NASA
Technical
Paper
3303

1992

The Effects of Compressive Preloads on the Compression-After-Impact Strength of Carbon/Epoxy

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MSFC Center Director's Discretionary Fund Final Report, Project No. P-11

INTRODUCTION

Foreign-object impact damage to composite materials is of concern because of the low level of damage tolerance some composite materials exhibit. In order for composite materials to be more widely utilized in primary structures, the impact resistance of carbon/epoxy composite systems must be understood and improved. Most impact testing currently consists of clamping the composite specimen in place over a 3-in hole and striking it with a one-half-inch impactor (or tup). This testing is very useful for screening and comparing specimens for damage resistance since the impactor is instrumented to record load and impact energy. However, it may be of concern to predict the degree of damage in materials that are under a stress when impacted. For example, a worker may drop a tool on a structure that is in a state of compression. Compression is usually of more concern than tension since damaged composites are much more susceptible to compressive failures, particularly if the damage is in the form of delaminations.[1 2]

Preloads and their effects on impact damage tolerance of composite materials have been researched very little. During a NASA workshop on impact damage to composite materials, held in 1991, it was determined that one of the actions to address in the area of technology deficiencies was to determine preload effects.[3] Rhodes and Sharma have published papers that contain experimental information on this subject.[4 5] Rhodes concluded that the residual compressive strength of specimens impacted while in a compressive stressed state is lower than those impacted with no stress applied. Those specimens that were damaged with a preload present also had greater areas of local damage. Rhodes did not use many specimens and thus could not give a quantitative relationship between preload and residual compression strength. Sharma came to the same conclusions as Rhodes concerning residual compression strength and compressive preloads. He found that at impact energies up to 25 J/cm (which translates to 5 J for the specimens tested in this project), the preload causes a "large" reduction in strength. Above this impact energy, the preload had little effect. No quantitative data were generated in this study either, mainly because a light air gas gun was used in both studies to fire the striking projectile, thus making a consistent impact energy impossible. By using an instrumented drop weight mechanism and studying the interaction of preload with impact energy, results can be more quantitative and of practical use.

One method for studying interactions of variables is advanced design of experiments. It can be used to simultaneously evaluate the effects of many variables on a given output. This use of multivariable experimental design strategies allows a simple identification of important variables and their interactions with one another, as well as a more efficient way to predict responses due to the different variables examined. The standard approach to test multivariables has been to look at one variable at a time and keep the others constant. This type of testing does not account for possible interactions between variables. If an interaction does exist, it would change the response values in an "irregular" way and would thus be difficult to interpret. In a multivariable (or factorial) experiment, the effects of numerous factors are examined at the same time. The test matrix can consist of all possible combinations of the different factors (full factorial) or a select combination of the variables (fractional factorial). This can demonstrate if the variables act independently or if they interact with one another. This method has been shown to save much time and money during a damage tolerance program because fewer experiments have to be run than what would have to be run in a "one factor at a time" approach to gain the same knowledge.[6]

APPROACH

The purpose of this research project is to examine the influence of preloading on the impact damage effects on composite materials. Two multivariable test matrices were used to produce results that would show the effects of compressive preload on compression-after-impact (CAI) strength. One used T300/934 carbon/epoxy and examined two variables (impact energy and preload), each at three different levels. The second test matrix used IM7/8551-7 carbon/epoxy with the same two variables, each at five levels (fig. 1).

Run No.	Preload Pounds (lb)	Impact Energy Joules (J)
1	200	1.0
2	200	5.5
3	200	9.0
4	2,100	1.0
5	2,100	5.5
6	2,100	9.0
7	4,000	1.0
8	4,000	5.5
9	4,000	9.0

Test Matrix 1. T300/934 material, two level, full factorial.

Run No.	Preload Pounds (lb)	Impact Energy Joules (J)
1	9,000.0	14.0
2	9,000.0	6.0
3	5,000.0	14.0
4	5,000.0	6.0
5	7,000.0	4.0
6	7,000.0	16.0
7	4,000.0	10.0
8	10,000.0	10.0
9	7,000.0	10.0

Test Matrix 2. IM7/8551-7 material, two level Box-Wilson.

Figure 1. Matrices used for preload study.

The specimens used were 16-ply [0, +45, 90, –45]$_s$ measuring 7.6 cm by 17.8 cm. Two strain gages were applied to the impacted side 2.5 cm apart and centered. Another gage was placed on the nonimpacted (back) side in the center of the specimen (fig. 2). These strain gages were used to measure the modulus of the material being tested and also to ensure that the impacted area was in a uniform strain state.

