NASA-TM-111879

IN-24-TM
81146

THE EFFECTS OF COMPRESSIVE PRELOADS ON THE COMPRESSION-AFTER-IMPACT STRENGTH OF CARBON/EPOXY

Alan T. Nettles
NASA, Marshall Space Flight Center
Mail Zone EH33
Huntsville, AL 35812

ABSTRACT

A fixture to apply compressive loads to composite specimens during an impact event was used to assess the effect of prestresses on the compression-after-impact (CAI) strength of 16 ply quasi-isotropic carbon/epoxy test coupons. Advanced design of experiments techniques were used to evaluate a range of prestresses and impact energies on two material systems, T300/934 and IM7/8551-7. An instrumented drop tower supplied impact energies between 1 and 9 Joules for the T300/934 material and between 4 and 16 Joules for the IM7/8551-7 material. The prestress values varied between a low of 5.7 MPa and a high of 287 MPa. Results showed some change in CAI strength that could be attributed to the prestresses on the specimens.

KEY WORDS: Composites, Impact Resistance, Testing Equipment

1. INTRODUCTION

A vast amount of research has been performed in the area of impact damage to composite materials. In virtually all studies conducted, the composite specimen was under no external stresses during the impact event. In actual practice a composite may be under a state of stress during an accidental foreign object impact, for example a worker hitting the bottom of a wing skin with a tool during service/maintenance. The wing, being a cantilever beam, will have its bottom skin mostly in a compressive state. The need of assessing the effects of prestresses on composite materials undergoing foreign object impact was identified at a NASA workshop on impact damage tolerance of composite materials held in 1991 (1). Thus the purpose of this research is to assess the effects of compressive preloads on the impact behavior of composite specimens.

Little experimental data exists on impact of preloaded composite specimens. Rhodes and Avva have presented data that contain information on this subject (2,3). Rhodes concluded that the residual compressive strength of specimens impacted while in a compressive stressed state is slightly lower than those impacted when no external stress was applied. Avva came to a similar conclusion but showed that at high impact energies, the preload had a smaller detrimental effect on CAI strength than at lower impact energies. Park (4) examined the tensile prestresses needed to cause catastrophic failure for a given impact energy in samples of a variety of materials including carbon fiber reinforced epoxy. Two tup sizes were used to represent an impact from a blunt and a sharp impactor. "Impact maps" or the line of catastrophic failure on an impact energy versus prestress chart were plotted for various materials. Little data on residual strength of surviving specimens was given.

Sun (5) and Dabyns (6) have analytically analyzed this problem and found that the most noticeable changes in impact parameters are those dealing with changes in the fundamental frequencies of the composite plates. Maximum load of impact was not effected very much by tensile or compressive preloads.

When performing experimental work, especially of a destructive nature, it can become time consuming and expensive to examine a number of variables by holding all but one constant and examining the response of the material to that one variable that is changing. In addition, if two variables interact with one another, this would not be noticed in one-variable-at-a-time testing. Thus utilizing advanced design of experiments to examine more than one variable can be a very efficient and effective way to conduct laboratory tests.

2. EXPERIMENTAL

2.1 Design of Experiments Two multivariable test matrices were used to assess the effects of compressive prestresses and impact energy on the CAI strength and maximum load of impact of two carbon/epoxy materials. A full factorial three level two parameter design was used to evaluate T300/934 carbon/epoxy, and a central composite five level two parameter design was used to evaluate IM7/8551-7 carbon/toughened epoxy. The test matrices are shown in tables 1 and 2. Data were analyzed with a designed experiments software package (BBN/Catalyst).

Run Number	Prestress (MPa)	Impact Energy (Joules)
1	5.7	1.0
2	5.7	5.0
3	5.7	9.0
4	60.3	1.0
5	60.3	5.0
6	60.3	9.0
7	115	1.0
8	115	5.0
9	115	9.0

Table 1. Parameter settings for T300/934 material.

