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POST IMPACT COMPRESSIVE STRENGTH IN COMPOSITES

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SUMMARY

Presented in this paper are the plan, equipment, procedures and findings of an experimental investigation of the tolerance to low velocity impact of a graphite epoxy (AS4/3501- 6) and graphite bismaleimide (IM6/CYCOM3100) advanced composites. The applied impacts were governed by the Air Force Guide Specification 87221. Specimens of each material system having a common nominal layup (10%0^o; 80% ±45^o; 10% 90^o), a common 7 inch (17.78 cm) by 10 inch (25.40 cm) size, five different thicknesses (9, 26, 48, 74 and 96 plies) and ambient moisture content were impacted and strength tested at room temperature. Damaged areas and post impact compression strengths (PICS) were among the most significant findings obtained. While the undamaged per ply compression strength of both materials is a strong function of laminate thickness, the per ply PICS is not. The average difference in per ply PICS between the two material systems is about seven percent. Although a smaller percentage of the applied kinetic energy was absorbed by the Gr/BMI than by the Gr/Epoxy composites, larger damaged areas were produced in the Gr/BMI than in Gr/Epoxy. Within the limitations of this investigation, the Gr/BMI system seems to offer no advantage in damage tolerance over the Gr/Epoxy system examined.

INTRODUCTION

The US Air Force, in its aim to provide a desired degree of structural integrity that would preclude catastrophic failures due to barely visible impact damage, currently requires that a damage tolerant design of an airframe incorporates an initial damage due to either a 0.1 inch (2.54 mm) deep dent or a 100 ft -lb (136 joules) impact, whichever is less, both caused by a 1 inch (2.54 cm) diameter impactor traveling at 16 ft/sec (4.88 m/sec). This requirement is based on data obtained in an Air Force sponsored damage tolerance program where a graphite epoxy (AS4/3501-6) composite was investigated. Also, in this program it was found that among various common types of damage the barely visible damage due to low velocity impact was the worst type and that it could reduce the original compression strength by as much as 60%. Assuming that different damage tolerance findings may be obtained in composites of different material systems, the need for investigating impact responses by different composites was recognized.

OBJECTIVE AND SCOPE

The main objective of the investigation presented in this paper is to experimentally determine the room temperature post impact compressive strength (PICS) of moisture non-preconditioned ("dry")AS4/3501-6 graphite epoxy (Gr/Ep) and IM6/CYCOM 3100 graphite bismaleimide (Gr/BMI) specimens that had been subjected to low velocity impact in accordance with the above US Air Force requirements. The paper will also present the description of the test plan, including the selected layup, stacking sequences, and thicknesses; the non-destructive inspection of specimens before and after impact; the apparatus for inducing impact; and the residual strength test procedures. The discussion of test results and conclusions will be presented here as well.

TEST PLAN

The following is the rationale for selecting AS4/3501-6 graphite epoxy and IM6/CYCOM3100 graphite bismaleimide as the composite material systems for the low velocity impact resistance investigation presentation in this paper. The Gr/Ep, being one of the most characterized and hence popular systems, was to serve as the base line. The low velocity impact resistance of the Gr/BMI system represents a modified and allegedly more damage tolerant system, and was to be observed and compared with that of the baseline. The nominal laminate layup for each of the two selected material systems was chosen as 10/80/10 (10% 0^{o}, 80% $\pm45^{o}$ and 10% 90^{o} plies) for the reason that such a layup, due to its relatively high potential ultimate strain in the 0^{o} direction, would buy maximum damage tolerance while still maintaining a reasonable strength in the 0^{o} direction. To investigate the effect of laminate thickness on impact resistance, test specimen thicknesses of 9, 26, 48,74 and 96 plies were selected. Using the selected number of plies, most of the resulting layups were slightly different than the nominal 10/80/10 as shown in Table I. Panels from both material systems were cured in an autoclave. The total cure cycle for Gr/Ep, including heat-up and cool-down ramps, lasted six hours, two of which included 100 psi (0.689 MPa) pressure and 350^{o}F (177^{o}C) temperature. There was no post cure for Gr/Ep. The Gr/BMI panels were cured at 85 psi (0.586 MPa) pressure and 350^{o}F (177^{o}C) temperature for four hours. Including heat-up and cool down ramps, it took 7 3/4 hours to complete the cure cycle. The Gr/BMI was subsequently postcured at 400^{o}F (204^{o}C) and atmospheric pressure for four hours. The resulting fiber volumes for each of the two composites were 63% for AS4/3501-6 and 57% for IM6/CYCOM3100. The cured panels were ultrasonically inspected for manufacturing quality and those with acceptable quality were then cut into specimens with an eight-inch diameter and 1/8 inch wide diamond saw. The size of the test specimens varied depending on the purpose of the test. Specimens for characterizing the material systems (Table II) were of the following sizes: 3/4" (1.905 cm) x 10" (25.4 cm) for 0^{o} tension; 1" (2.54