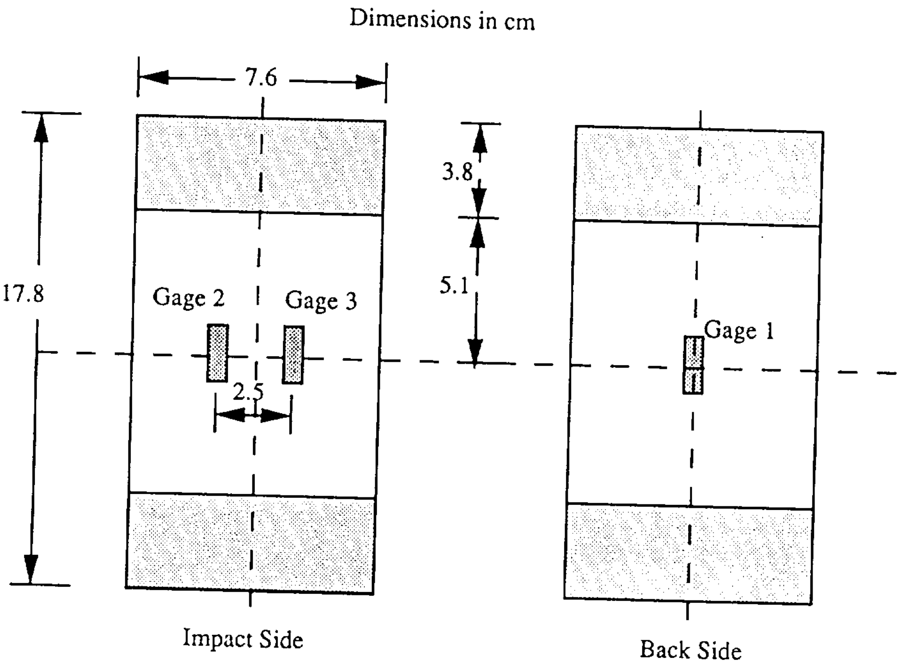


Figure 2. Placement of strain gages and dimensions of specimens.

Each composite specimen was placed on a clamp plate and held down by a removable anti-buckling plate with a hole in the center for an impact area. The two ends lay against a back wall and a pressure plate. Specimen end clamps were placed over the ends against the walls to keep the specimens from moving up or down during loading (figs. 3 and 4). The strain gages were wired to a Micromeasurements P-3500 strain indicator. A hydraulic hand pump was used to apply load to the specimen via a two-cylinder ram. The entire apparatus was placed under a drop-weight impact machine so that the specimen would be hit at its center (figs. 5 and 6). The impact energy could be changed by varying the drop height of the impactor. After impact, a Dynatup 730 data acquisition system would yield values of maximum load of impact, energy of impact, energy absorbed during impact, and a load-time curve for the impact event. The specimens were then removed and tested for residual compression strength using a technique developed at Marshall Space Flight Center (MSFC).[7] After testing, data were entered into a software package (BBN/catalyst) that would generate data to help determine the influence of impact energy and preload on the measured response (CAI strength in this study).

RESULTS

Load-Strain Data

The load/strain data were taken at various increments of loading for all of the specimens tested. The strain readings of all three gages were read at each load increment and recorded. If a large deviation (>20 percent) was present at any of the load increments, the specimen was removed and checked for improper loading in the compression fixture, or for nonparallel ends, which would contribute to an