The output data consists of one constant and five coefficients. The constant is the value of the response variable (either maximum load of impact or CAI strength) when the two independent variables (prestress and impact energy) are at their centermost or mean values. The five coefficients relate the linear effects of the two parameters, their interaction and each of their quadratic effects on the constant value. In order to use these coefficients, the values of the independent variables must be normalized between a low of -1 to a mean of zero, up to a high value of +1. For example, in table 1, the values of prestress become 5.7 MPa = low = -1, 60.3 MPa = medium = 0 and 115 MPa = high = +1. The values of the impact energy become 1.0 Joules = low = -1, 5.0 Joules = medium = 0 and 9.0 Joules = high = +1. The normalized values are dimensionless. The effect of the five coefficients are found by multiplying each coefficient by the normalized independent variable(s) it represents and then adding this value to the constant. This will yield the predicted response value for the given independent variables' values.

Run Number	Prestress (MPa)	Impact Energy (Joules)
1	258	14.0
2	258	6.0
3	144	14.0
4	144	6.0
5	201	4.3
6	201	15.7
7	115	10.0
8	287	10.0
9	201	10.0

Table 2. Parameter settings for IM7/8551-7 material.

2.1.1 Example of Design of Experiments Suppose that the constant for a given set of runs for the T300/934 material is found to be 5000 Newtons and the coefficients are:

Prestress = -500 N
Impact Energy = 1000 N
Prestress/Impact Energy Interaction = - 100 N
Quadratic Prestress = -250 N
Quadratic Impact Energy = -750 N

This indicates that when the prestress is set at 60.3 MPa and the impact energy is 5.0 Joules, the resulting maximum load of impact will be 5000 N. To normalize the prestress and impact energy values, set the low values to -1, the medium values to 0 and the high values to +1. The corresponding actual values to normalized values is given in table 3.

Prestress (MPa)	Normalized	Impact Energy (J)	Normalized
5.7	-1	1.0	-1
19.4	-.75	2.0	-.75
33.0	-.5	3.0	-.5
46.7	-.25	4.0	-.25
60.3	0	5.0	0
74	+.25	6.0	+.25
88	+.5	7.0	+.5
101	+.75	8.0	+.75
115	+1	9.0	+1

Table 3. Actual and corresponding normalized values of the two independent variables.

Now suppose the value of the maximum load of impact is to be predicted for a prestress of 101 MPa and 3.0 J of impact energy. The normalized values are now, prestress = +.75 and Impact energy = - .5. The predictive equation is:

$$\begin{aligned}\text{Response} = {} & 5000\text{N} - 500\text{ N}(+.75) + 1000\text{ N}(-.5) \\ & -100\text{ N}(+.75)(-.5) - 250\text{ N}(+.75)^2 - 750\text{ N}(-.5)^2 = 3834\text{ N}\end{aligned}$$

The general equation can be written as:

Response = Constant + (Prestress Coefficient)(Normalized Prestress) + (Impact Energy Coefficient)(Normalized Impact Energy) + (Interaction Coefficient)(Normalized Prestress)(Normalized Impact Energy) + (Quadratic Prestress Coefficient)(Normalized Prestress)^2 + (Quadratic Impact Energy Coefficient)(Normalized Impact Energy)^2

2.2 Test Coupons The specimens used were 16 ply $[0,+45,90,-45]_{2S}$ quasi-isotropic with a nominal ply thickness of .127 mm. The specimen dimensions were 178 mm long by 76 mm wide with a gage length of 102 mm leaving 38 mm on each end for tabs. The compressive preloads were introduced into the specimens using an end loading technique. Figure 1 shows the apparatus used to apply the prestress to the specimens during impact.