cm) x 10" (25.4 cm) for 90^{o} tension; 1" (2.54 cm) x 10" (25.4 cm) for in-plane shear; 3/4" (1.905 cm) x 5" (12.7 cm) for 0^{o} compression and 3/4"(1.905 cm) x 5" (12.7 cm) for 90^{o} compression. Those specimens for determining virgin compressive strength of the impact specimens were 5" (12.7 cm) by 10" (25.4 cm) while the size of the low velocity impact test specimens was 7" (17.8 cm) wide and 10" (25.4 cm) long. Since the specimens were neither desiccated nor deliberately moisture preconditioned, their moisture content at the times of impact introduction and residual strength determination was ambient, i.e., specimens had absorbed moisture from surrounding air only. A commercially available Dynatup drop tower was employed to introduce impact to the specimen. This was achieved by a vertically falling steel impactor with a 1 inch (2.54 cm) diameter hemispherical end. The specimen was placed between a 1 inch (2.54 cm) thick steel plate and a 0.75 inch (1.90 cm) thick aluminum cover plate, each having in its center a 5 inch (12.70 cm) square opening whose center coincided with those of the specimen and the impactor. The assembly of the plates and the specimen was held together by clamps at the four corners (Reference 1). The resulting boundary conditions for the specimen were neither hinged nor fixed but somewhere between the two. Before proceeding with impact introduction, a velocity check of the free falling impactor was performed. This check consisted of comparing the theoretical free falling velocity evaluated from the impactor's drop height ($h=V^2/2g$) with the recorded velocity sensed by a velocity detector built into the drop tower. In case of a significant disagreement, the guide bars were cleaned to reduce friction between the bars and the falling impactor until there was no significant difference between the two velocities. Since the drop height was limited to the available maximum of 3.5 ft (1.07 m), the maximum velocity of the free falling impactor was also fixed. Thus the impactor weight was the only variable in those series of tests governed by the 0.1 inch(2.45 cm) deep dent (9, 26, 48 plies thick specimens) and 100 ft-lbs (136 joules) for 74 and 96 plies thick specimens.

Among the quantities recorded during the short impact event (6-7 milliseconds) were: the histories of contact load and energy absorbed by the specimen, test temperature, impactor velocity just before touching the specimen, and other important useful load and energy quantities that are post-test calculated (Figure 1). An accelerometer built into the impactor sensed the magnitude of the contact load that was used to calculate the energy absorbed by the specimen.

All testing was conducted at room temperature. Dent depths were found using shadow Moire techniques (References 2 and 3). The impacted specimens were ultrasonically examined to determine the damaged areas (Table I). The residual post impact compression strength (PICS) of each specimen was found in a test conducted in an INSTRON test machine. The specimen that was cut to a 5 inch (12.7 cm) by 10 inch (25.4 cm) size was supported in a compression fixture that prevented lateral displacement of the specimen edges. This fixture, originally known as the NASA-Boeing fixture, was modified by Dr R. S. Sandhu who provided a lateral restraint to the top portion of specimen edge that previously did not have such restraint.

