COMPRESSIVE RESIDUAL STRENGTH PREDICTION IN FIBER-REINFORCED LAMINATED COMPOSITES SUBJECTED TO IMPACT LOADS

V. Sarma Avva* and H. L. Padmanabha**

**Department of Mechanical Engineering, North Carolina A. and T. State University, Greensboro, NC, USA*

***ABC of Hartsville, Inc., Hartsville, SC, USA*

ABSTRACT

This article is concerned with the experimental determination of the failure threshold of a graphite/epoxy material system subjected to low velocity projectile impact. The experimental results were compared with the results obtained using a proposed analytical model and the comparison was found to be good.

KEYWORDS

Composite materials; compression mode; low velocity impact; residual strength prediction and validation.

INTRODUCTION

Due to the advantage of high strength to weight ratio, advanced composite materials are being used increasingly in the design of aircraft structures. One of the problems that required attention in the use of the composite materials was the load-carrying ability of these materials subjected to the impact of foreign objects. Aircraft structural components could be damaged due to impact by hard and soft objects (stones, rivets, birds, etc.) resulting in their strength degradation. Hard-object impact causes mainly local damage resulting in major degradation of strength or subsequent fatigue failure. Soft-body impact causes large deformations which might result in overall structural failure. In general, the static residual strength of the composite materials decreases as the velocity of impacting object increases. It reaches a minimum value at or near the complete penetration of the impacting body. Beyond the complete penetration, the residual strength is very slightly higher than the minimum because the initial penetration causes more damage by removing material around the hole than the damage caused when the velocity is high enough to produce a clean hole.

There have been numerous studies, both experimental and theoretical, associated with the behavior of the laminated composite materials subjected to low velocity projectile impact. Some of the theoretical models proposed by various authors deal with the study of the effect of implanted flaws of known dimensions on the load-carrying ability of the composite laminates. The extent of the damage caused by the impact of a hard or soft object to the laminate, resulting in its strength degradation, is hard to determine precisely.

The purpose of the present study was to determine the failure threshold of a graphite/epoxy composite laminate subjected to low velocity projectile impact. In order to predict the strength degradation due to impact loads, an analytical model was developed. Analytical results were compared with the experimental values to verify the applicability of the model. The projectile used in simulating the impact damage was a 12.7 mm (0.5") diameter aluminum sphere. The forward velocity range used in these tests was varied from 18.3 to 106.7 m/s (60 to 350 ft/s). To determine the actual kinetic energy absorbed by the specimen, the rebound velocity of the projectile was measured using a special technique as presented in this paper.

ANALYTICAL MODEL

Waddoups, Eisenmann and Kaminski (1971) developed a method for predicting the strength of fiber-reinforced composite materials with an induced flaw. Whitney and Nuismer (1974), Nuismer and Whitney (1975) made use of point- and average-stress criteria to derive failure criteria for notched composite specimens. Various theoretical approaches to study the behavior of notched composites based on linear elastic fracture mechanics and other methods were reviewed by Yeow, Morris and Brinson (1979). Some of the experimental investigations by Avva (1981, 1983) were concerned in the development of graphite/epoxy composite failure thresholds leading to some design implications. A theoretical model to predict the residual strength in laminated composite materials subjected to low velocity impact was developed by Husman, Whitney and Halpin (1975). This model was developed based on an analogy between the damage caused by a projectile and an

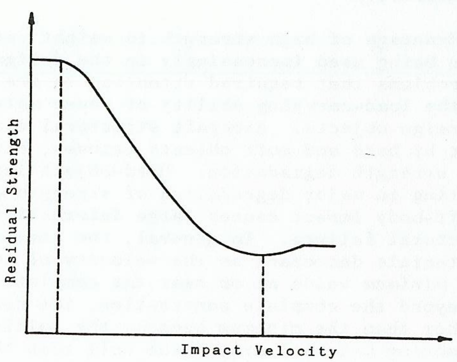

Fig. 1. Schematic diagram of post-impact residual strength versus projectile impact.

implanted flaw of known dimensions in composite laminates. With the research work of the preceding authors in the background, an improved analytical model is developed to predict the strength degradation of graphite/epoxy composites subjected to low velocity projectile impact.