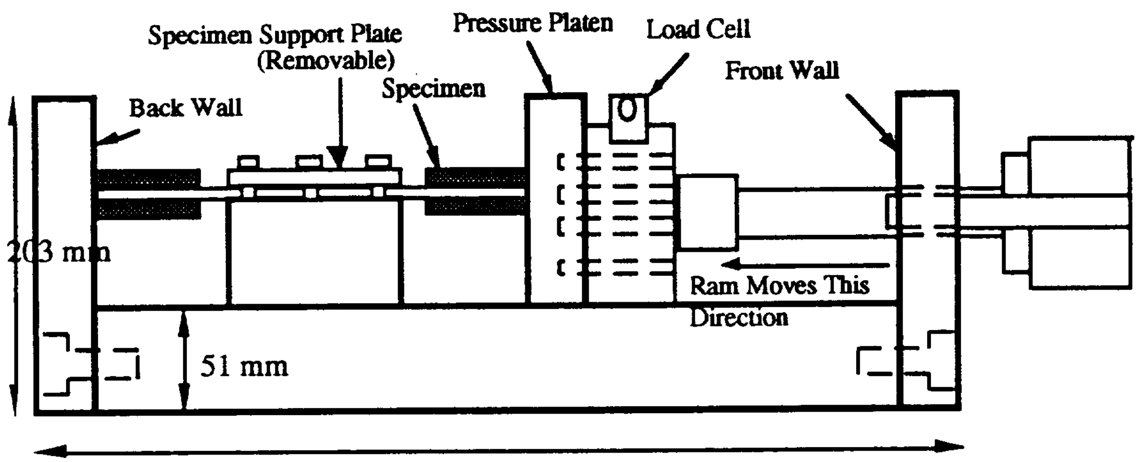

Figure 1. Compression preload device.

In order to ensure a uniform prestress was present at the area to be impacted, three strain gages were placed on the specimen as shown in figure 2.

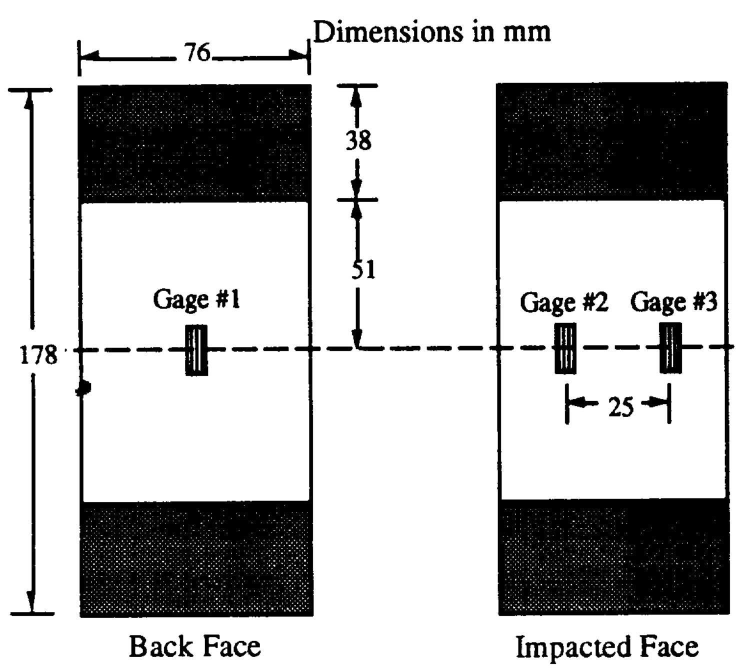

Figure 2. Placement of strain gages and dimensions of specimens.

The strain gages were monitored as the prestress was applied and if a deviation of more than 10% occurred between any of the three gages, the test was halted and another specimen was used. A deviation in the gages usually indicated that the specimen ends were not cut to close enough tolerances to evenly distribute the stress being applied to the ends of the specimen.

2.3 Compression Preload Device A fixture consisting basically of two steel plates and a hydraulic ram was used to apply the appropriate preloads before impact. The ram was manually driven via a hand pump such that the two, parallel plates would approach each other and apply a compressive load to the specimen located between the two plates (see figure 1). A load cell was placed between the ram and one of the steel plates to record the applied preload. The specimen rested on a steel block with a 63 mm diameter hole cut through it. A removable specimen support plate with a matching 63 mm circular cutout was placed on top of the specimen and clamped lightly to the steel block so as to sandwich most of the gage length of the specimen providing an anti-buckling support.

2.4 Compression-After-Impact Testing After the specimens were impacted while subjected to the various preloads, they were tested for residual compression strength. A shear loading fixture with supporting faceplates was used to test the relatively thin specimens. A more detailed description of this test method can be found elsewhere (7).

3. RESULTS AND DISCUSSION

3.1 Load/Strain During Preload The load/strain data from the three strain gages were taken at various increments of loading for all of the specimens tested. This assured that a uniform external stress field was being applied at the area to be impacted. Figure 3 shows a plot of the load/strain data for T300/934 specimen # 6.