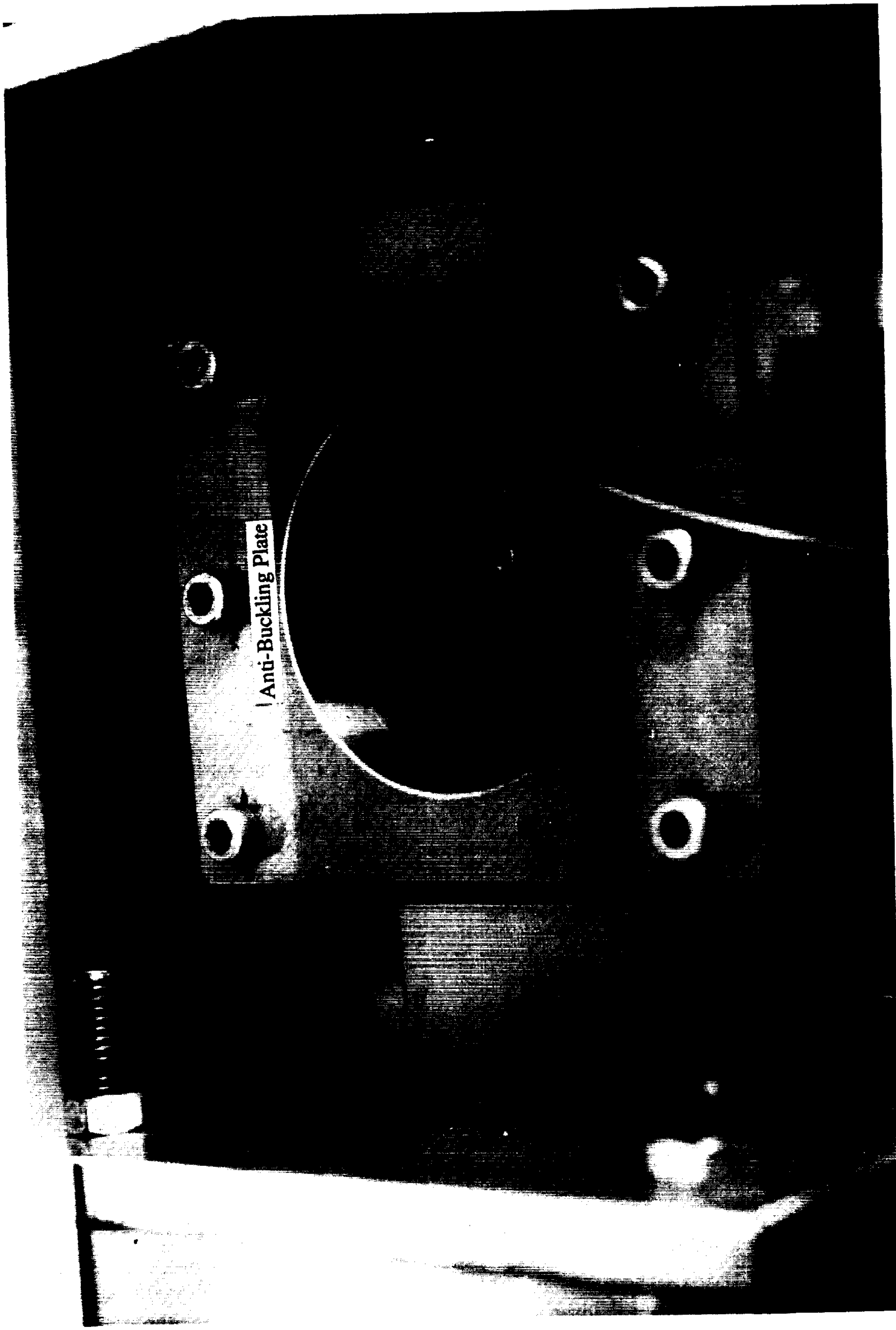


Figure 3. Antibuckling plate on specimen.

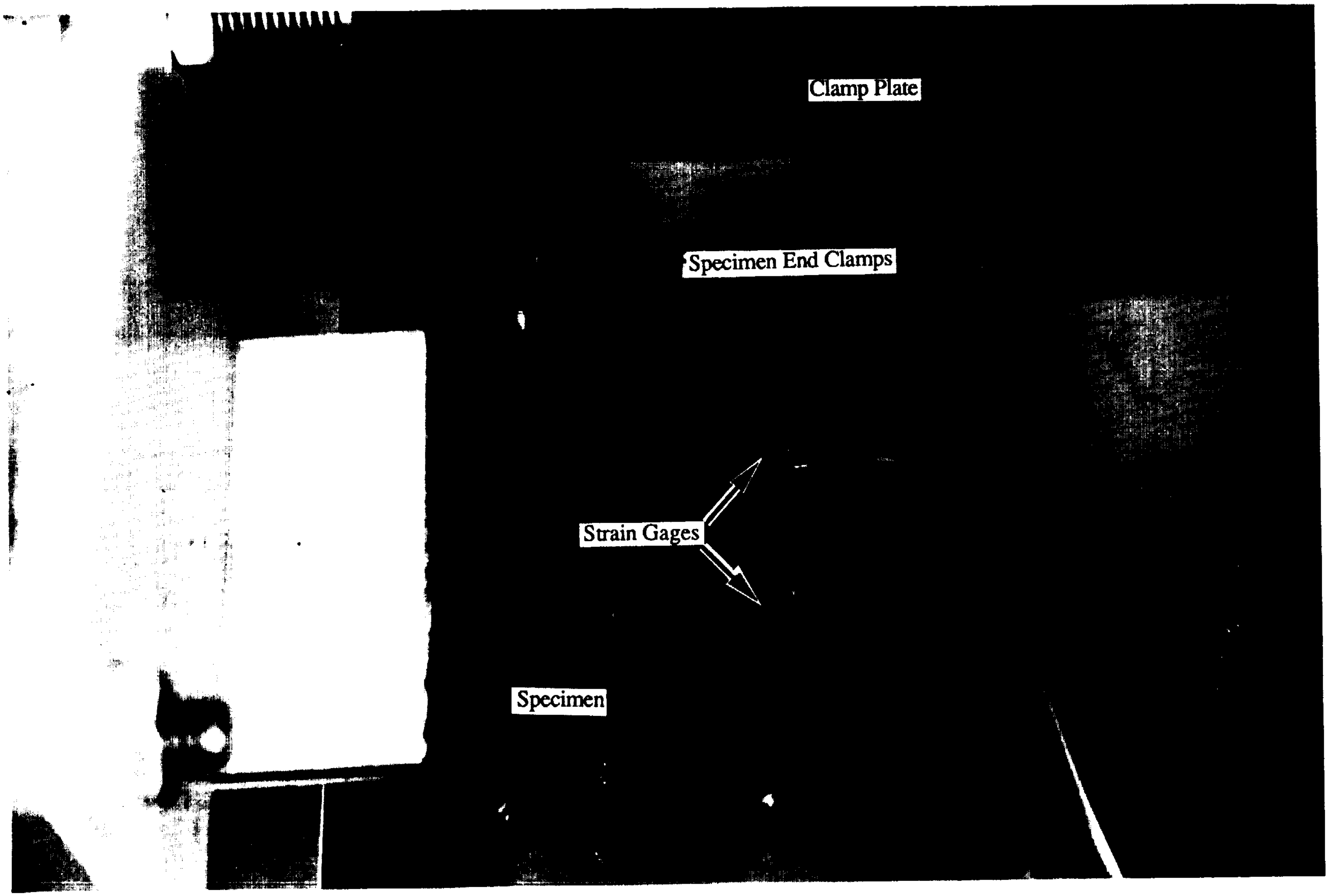


Figure 4. Specimen on clamp plate with end clamps.