In fiber-reinforced resin matrix composites, small object impact causes local damage in the impacted area which may appear in the form of indentation, perforation, delamination and spallation. Damage thus induced causes reduction of strength of the material. Post-impact strength degradation with respect to impact velocity (Awerbuch and Hahn, 1976) is schematically represented in Fig. 1. At low impact velocities, the damage caused is insignificant to result in any appreciable reduction of the strength. Beyond a certain velocity, a steep reduction of strength takes place. Velocity at this point is referred to as the threshold damage velocity. With increase in velocity, the residual strength decreases until it reaches a minimum, where the impact causes maximum damage. This is the ballistic limit velocity. Further increase of impact velocity results in complete penetration of the projectile. The residual strength will be slightly higher than the minimum and is equal to the strength of the specimen with a clean drilled hole of the same size. Beyond the ballistic limit, residual strength is independent of the impact velocity.

Since failure does not take place at velocities less than the threshold damage velocity, it may be assumed that the damage is proportional to the difference between the kinetic energy of impact and the threshold damage kinetic energy. Therefore, the preceding statement may be expressed (Whitney, 1979) as

$$c = k\,(W - W_o) \tag{1}$$

where c = damage as an effective through the thickness crack of length, $2c$

k = a constant, dependent on the material and the laminate

W = kinetic energy of impact per unit thickness

W_o = threshold damage kinetic energy per unit thickness

The average stress criterion developed by Whitney and Nuismer (1974) for an isotropic laminate is given by

$$(\sigma_N^\infty/\sigma_o) = [(1 - \zeta_1)/(1 + \zeta_1)]^{\frac{1}{2}} \tag{2}$$

where σ_N^∞ = failure stress of an infinite plate containing a crack (notch) of length, $2c$

σ_o = failure stress of an unnotched plate

ζ_1 = $c/(c + a_o)$

a_o = characteristic dimension adjacent to discontinuity.

Substituting for ζ_1 in equation (2), it may be rewritten as

$$(\sigma_N^\infty/\sigma_o) = [(a_o)/(2c + a_o)]^{\frac{1}{2}} \tag{3}$$

Equations (1) and (3) can be combined resulting in the following equation,

$$(\sigma_N^\infty/\sigma_o) = 1/[(2k/a_o)(W - W_o) + 1]^{\frac{1}{2}} \qquad (4)$$

Assuming $\sigma_N^\infty = \sigma_r$, the residual strength of the specimen and $(k/a_o) = K$, a constant, equation (4) can be rewritten in the following form:

$$(\sigma_r/\sigma_o) = [2K(W - W_o) + 1]^{-\frac{1}{2}} \qquad (5)$$

The above relationship can be used to predict the residual strength of a laminate for different values of kinetic energy. In order to determine the values of 2K and W_o, equation (5) is rewritten in linear form as:

$$y = ax + b$$

where $y = (\sigma_o/\sigma_r)^2$

$x = W$

$a = 2K$

$b = (1-2KW_o)$

The ultimate strength σ_o and the post-impact residual strength σ_r at different velocities are to be determined by performing tests on a few specimens. Using linear regression analysis, a best fit is obtained for the data and the values for 2K and W_o are thus determined. These values are used in equation (5) to predict the residual strength at any velocity of impact.

SPECIMENS AND TEST PROCEDURE

The compression tests were performed in four different stages: viz., (a) ultimate strength test to record the stress-strain data, (b) impact tests on pre-loaded specimens to generate a failure threshold curve, (c) impact tests without pre-load at three different velocities to record the post-impact residual strength, and (d) impact tests with pre-load at three different velocities to study the residual strength scatter and to compare this data with that of part (b). Detailed experimental set-up, measuring techniques, and experimental data pertaining to this research work were reported by Avva (1982).

The graphite/epoxy composite material used in the compression tests is Thornell 300/Rigidite 5208. The test specimens have 16 plies with a laminate stacking sequence of $(45_2, -45_2, 0_2, 90_2)_s$. The nominal cured thickness of each lamina is 140 μm (0.0055 in.) and the nominal width of each specimen is 76 mm (3 in.). Other nominal dimensions of the specimen and gripping arrangement are shown in Fig. 2.

A special fixture shown in Fig. 3 was used to prevent the specimen from column-type buckling failure. The cylindrical rollers shown in the side view, Fig. 3, provided a firm but nonpenetrating side-support in the longitudinal direction of the specimen. The testing of specimens was performed on a closed-loop hydraulic material testing system.