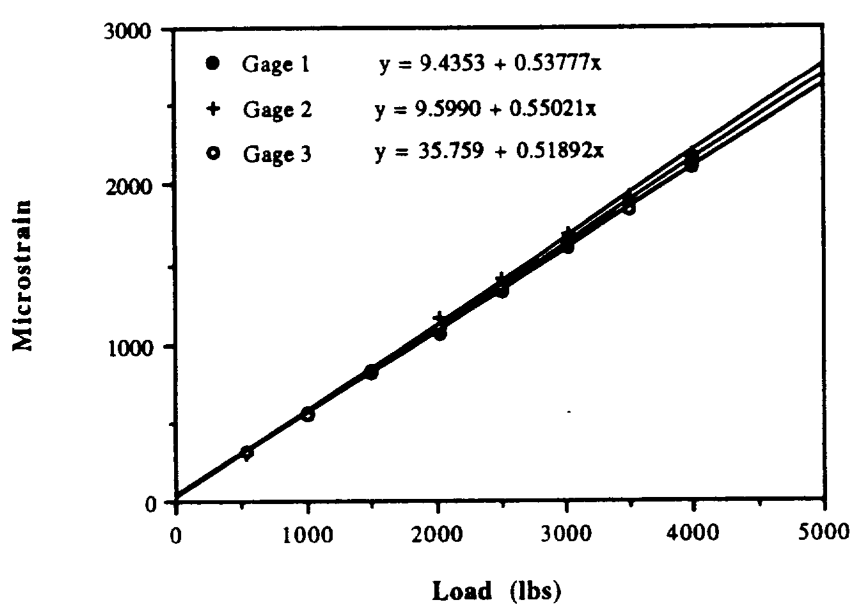

Figure 3. Preload/strain data for T300/934 specimen # 6.

This specimen demonstrated a very uniform strain field at the area to be impacted. An example of a specimen that had to be discarded is given in figure 4 where the deviation in the strain gages exceeds 20%.

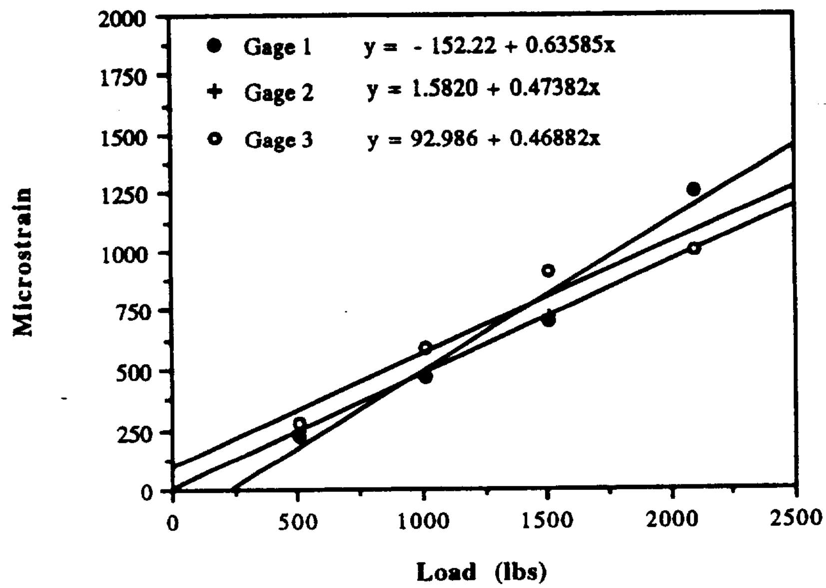

Figure 4. Preload/strain data for a discarded T300/934 specimen.

3.2 Impact Testing The maximum impact load, as well as several other parameters, were recorded after each impact. A Dynatup 730 data acquisition system was used with an instrumented tup of 12.7 mm diameter. After each impact, the specimen was removed from the preload device and the visual damage was noted and recorded. No catastrophic failures occurred for the T300/934 material. A catastrophic break is an event where the specimen fails in compression due to the combination of preload and impact thus yielding a specimen with zero residual strength.

The maximum impact loads for the T300/934 specimens are given in table 4.

Run #	Prestress (MPa)	Impact Energy (J)	Maximum Load of Impact (N)
1	5.7	1.0	1129
2	5.7	5.0	3054
3	5.7	9.0	3772
4	60.3	1.0	1075
5	60.3	5.0	2503
6	60.3	9.0	3267
7	115	1.0	925
8	115	5.0	2630
9	115	9.0	2928

Table 4. Maximum impact load for the T300/934 specimens.