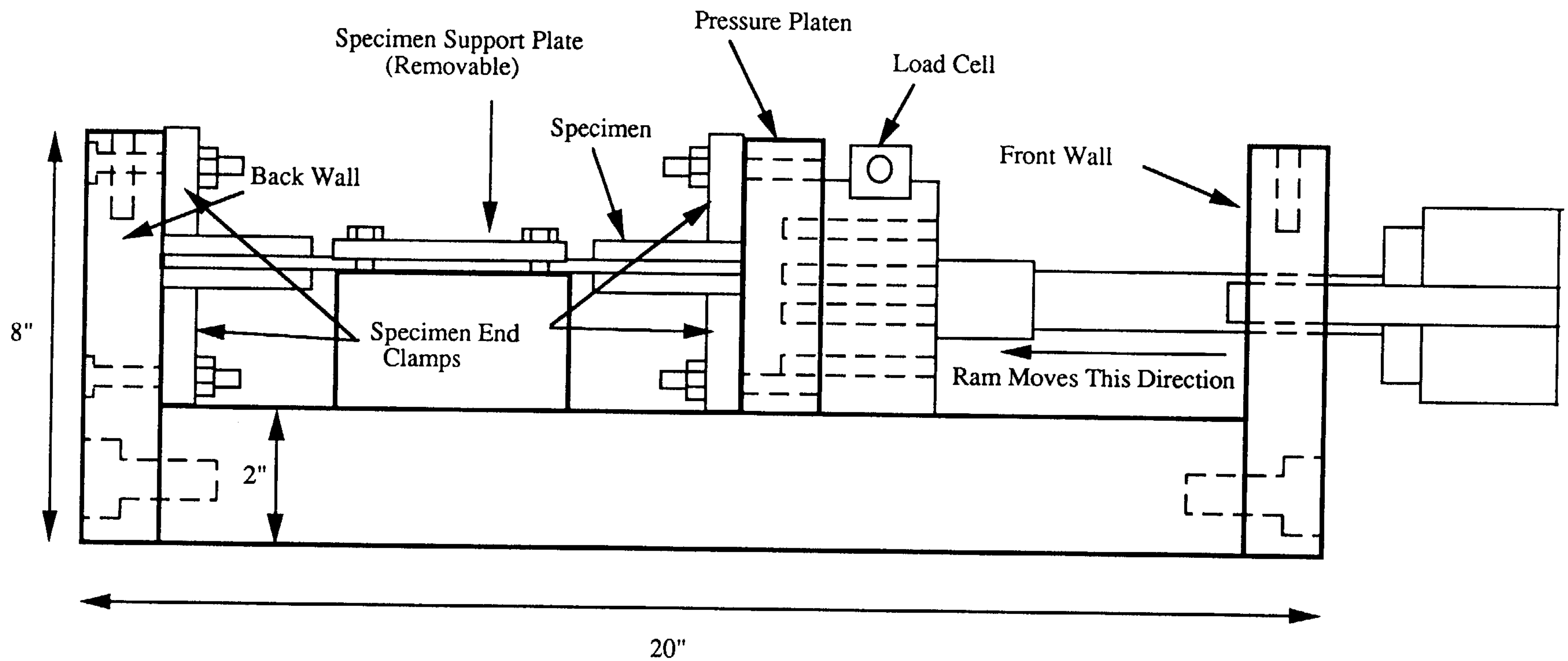


Figure 5. Preload device.

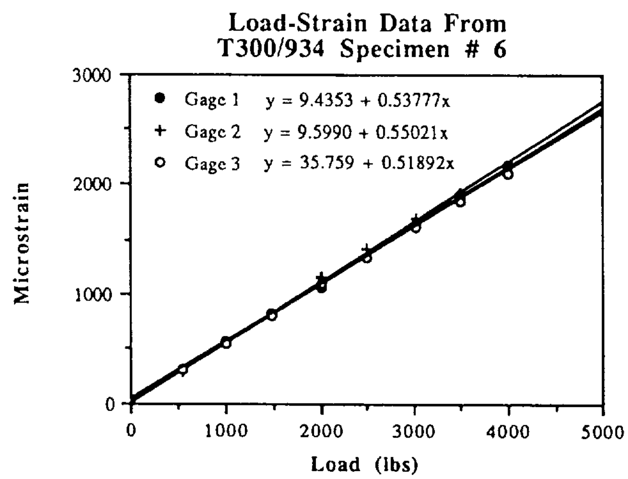
Figure 6. Test setup.

uneven strain being induced into the specimen. As long as the strain readings on the three gages were within 20 percent of each other, the test continued. The only exception to this was T300/934 specimen No. 11 which was barely beyond the 20-percent strain difference at >1,500 lb. A plot of load-strain for T300/934 specimens No. 6 and No. 11 is given in figure 7. From the data for T300/934 specimen No. 6, the modulus can be calculated using the average slope of the three lines as follows. The average slope is 0.5356 microstrain/load.

$$\text{Modulus} = E = \text{Stress/Strain} = \frac{\text{Load}}{\text{Area}} / \text{Strain} \ , \tag{1}$$

$$E = \frac{0.5356 \times 10^6}{0.24 \text{ in}^2} = 2{,}170{,}000 \text{ lb/in}^2 \ . \tag{2}$$

Thus, the modulus, as measured from T300/934 specimen No. 6, is 2.17 million square inches (M in^2). The data from T300/934 specimen No. 11 show that a nonuniform strain state was present in the specimen. Determining the modulus from this data by averaging slopes yields a value of E = 2,190,000 or 2.19 M in^2. This value is very close to that found in specimen T300/934 No. 6. An examination of this type of data from all of the T300/934 specimens reveals that a modulus of 2.2 M in^2 can be reported. Figure 8 shows load-strain data for IM7/8551-7 specimens No. 1 and No. 7. Using the average slope for each of these plots, the modulus of this material is found to be 2.1 M ^{2}.