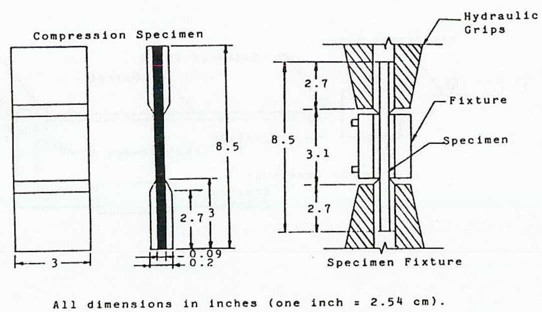

Fig. 2. Schematic representation of specimen configuration and gripping arrangement.

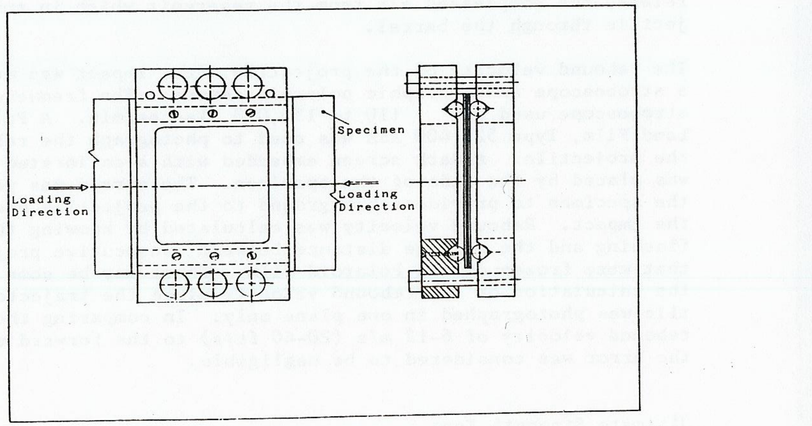

Fig. 3. Fixture for compression test

A schematic view of the projectile firing mechanism is shown in Fig. 4. An air supply line is connected to a reservoir through a butterfly valve. A (gun) barrel connected to the reservoir acts as a smooth guide to the projectile. Two photo-diodes located at 15.24 cm. (6 in.) apart at the other end of the barrel are connected to an electronic counter. As the

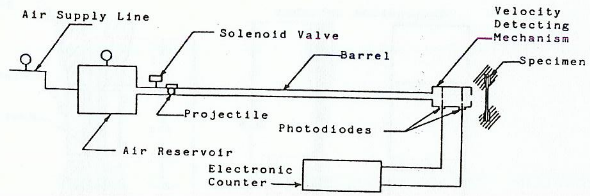

Fig. 4. Schematic of projectile firing and detecting mechanism

projectile travels through the barrel, light beams emitted by the photodiodes are interrupted. An electronic counter starts when the first light beam is interrupted by the projectile and stops when the second light beam is interrupted. Thus, the counter records the time taken by the projectile to travel a distance of 15.24 cm. (6 in.) and hence the average forward velocity of the projectile can be determined. A solenoid valve is used to release the compressed air from the reservoir which in turn propels the projectile through the barrel.

The rebound velocity of the projectile after impact was determined by using a stroboscope and a graphic polaroid camera. The frequency range of the stroboscope used was 110 to 150,000 flashes/min. A Polaroid, Polapan Land Film, Type 52, 400 ASA was used to photograph the rebounding path of the projectile. A dark screen embedded with a calibrated rectangular grid was placed by the side of the specimen. The screen was positioned close to the specimen to provide a background to the projectile photographed during the impact. Rebound velocity was calculated by knowing the frequency of the flashing and the average distance between consecutive projectile positions that were frozen on the Polaroid film. There may be some error involved in the calculation of the rebound velocity since the trajectory of the projectile was photographed in one plane only. In comparing the magnitude of the rebound velocity of 6-12 m/s (20-40 ft/s) to the forward velocity, however, the error was considered to be negligible.

Ultimate Strength Test

Five specimens were tested for determining the ultimate static strength. Two strain gages, one on each face of the specimen, back-to-back, were bonded at the center. The strain gage bridge completion network was arranged to record the average axial strain only, and the bending strains, if any, were eliminated in the recording. The specimens were held between the hydraulic grips for the full length of the tabs and the compressive load was applied to achieve a strain rate of .02 in./in. per minute until the specimen failed. The load and the corresponding axial strain data were recorded.