As theorized by Sun and Chen (4), an initial compressive stress will give rise to a "softening" effect on the laminate stiffness and thus lower maximum impact loads for a given impact level. This seems to be the case for the T300/934 material since the highest impact loads occurred consistently at the lowest prestress levels. A more detailed analysis of these data will be presented later in this paper.

The maximum load of impact for the IM7/8551-7 specimens are given in table 5.

Run #	Prestress (MPa)	Impact Energy (J)	Maximum Load of Impact (N)
1	258	14.0	3056
2	258	6.0	2844
3	144	14.0	3249
4	144	6.0	3168
5	201	4.3	2584
6	201	15.7	3570
7	115	10.0	3392
8	287	10.0	2948
9	201	10.0	3418

Table 5. Maximum impact load for IM7/8551-7 specimens.

These data also show a "softening" effect on the laminate stiffness due to a compressive preload. This will also be examined in further detail later in this paper.

3.3 Residual Compression Strength For the specimens that did not fail catastrophically on impact, the compression-after-impact (CAI) strength was measured as described earlier. The results for the T300/934 material are given in table 6 and the results for the IM7/8551-7 material are given in table 7.

Run #	Prestress (MPa)	Impact Energy (J)	(CAI) Strength (MPa)
1	5.7	1.0	372
2	5.7	5.0	291
3	5.7	9.0	293
4	60.3	1.0	395
5	60.3	5.0	288
6	60.3	9.0	297
7	115	1.0	446
8	115	5.0	294
9	115	9.0	276

Table 6. Compression-after-impact strength data for T300/934 specimens.

Run #	Prestress (MPa)	Impact Energy (J)	(CAI) Strength (MPa)
1	258	14.0	Catastrophic Impact
2	258	6.0	302
3	144	14.0	308
4	144	6.0	315
5	201	4.3	328
6	201	15.7	261
7	115	10.0	299
8	287	10.0	Catastrophic Impact
9	201	10.0	290

Table 7. Compression-after-impact strength data for IM7/8551-7 specimens.

All of the specimens tested for residual strength broke at the impacted area.

3.4 Analysis of Data The data for maximum load of impact and for residual compressive strength were evaluated with an advanced design of experiments methodology. The T300/934 material was evaluated using a full factorial experiment while the IM7/8551-7 material was evaluated with a central composite fractional factorial experiment.

3.4.1 Maximum Load of Impact; T300/934 The data from table 4 were entered into a software program that would generate quantitative 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 following coefficients were generated:

Constant = 2646 N
Prestress = -245 N
Impact Energy = 1140 N
Prestress/Impact Energy Interaction = -160 N
Quadratic Prestress = 125 N
Quadratic Impact Energy = -546 N

A good way to examine these coefficients is to create a "surface response" plot, or a plot of maximum load of impact on the vertical (z) axis versus preload on one horizontal (x) axis and impact energy on the other horizontal (y) axis. Figure 5 is a surface response plot of maximum load of impact versus impact energy and preload.

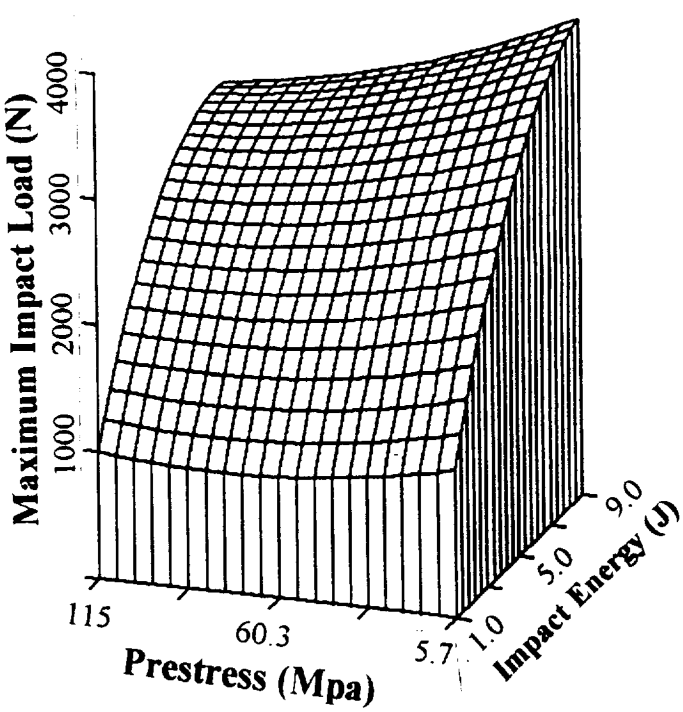

Figure 5. Maximum load of impact versus impact energy and prestress: T300/934.