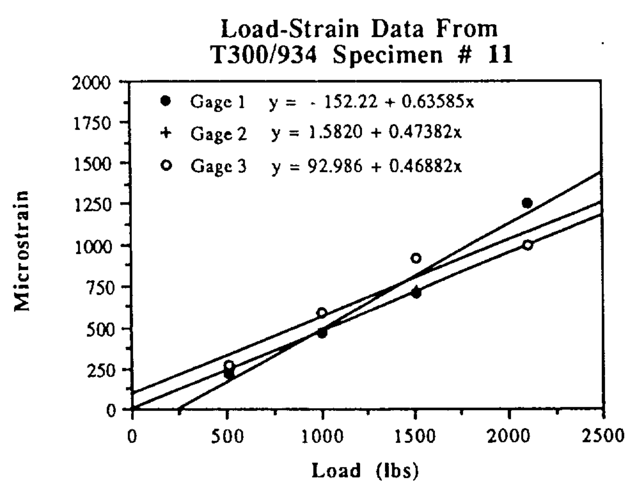
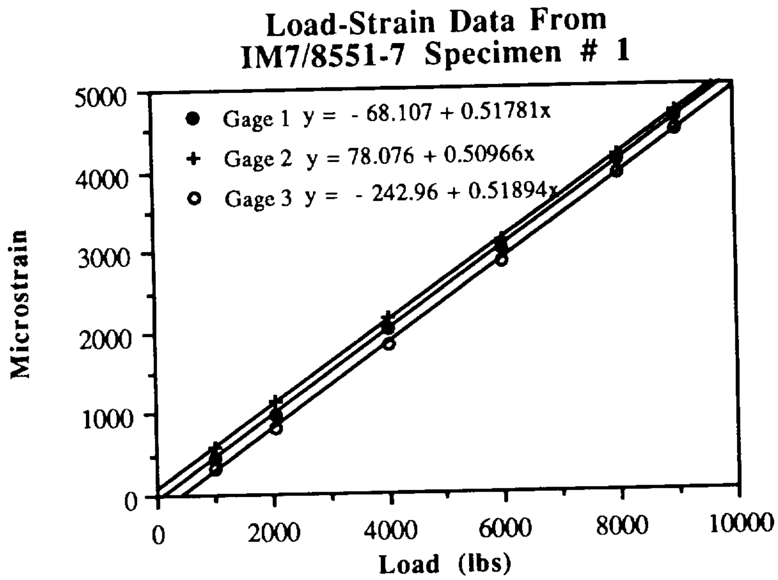


Figure 7. Load-strain data for two T300/934 specimens.



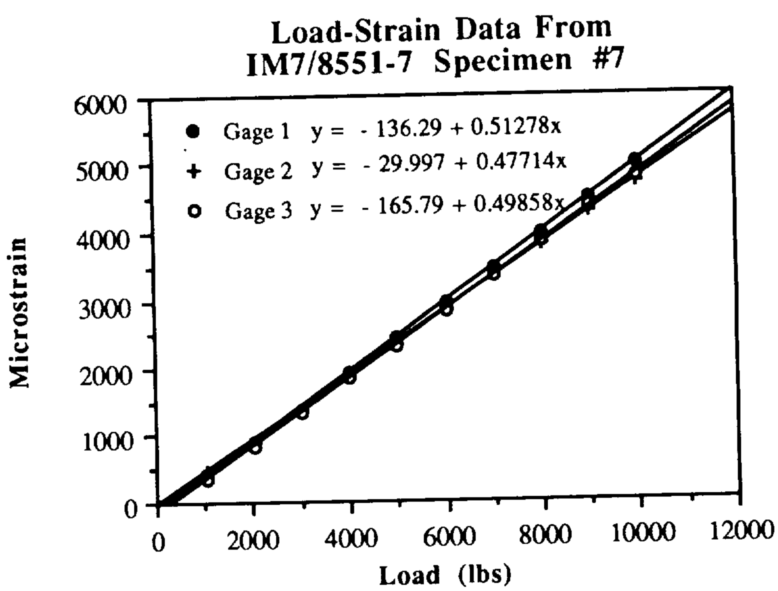


Figure 8. Load-strain data for two IM7/8551-7 specimens.

Residual Compressive Strength

All of the impacted specimens were tested for CAI strength at a loading rate of 0.1 in/min using a shear loading, face-supported fixture detailed in reference 7. The specimens all failed without global buckling (no bending). The residual compressive strength was the dependent variable in the design-of-experiments portion of this study.

Design-of-Experiments Results

The two sets of tests were entered into a design-of-experiments program that would generate quantitative (numerical) values for the influence of first- and second-order (quadratic) effects of both preload and impact energy, as well as any interaction these two variables may have with one another. The first set of tests consisted of a full-factorial, two-variable, three-level design using T300/934 material. The variable limits for this test were a preload of 210 to 4,000 lb and an impact energy of 1 to 9 J. The results generated for these data should not be extrapolated outside these regions. The complete results of the first set of tests are given in table 1.

Table 1. Run summary for T300/934 material.

Run No.	Preload (lb)	Impact Energy (J)	Residual Strength (MPa)
1	200	1.0	372
2	200	5.5	291
3	200	9.0	293
4	2,100	1.0	395
5	2,100	5.5	288
6	2,100	9.0	297
7	4,000	1.0	446
8	4,000	5.5	294
9	4,000	9.0	276

Some specimens were repeated to gain insight into the amount of scatter that may exist. The largest deviation was 15 percent of the mean (run No. 8). When the results were entered into a Box-Wilson advanced experimental design program, the following coefficients were generated:

Constant = 296.1 MPa

Preload = +11.0 MPa

Impact energy = −57.8 MPa

Preload-impact energy interaction = −23.2

Quadratic preload = 2.0 MPa

Quadratic impact energy = 49.0.