Impact Tests on Pre-Loaded Specimens (Failure Threshold)

These tests were conducted to determine the failure threshold level of the composite laminate. The specimens were subjected to different pre-loads in compression and were then impacted by the projectile at velocities ranging from 17.7 to 95.4 m/s (58 to 313 ft/s). Some of the specimens failed catastrophically upon impact. Those specimens that survived the impact were subjected to continued loading until failure occurred and the residual strength was found. The complete penetration of the laminate occurred at a projectile velocity of 80 m/s (262 ft/s) or higher depending on the magnitude of the pre-load.

Impact Tests without Pre-Load

In these tests, the specimens were first impacted with one of the three projectile velocities at 30.5 m/s (100 ft/s), 61 m/s (200 ft/s), or 91.5 m/s (300 ft/s) and then loaded in compression until failure took place.

Impact Tests with Pre-Load

These tests were performed at the same three impact velocities as in the previous case. The specimens were subjected to the projectile impact after pre-loading them in compression to a load level slightly below and above the failure threshold values.

EXPERIMENTAL RESULTS, ANALYSES AND DISCUSSION

Since the strength of any laminate is dependent on the material, stacking sequence and orientation, the compressive stress-strain values of the laminate were first established using five virgin (undamaged) specimens. The average ultimate compressive strength, σ_o and the corresponding average strain were found to be 308.5 MPa (44.7 ksi) and 0.6% respectively. This average utlimate strength value was used in subsequent numerical calculations.

Impact Test Results on Pre-Loaded Specimens (Failure Threshold)

Impact tests on specimens subjected to the compressive pre-loads were conducted. The normalized stress as a function of the kinetic energy of the projectile per unit thickness of the specimen is shown in Fig. 5. The normalized pre-stress is indicated by an open circle, the normalized residual stress is shown by a circle with a slash in the center and the stress at catastrophic failure upon impact is represented by a darkened circle. A faired curve through the data points indicating a failure threshold for the laminate is drawn. The solid triangles in Fig. 5 represent the analytical data points obtained from equation 5. The points shown above the faired curve represent either a catastrophic failure or a failure due to the continuation of loading (residual stress) after impact and the points below the faired curve represent pre-stress at impact but no failure. As can be seen from this figure, the analytical and the experimental results show a good correlation. The values of 2K and W_o were determined using linear regression analysis. For the particular test under consideration, it was found that 2K = 0.073 and W_o = -53.85 J/cm.

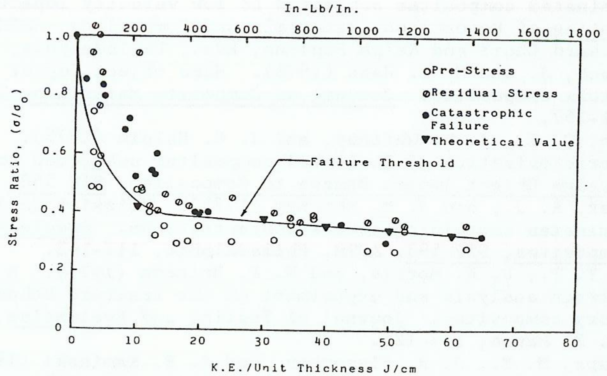

Fig. 5. Normalized stress vs. K.E. of projectile (compression)

The faired curve in Fig. 5 may be divided into two parts. In the first part, up to an impact energy level of 13 J/cm (292 in-lb/in), the stress ratio reduced very rapidly from 100% to about 40%. In the second part of the curve, beyond 13 J/cm (292 in-lb/in), there is a gradual but small reduction in the stress ratio with an increase in the impact energy. This observation of the behavior of the failure threshold for the laminate under consideration may be interpreted to mean that the strength-carrying ability of the laminated composite is dependent on the magnitudes of the pre-load and the impact energy applied to the specimen up to a point closer to the projectile penetration velocity. Beyond this point, the laminate failure may be considered to be independent of the projectile impact energy.

Impact Test Results without Pre-Load

As mentioned earlier, the impact tests without pre-load were conducted at velocities close to 30.5 m/s (100 ft/s), 61 m/s (200 ft/s), and 91.4 m/s (300 ft/s). The objective here was to assess the impact damage tolerance of the composite laminates with and without pre-load. The mean σ_r/σ_o and the standard deviation of the mean σ_r/σ_o at these three impact energy levels were determined. These results are shown in Table 1.