The prestress has little influence on the maximum load of impact. A slight increase of this variable is seen when the prestress is at the lower end of settings which demonstrates the laminate "softening" due to compressive preloads. As expected, the higher impact energies yield much higher maximum impact loads with a leveling off occurring at the high end when fiber breakage begins to develop in the specimen and the impact load comes closer to that needed to perforate the specimen.

3.4.2 Maximum Load of Impact; IM7/8551-7 The data from table 5 will give the response plot shown in figure 6.

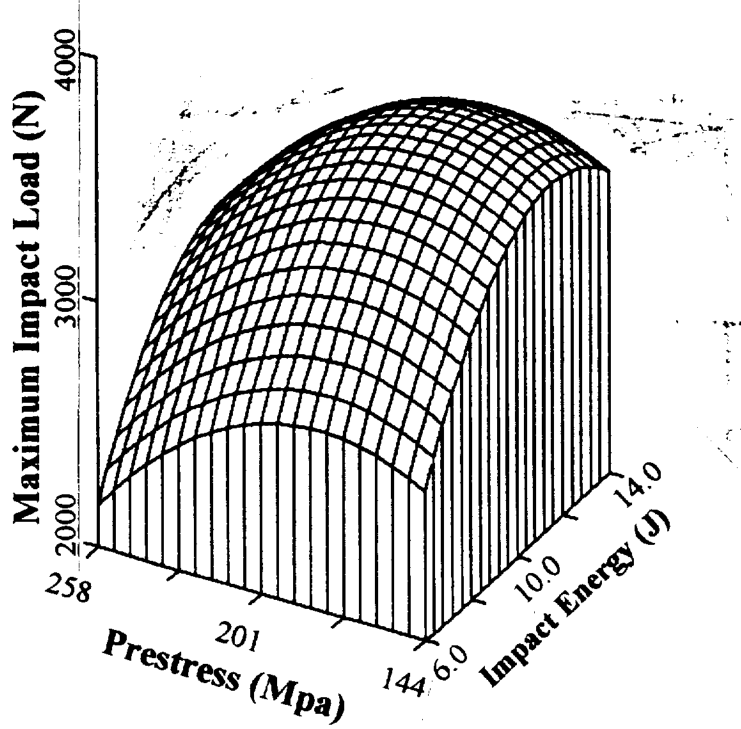

Figure 6. Maximum load of impact versus impact energy and prestress: IM7/8551-7.

The following coefficients were generated for the maximum impact load response for the IM7/8551-7 material:

Constant = 3418 N
Prestress = -216 N
Impact Energy = 316 N
Prestress/Impact Energy Interaction = 0 N
Quadratic Prestress = -308 N
Quadratic Impact Energy = -409 N

This material has a maximum impact load that is also dependent on the amount of prestress. The largest impact loads occur when the prestress is near the medium or 201 MPa setting. At the other extremes the impact load decreases. This trend holds for all values of impact energy (indicating no interaction). As the prestress is increased, a "softening" of the laminate is to be expected and the maximum impact load will decrease for a given impact energy. As the prestress decreases, the reason for the decrease in maximum impact load is not as obvious.

A direct comparison of the maximum impact load data for the T300/934 material and the IM7/8551-7 material is not practically feasible since the prestress and impact energy levels were more severe for the toughened IM7/8551-7.