These numbers are interpreted as follows: The range of preloads used was from a low of 200 lb to a median of 2,100 lb and, finally, a high of 4,000 lb. Impact energy ranged from a low of 1 J to a median of 5.5 J to a high of 9 J. These low, median, and high values must be normalized to low = −1, median = 0, and high = +1. For example, a preload of 2,100 lb and an impact energy of 9 J now becomes a preload of 0 and an impact energy of +1 (unitless since the coefficients are already in the units of the dependent variable). The output is determined by the following equation:

$$\text{Residual Stress} = 296.1\ \text{MPa} + 11\ \text{MPa (normalized preload)} - 57.8\ \text{MPa (normalized impact energy)} - 23.2\ \text{MPa (normalized preload)(normalized impact impact energy)} + 2.0\ \text{MPa (normalized preload)}^2 + 49.0\ \text{MPa (normalized impact energy)}^2 \quad (3)$$

The constant is the value that is obtained when all variables are at the median (or 0) setting. The data give an average of 288±11 MPa for this value, while the equation yields 296.1 MPa. These values are very close and well within the scatter inherent in the test.

An examination of the coefficients shows that the linear impact energy term is the most important at –57.8 MPa with a higher impact energy causing a lower residual strength (due to the negative sign). The next largest term is the quadratic impact energy term at +49.0, which is positive. This indicates that as the impact energy goes from a normalized value of 0 to 1 (or 0 to –1 since the normalized value is squared and thus always positive), the strength increased exponentially to the second power. This accounts for the "saturation" portion of the CAI strength versus impact energy plots typically seen exhibited by composite materials. One of these plots is shown in figure 9.

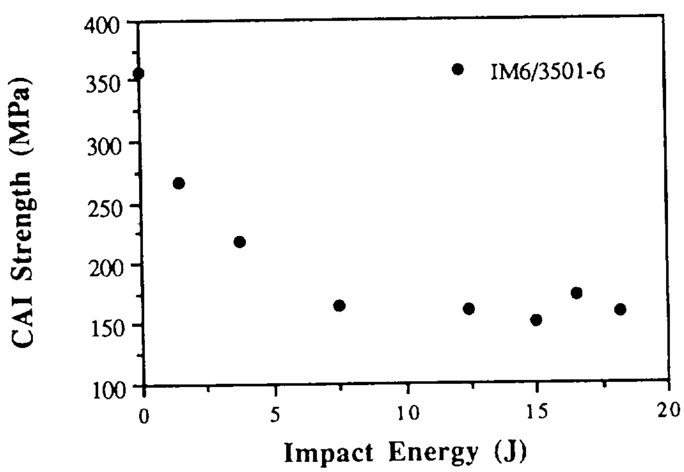


Figure 9. A typical CAI versus impact energy plot for carbon/epoxy.

A sharp drop in strength is seen at the initial portion of the curve, but then as impact energy increases, much less detriment to the compressive strength of the material is observed. This "saturation" is due to the indenter causing near perforation of the material with the damage mode changing from expanding delaminations to fiber breakage. Since CAI strength is driven by total delaminated area, the broken fibers, which always occur over heavily delaminated areas, do not further degrade the specimen's compressive strength. The interaction coefficient is the next largest term at –23.2 MPa. This indicates that at higher impact energies, a higher preload degrades the strength. The opposite occurs at lower impact energies, where a higher preload increases the CAI strength values. This may be due to the preload acting as a stabilizer of sorts, preventing the material from buckling as much as it would had there been no preload.

A three-dimensional plot of the resulting function for CAI strength (equation (3)) is shown in figure 10.