TABLE 1 Mean Residual Stress

Mean Kinetic Energy/Thickness J/cm (in-lb/in)	Mean Residual Stress, σ_r MPa (ksi)	Mean Stress Ratio, σ_r/σ_o	Standard Deviation of Mean σ_r/σ_o
5.3 (119.1)	257.8 (37.4)	0.84	±0.01
23.7 (532.8)	133.7 (19.4)	0.43	±0.01
58.7 (1319.6)	11.0 (16.1)	0.36	±0.01

From the above values, the normalized residual strength as a function of K.E./unit thickness is plotted in Fig. 6. A comparison of Figs. 5 and 6 indicates that the residual strength of specimens impacted without pre-load is higher than that of the pre-loaded specimens up to an impact energy of 25 J/cm. Beyond this impact energy level, the difference is only about 3%. From this observation, one may infer that the combination of pre-load and impact causes greater damage to the material than impact alone without any pre-load at low impact energy levels. In the present case, the values of 2K = 0.12 and W_o = -5.192 J/cm were calculated by using the linear regression technique. The theoretical values of (σ_r/σ_o), plotted in Fig. 6, show good agreement with the experimental values.

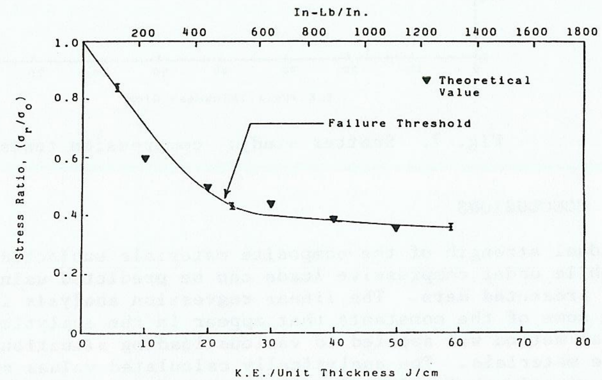

Fig. 6. Normalized residual stress vs. K.E. of projectile (compression)

Impact Test Results with Pre-Load (Scatter Study)

These tests were performed to study the scatter in the residual stresses and the catastrophic failure stresses at the three impact energy levels. The results obtained are plotted as shown in Fig. 7. For the purpose of comparison, the faired curve drawn in Fig. 5 is shown again in Fig. 7. Most of the specimens impacted at a pre-stress above the faired curve had catastrophic failure, and those impacted below the faired curve survived. Therefore, one can infer that the faired curve is a true representation of the failure threshold for these laminates. It can be observed from Fig. 7 that the scatter of residual stress points was high at an energy level of 5.6 J/cm (125.9 in-lb/in) whereas at 24.4 J/cm (549 in-lb/in) and 56.8 J/cm (1277 in-lb/in), these points were found to be in the vicinity of the faired curve.

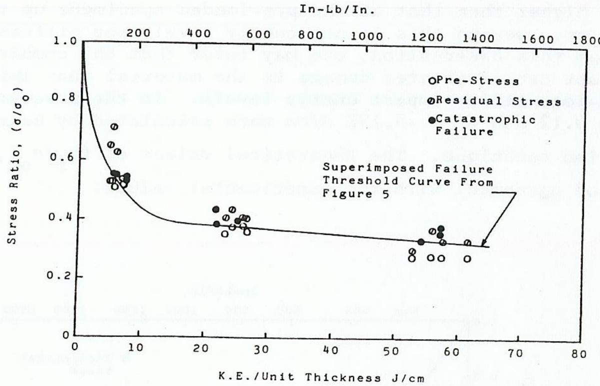

Fig. 7. Scatter study: compression tests

CONCLUSIONS

The residual strength of the composite materials subjected to projectile impact while under compressive loads can be predicted using the analytical model as presented here. The linear regression analysis is adopted for calculating some of the constants that appear in the analytical model. The analytical method was applied to various loading situations in the laminated composite materials. The analytically calculated values show good agreement with the experimental values in all cases. This model may be adopted in predicting the residual strength of impact-damaged composite materials having different orientations, laminate stacking sequences, etc. However, before one could apply the model, some of the material constants will have to be determined by performing tests on a few specimens for each laminate orientation and stacking sequence.

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