DISCUSSION OF RESULTS

Table I summarizes the more significant results of this investigation. In addition, Figures 1, 2 and 3 exemplify some of these findings graphically. The values shown in Table I for each of the five specimen thicknesses are the averages of a number of replicates varying between three and ten. It must be emphasized that the impact intensity in this investigation was governed by current US Air Force suggested requirements to assure a damage tolerant airframe as described in the INTRODUCTION of this paper. One exception to the requirements is the 9-ply laminate where it is impossible to achieve the required 0.1 inch (2.54 mm) deep dent without penetration since the laminate itself is only 0.0468 inch (1.189 mm) thick. Hence in this case the impact intensity was selected such as to cause an indentation approximately equal to the thickness of the 9-ply specimens (Reference 3). Among the most significant data were the absorbed energy, damaged areas and post impact compressive strength (PICS). Since the applied kinetic energies for laminates of both material systems had been selected according to the requirements of the Air Force Guide Specification 87221, for the same thickness they were almost the same (columns 7 and 16 of Table I). While the graphite epoxy thinner laminates absorbed more energy than the thicker ones (column 9, Table I), the graphite bismaleimide did not show such a trend as the percentages were fairly uniform for all thicknesses (column 18, Table I). It is quite obvious though that the Gr/Ep specimens absorbed a greater percentage of applied kinetic energy than the Gr/BMI specimens. In spite of this observation and possible intuitive conclusion, the damaged areas in Gr/Ep were smaller than those in Gr/BMI. A possible explanation for this is the generally greater brittleness for bismaleimides of the type similar to CYCOM3100. As Figure 3 clearly depicts, the per ply compressive strength of the undamaged specimens of both material systems strongly depends on the thickness of the specimen. The undamaged Gr/BMI strength exceeds that of Gr/Epoxy by an average of 20%. However, the per ply PICS of both composites is essentially the same for all thicknesses. The loss of per ply compressive strength is greater in the Gr/BMI composites than in the Gr/Epoxy composites. This is reflected graphically in Figure 3 and numerically in columns 13 and 22 of Table I.

CONCLUDING REMARKS

Based on the data obtained in this experimental investigation, it may be concluded that the per ply post impact compressive strength for either the graphite epoxy or the graphite bismaleimide composites is fairly constant for all thicknesses investigated. Thus there appears to be no strength advantage to prefer the Gr/BMI system over the Gr/Epoxy system for designs governed by damage tolerance.

REFERENCES

1. NASA Reference Publication 1092, 1982.

2. Handbook of Experimental Mechanics, Society for Experimental Mechanics, Prentice-Hall, 1987.

3. Demuts, E.; Sandhu, R. S.; Maddux, G. E.: Barely Visible Damage Threshold In Graphite Epoxy. Proceedings of the Eighth International Conference on Composite Materials, July 1991, SAMPE, Vol 4, pp 32- N -1 to 32 -N -12.

TABLE I - SUMMARY OF TEST RESULTS

NO. OF PLIES	STK SEQ	ACTUAL LAYUP % (0°/±45°/90°)	IMPACT GOVERNOR	AS4/3501-6 GRAPHITE EPOXY: NO. OF REPLICATES	MEASURED VELOCITY m/sec	MEASURED ENERGY joules	ABSORBED ENERGY joules	ABSORBED ENERGY %	DAMAGED AREA (cm^2)	UNDAM. COMPR. STR'TH N/ply	PICS N/ply	PICS % OF UNDAM %
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
9	C	22.2/66.7/11.1	D1	10	2.51	12.34	10.02	81	6.45	1,561	1,753	123
26	D	11.5/77.0/11.5	D2	3	4.48	48.28	39.96	83	19.35	3,345	2,522	75
48	E	12.5/75.0/12.5	D2	8	3.71	123.82	97.65	79	103.23	6,241	1,908	31
74	F	12.2/75.6/12.2	E	8	3.88	135.78	66.04	49	116.13	6,610	2,082	31
96	G	12.5/75.0/12.5	E	5	3.88	135.81	51.57	38	116.13	5,551	2,340	42

NO. OF PLIES	STK SEQ	ACTUAL LAYUP % (0°/±45°/90°)	IMPACT GOVERNOR	IM6/CYCOM3100 GRAPHITE BMI: NO. OF REPLICATES	MEASURED VELOCITY m/sec	MEASURED ENERGY joules	ABSORBED ENERGY joules	ABSORBED ENERGY %	DAMAGED AREA (cm^2)	UNDAM. COMPR. STR'TH N/ply	PICS N/ply	PICS % OF UNDAM %
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
9	C	22.2/66.7/11.1	D1	4	2.43	12.40	4.62	37	6.27	1,842	1,997	108
26	D	11.5/77.0/11.5	D2	4	3.74	48.15	17.54	36	132.97	4,675	2,229	48
48	E	12.5/75.0/12.5	D2	4	4.22	124.07	33.58	27	169.62	7,175	1,922	27
74	F	12.2/75.6/12.2	E	5	4.42	136.28	51.93	38	151.02	7,215	1,957	27
96	G	12.5/75.0/12.5	E	4	4.42	136.12	58.64	43	138.26	6,597	2,318	35