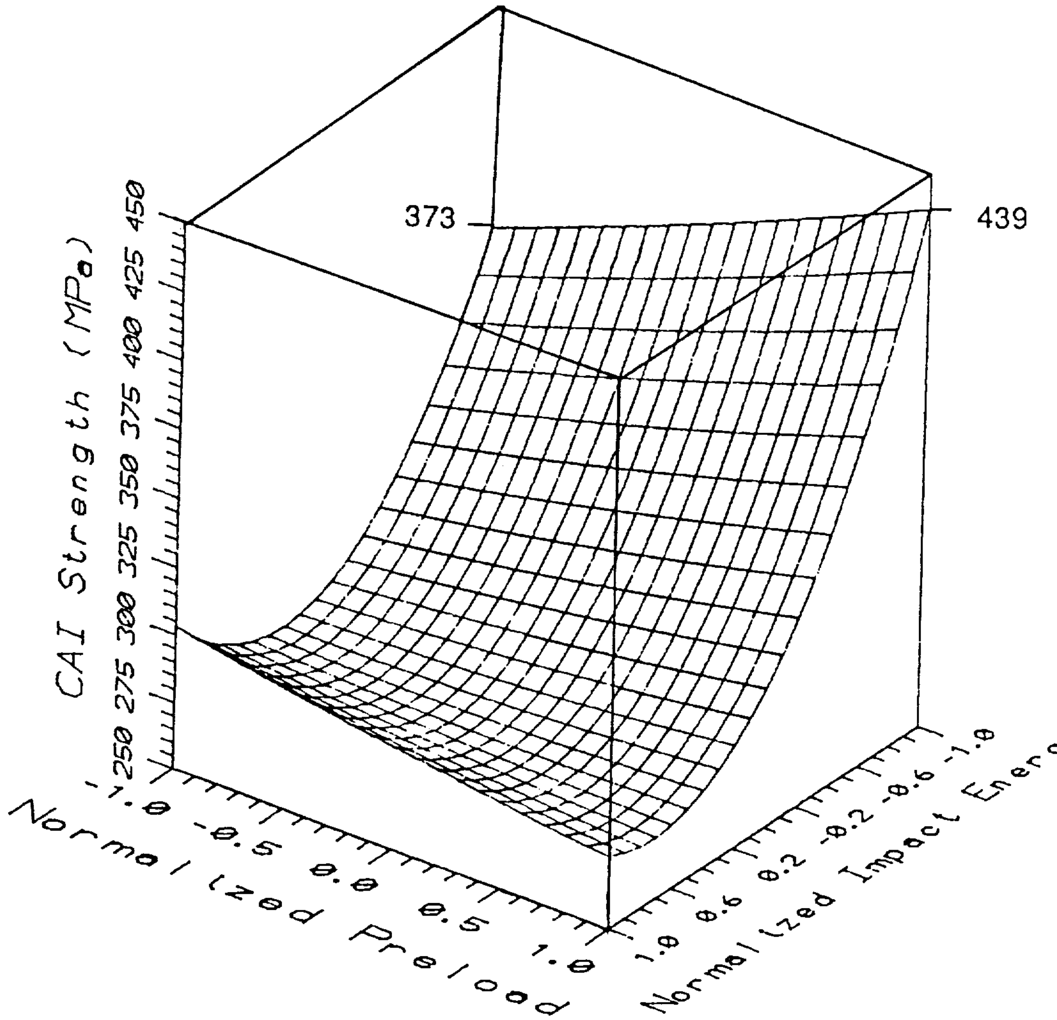


Figure 10. CAI strength as a function of preload and impact energy for T300/934 material.

This plot shows the CAI strength of the specimens as a function of the normalized preload and normalized impact energy. This plot is called a response surface of the two independent variables tested. The effects of each of the independent variables can easily be visualized using this type of surface plot. The strong influence of impact energy is easily identified, as is the quadratic impact energy term, since at any given preload the curve is obviously nonlinear. The "saturation" at the higher impact energies tested can be seen as the surface levels off and actually begins to curve up at a normalized impact energy of about 0.6, which corresponds to 7.6 J of impact energy. This is approximately the same impact energy at which identical specimens of a similar carbon/epoxy with no preload began to show no further decreases in compression strength with increasing impact energy (fig. 9).

The linear preload effects can be most easily seen at the extremes of the impact energy. At the low impact energy, the preload shows increasing strength retention with increasing impact energy, and at high impact energies, the preload causes a strength reduction with increasing preloads. The interaction term causes the slopes to change in sign from one end of the surface to the other.

From this surface response, it is evident that the effects of compressive prestress up to 115 MPa (4,000 lbf on the specimen geometry tested in this study) can slightly alter the behavior of CAI strength values when impact energies of between 1 and 9 J are used.

The second set of tests consisted of a fractional factorial, two-variable, three-level design using IM7/8551-7 material. The independent variable limits for this test were a preload of 4,000 to 10,000 lb and an impact energy of 4 to 16 J. This represents an "extrapolation" of 25 percent of the overall test "cube." This technique is good to use when information is to be gathered that covers a relatively large bracket of independent variable values. The actual values translate as: preload, –1 = 5,000 lb, 0 = 7,000 lb, +1 = 9,000 lb, and impact energy, –1 = 6 J, 0 = 10 J, +1 = 14 J. The two extremes of preload are low = 4,000 lb and high = 10,000 lb. The two extremes of impact energy are low = 4 J and high = 16 J. As in the first set of tests, the data should not be extrapolated outside these regions. The run summary for these data is given in table 2*a*. Each run was repeated twice and the mean value of these two runs is reported as the CAI strength. The 25-percent extrapolation indicates what is termed as an alpha value of 1.5, that is, a normalized preload of +1.5 lb is translated to a real value of 10,000 lb and covers 25 percent past the bracket values of –1 to +1, or 5,000 lb to 9,000 lb. The two recorded values for each run are given in table 2*b*, along with the corresponding standard deviation.

Table 2*a*. Run summary of IM7/8551-7 material.

Run No.	Preload (lb)	Impact Energy (J)	Residual Strength (MPa)
1	9,000.0	14.0	273
2	9,000.0	6.0	300
3	5,000.0	14.0	287
4	5,000.0	6.0	319
5	7,000.0	4.0	316
6	7,000.0	16.0	267
7	4,000.0	10.0	298
8	10,000.0	10.0	258
9	7,000.0	10.0	295

Table 2*b*. Measured CAI strength values for the two replicates at each run.

Run No.	Residual Strength No. 1 (MPa)	Residual Strength No. 2 (MPa)	Standard Deviation (MPa)
1	287	258	21
2	297	302	4
3	266	308	30
4	322	315	5
5	305	328	16
6	272	261	8
7	296	299	2
8	258	258	0
9	300	290	7

For the specimens that failed catastrophically upon impact (i.e., failed in the preload device), a value of 258 MPa was used. This was the lowest calculated CAI strength and occurred on the second specimen of run No. 1. The CAI strength value was determined by assuming the specimen could not hold the 9,000 lb of preload placed upon it. This yields:

$$9{,}000 \text{ lb}/0.24 \text{ in}^2 \ (0.00689 \text{ MPa/lb/in}^2) = 258 \text{ MPa} \tag{4}$$

Considering only two samples were tested for each run, the standard deviations are low, which implies good repeatability.

