber breakage during impact.

Table 2 Residual tensile strength of impacted specimens

Panel No.	Preload, kN	Impact velocity, m/s	Ultimate strength, kN
1	0	0	80.7(100)[a]
	0	26.8	64.5(80)
	0	30.3	49.5(61)
	0	34.2	53.4(66)
	22	27.4	60.1(75)
	22	31.4	53.4(66)
	22	33.9	49.0(61)
2	22	9.1	60.1(98)
	22	14.8	62.7(102)
	22	20.0	59.6(97)
	22	26.9	48.5(79)
	22	26.2	55.6(91)
3	0	0	72.3(100)
	0	32.7	52.4(73)
	0	34.2	55.6(77)
	22	29.8	57.9(80)
4	0	0	71.2(100)
	0	20.6	72.3(102)
	0	33.3	61.2(86)
	22	20.4	64.7(91)
5	0	0	72.9(100)
	0	25.6	69.5(95)
	0	28.6	68.1(93)
	0	36.3	52.8(72)
	22	26.1	51.7(71)
	22	28.3	46.1(63)
	22	35.1	0.(0)
6	0	0	72.9(100)
	0	31.3	45.6(63)
	0	33.0	56.7(78)
	22	18.8	72.9(100)
	22	23.2	60.5(83)
	22	28.0	59.7(82)

[a] Numbers in parentheses are residual strength as the percentage of strength of virgin specimens.

In the tension tests, specimens impacted under preload suffered a clean cut at the impact point. There was not much delamination and it resembled the failure of virgin specimens, whereas the specimens impacted without any preload showed more delamination in the impact area after failure in the tension tests.