STACKING SEQUENCES (COLUMN 2)

C: $(\pm45/0/45/90/45/0/\mp45)$
D: $(\pm45/0/\pm45_2/90/\pm45_2/0/90/\mp45_2/90/\mp45_2/0/\mp45)$
E: $(\pm45/0/\pm45_2/90)_{3s}$
F: $[(\pm45/0/\pm45_2/90)_4/\pm45_2/0/90/\mp45_2/(90/\mp45_2/0/\mp45)_4]$
G: $(\pm45/0/\pm45_2/90)_{6s}$

IMPACT GOVERNOR (COLUMN 4)

D1 - DENT = SPEC. THICKNESS
D2 - DENT = 0.1 in. (2.54 mm)
E - ENERGY = 100 ft-lb (136 joules)

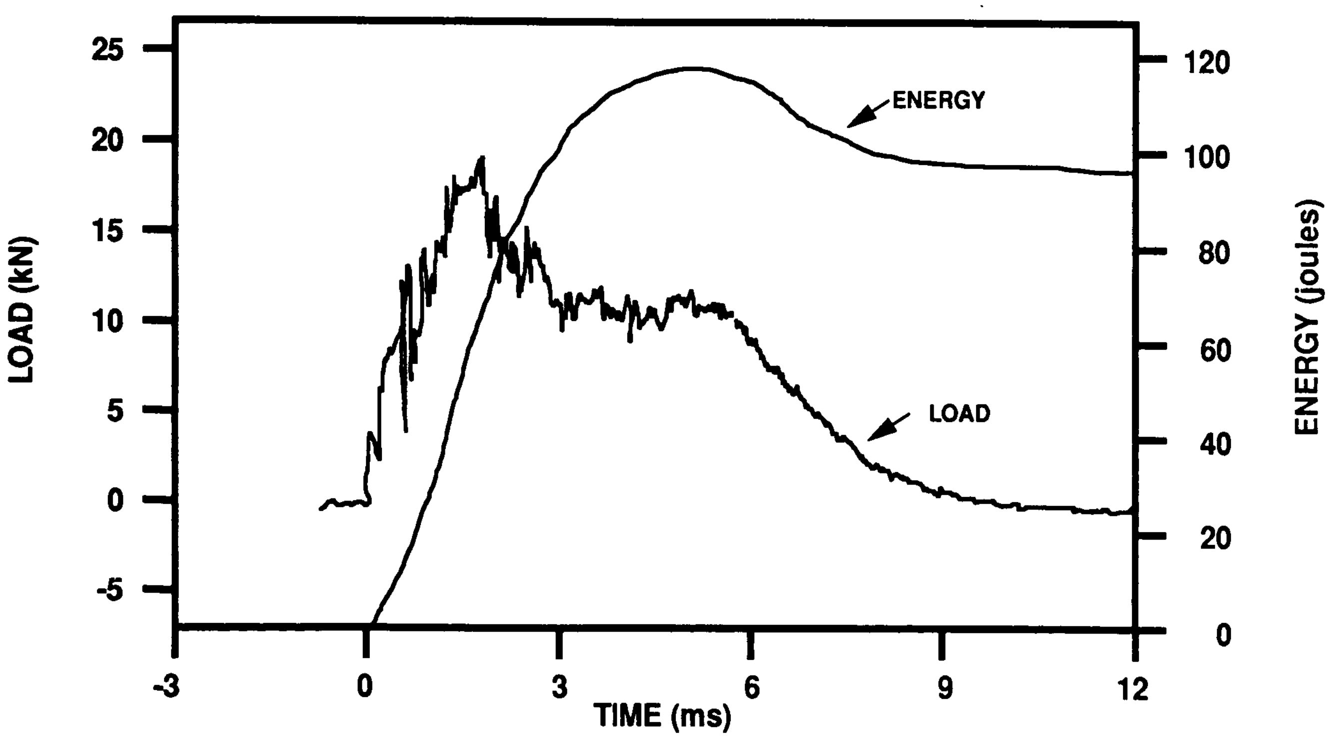
TEST TEMPERATURE: ROOM TEMPERATURE (RT)