3.4.3 Compression-After-Impact Strength; T300/934 Figure 7 shows the response surface of compression-after-impact versus impact energy and prestress for the T300/934 material. The coefficients are:

Constant = 291 MPa
Prestress = 10.0 MPa
Impact Energy = -57.8 MPa
Prestress/Impact Energy Interaction = -22.8 MPa
Quadratic Prestress = 0 MPa
Quadratic Impact Energy = 55.5 MPa

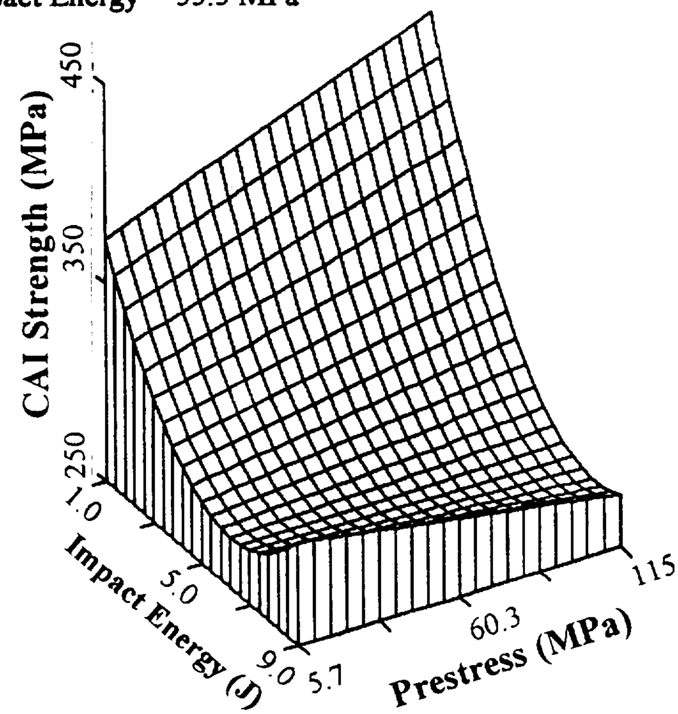

Figure 7. CAI strength versus impact energy and prestress: T300/934.

The CAI strength is heavily dependent upon the impact energy used (as expected) but is also dependent on the amount of prestress in the specimen. The dependence is linear and interacts with the amount of impact energy that is being used. At the low end of impact energy, the CAI strength increases with increasing prestress, and at the larger impact energies, the CAI strength decreases slightly with increasing preload. This can be attributed to the "softening" effect mentioned earlier where a compressive prestress will decrease the effective stiffness of the laminate thus producing a more damage resistant material. The maximum load of impact plot (figure 5) shows this effect where the more highly prestressed specimens show a small decrease in maximum impact load. The change in this trend at the high end of impact energies can be attributed to the specimen reaching its perforation level and in this case the "softening" seen at lower impact energies will become negligible due to the extremely hard hits the specimen is undergoing. The slight decrease in CAI strength at higher preloads is due to the specimens reaching their catastrophic breaking point which indicates that the preload can further damage the specimen while the impact damage is being induced into the specimen.

3.4.3 Compression-After-Impact Strength; IM78551-7 Figure 8 shows the response surface of compression-after-impact versus impact energy and prestress for the IM7/8551-7 material. The coefficients are:

Constant = 297 MPa
Prestress = -93.0 MPa
Impact Energy = -50.5 MPa
Prestress/Impact Energy Interaction = -73.8 MPa
Quadratic Prestress = -70.9 MPa
Quadratic Impact Energy = 0 MPa

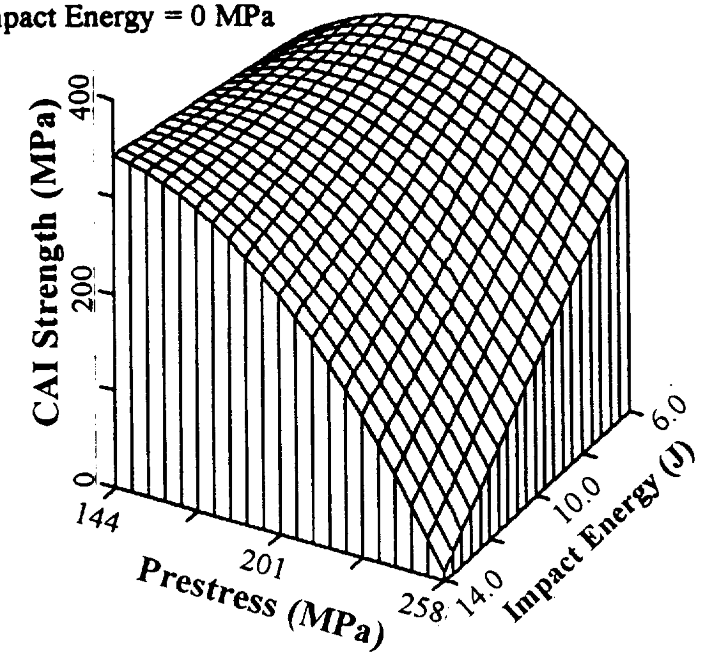

Figure 8. CAI strength versus impact energy and prestress: IM7/8551-7.