When the data are inserted into a Box-Wilson type analysis, the resulting equation for CAI strength is:

$$\begin{aligned}\text{Residual Stress} = {} & 297.1 \text{ MPa} - 10.9 \text{ MPa (normalized preload)} - 15.6 \text{ MPa (normalized} \\ & \text{impact energy)} + 1.2 \text{ MPa (normalized preload)(normalized impact} \\ & \text{impact energy)} - 6.6 \text{ MPa (normalized preload)}^2 - 0.6 \text{ MPa} \\ & \text{(normalized impact energy)}^2 \ .\end{aligned} \tag{5}$$

At the median, or all zero setting, this equation gives a value of 297.1 MPa for CAI strength. The experimental value was found in run No. 9 to be 295±7 MPa.

An examination of the coefficients show that the linear terms dominate this equation. As the preload and impact energy increase, the CAI strength decreases in primarily a linear fashion. There appears to be little interaction between the two independent variables. These results are due primarily to the high impact energies used for the IM7/8551-7 material. The quadratic preload term at –6.6 MPa accounts for the preload causing catastrophic CAI failures at the higher impact energies tested.

A three-dimensional plot of the resulting function for CAI strength (equation (5)) is shown in figure 11.

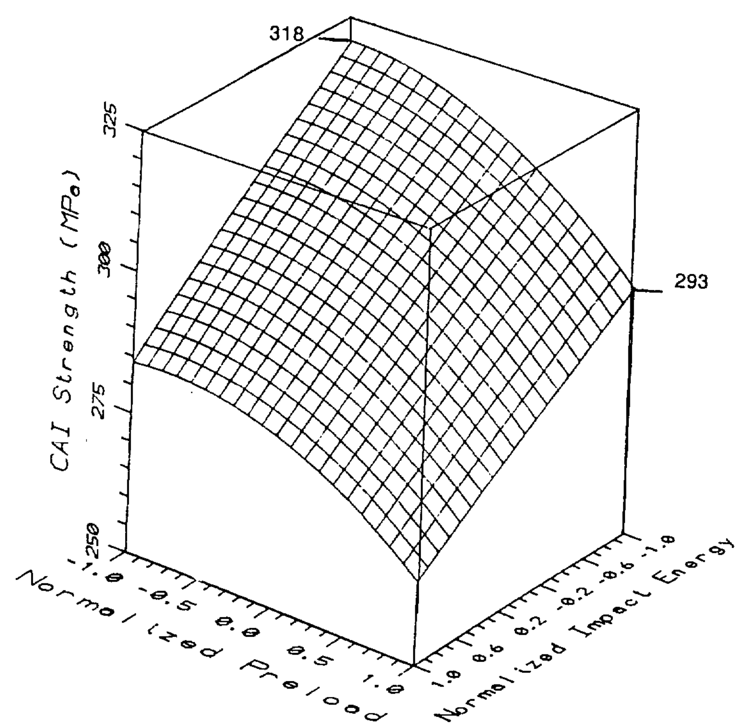


Figure 11. CAI strength as a function of preload and impact energy for IM7/8551-7 material.

From this surface response profile, it can be seen that the impact energy degrades the residual compression strength in a linear manner, while the preload has a degradation effect on CAI strength that becomes stronger with increasing preload. There is little interaction between the preload and the impact energy as is evidenced by the lack of "twist" in the surface response.

Comparing the two material systems tested, it is apparent that the IM7/8551-7 is a tougher material. Its mean CAI strength was determined under much more severe conditions than the T300/934: a preload of 7,000 lb for the IM7/8551-7 versus 2,100 lb for the T300/934 and an impact energy of 10 J for the IM7/8551-7 versus 5.5 J for the T300/934, yet the mean CAI strength value is essentially the same, 297.1 MPa for the IM7/8551-7 and 296.1 MPa for the T300/934. In fact, a comparison of tables 1 and 2 shows that the IM7/8551-7 material hit at 6 J has more strength retention than any of the T300/934 specimens hit at 5.5 J. The surface response plots provide an easily understood method of "seeing" the effects of two independent variables on a given output (dependent variable). These surfaces can be constructed with relatively few test runs (nine in this study) if advanced design of experiments techniques are used. Many advanced design-of-experiments software packages exist, making the testing process much easier and more economical.

CONCLUSIONS

For a brittle carbon/epoxy system such as T300/934, layered up at 16-ply $(0,+45,90,-45)_{2s}$ flat coupons tested at impact energies up to 9 J, the effects of compressive preloads up to 4,000 lb (115 MPa stress) on CAI tests are shown to be small, causing an 18-percent increase in CAI strength values at the area of most influence of this variable (the lowest impact energy level). It is also shown that within these parameters, there is an interaction between preload and impact energy since at the highest impact energy level, an 8-percent decrease in CAI strength is seen between the highest and lowest preload values used.

For a toughened carbon/epoxy system such as IM7/8551-7, with the same stacking sequence, tested between preloads of 4,000 to 10,000 lb and impact energies between 4 and 16 J, the preload has a smaller effect. At the area of most effect, the preload causes a CAI strength decrease of 7 percent. There is no interaction between impact energy and preload for these specimens.

It can thus be concluded that the amount of compressive preload a composite specimen is experiencing during an impact event will not decrease the compressive strength of the material with any statistical significance. A slight increase may be seen at low impact energies since the prestress acts as a stabilizer of sorts, preventing out-of-plane deflection which causes delaminations.

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