The extreme drop in CAI strength with increasing preload combined with increasing impact energy is due to the catastrophic breaks that occurred on runs # 1 and 8. (A catastrophic break implies zero residual strength). The linear dependence of CAI strength on impact energy is unusual and is probably due to the strong impact energy/prestress interaction coupled with a tough resin system. Toughened resin composites have shown different trends in loss of CAI strength with increasing impact energy (8). In addition, the IM7/8551-7 material was prestressed and impacted at much more severe levels than the T300/934 material and the level of impact at which a sudden drop in CAI strength occurs is not included.

4. CONCLUSION

For a brittle carbon/epoxy system such as T300/934, layed-up as 16 ply $(0,+45,90,-45)_{2S}$ coupons and tested at impact energies up to 9 J, the effects of compressive prestresses up to 115 MPa on maximum load of impact were found to be small compared to the effect of impact energy. At the impact level where the maximum impact load was most affected by the preload (9 J), a 27 % increase in maximum impact load is seen as the preload decreases from its highest level to its lowest level. Given that the impact energies and prestresses were not at a level severe enough to cause catastrophic failure, this difference may be significant.

For a toughened carbon/epoxy tested at much more severe impact energies and preloads, the prestresses have a slightly smaller effect on the maximum impact load. A 19 % increase is seen in this variable from the 258 MPa prestress to the 221 MPa prestress values at the impact energy that is most affected by the preloads which is the lowest level. This smaller difference could be from the fact that even at the lower end of prestresses used with this material, significant "softening" of the material being impacted still occurred. The IM7/8551-7 material was tested at much higher prestresses than the T300/934 material.

The compression-after-impact (CAI) strength of the T300/934 material was affected by the amount of prestress, especially at the extreme values of impact energy used. At the lowest level (1.0 J), a 18 % *increase* in CAI strength is seen as the preload increases from its lowest to highest values. At the highest (9.0 J) level, a 8.6 % *decrease* is seen in the CAI strength of the coupons as the preload increased from its lowest to highest values. The "softening" effect of the compressive preload can account for the behavior in the CAI strength at the lower impact energies. At the higher impact energies, the specimen was hit at a high enough level such that the "softening" effect did not contribute to helping the specimen have better impact resistance.

The CAI strength of the IM7/8551-7 specimens was severely effected by the prestress, especially at the higher end of impact energies used. This was due to catastrophic failures occurring on runs # 1 and 8. A 13 % decrease in CAI strength was seen at the lower end of impact energy (6.0 J) as the prestress was increased from its lower value of 144 MPa to the higher value of 258 MPa. At the higher impact energy (14.0 J) the decrease was 98 %.

5. SUMMARY

When a composite specimen is impacted while under a compressive prestress, a "softening" effect will occur that increases the specimens damage resistance, reducing the maximum load of impact and increasing the CAI strength. However, when the specimen is prestressed and impacted at severe levels near the breaking point of the specimen, the opposite trend occurs and the specimen can fail catastrophically resulting in zero residual compressive strength, or if the specimen survives, the CAI strength may decrease due to the preload, and any "softening" of the specimen by the compressive prestress is negated by the high level of impact.

6. REFERENCES

1. NASA CP 10075, Workshop on Impact Damage to Composites, Hampton, VA, (1991).
2. M. D. Rhodes, J. G. Williams and J. H. Starnes, Jr., Polymer Composites, 2, (1), 36 (1981).
3. V. S. Avva, J. R. Vala and M. Jeyasseelan in J. M. Whitney, ed., ASTM STP 893, ASTM, Philadelphia, 1986, pp.196, 206.
4. N. Park, IMechE, C400/019 (1990).
5. C. T. Sun and J. K. Chen, J.C.M., 19, 490 (1985).
6. A. L. Dobyns, J., AIAA J., 19, 642 (1981).
7. A. T. Nettles and A. J. Hodge, SAMPE International Technical Conference, 23, 177 (1991).
8. R. L. Dempsey and R. E. Horton, SAMPE International Symposium, 35, 1292 (1990).