SPECIMEN MOISTURE: AMBIENT (D)

TABLE II - ELASTIC CONSTANTS OF GR/EP AND GR/BMI

	E^T_1	E^C_1	E^T_2	E^C_2	G_{12}	μ^T_{12}	μ^C_{12}	σ^T_{1u}/ ε^T_{1u}	σ^C_{1u}/ ε^C_{1u}	σ^T_{2u}/ ε^T_{2u}	σ^C_{2u}/ ε^C_{2u}	τ_{12u}/ γ_{12u}
Gr/Epoxy	22.0	20.2	1.48	1.55	0.83	0.277	0.332	289.3/ 1.302%	188.1/ 1.05%	8.57/ 0.57%	34.19/ 2.21%	14.5/ 14.4%
Gr/BMI	22.2	20.7	1.54	1.50	0.85	0.313	0.379	280.0/ 1.18%	209.0/ 1.15%	7.36/ 0.55%	33.0/ 2.24%	10.6/ 2.40%

NOTE: **Youngs' modulii and stresses are in ksi (1.0 ksi = 6.895 MPa)**



TEMP (°C)	VELOC (m/s)	IMPACT ENERGY (joules)	TIME @ max ld (ms)	TIME final (ms)	MAX LOAD (kN)	ABSORBED ENERGY @ max ld (joules)	ABSORBED ENERGY final (joules)
21.1	4.215	124.02	1.85	10.90	19.494	75.328	104.176

Figure 1. Impact Load and Energy Histories

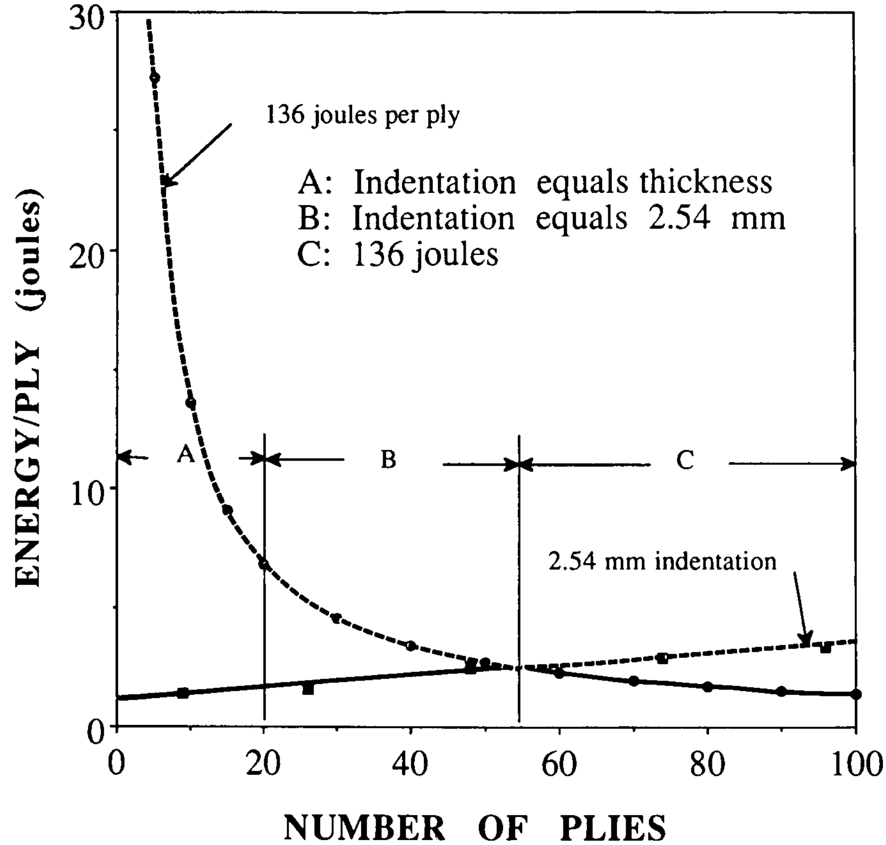


Figure 2. Initial Damage Assumption

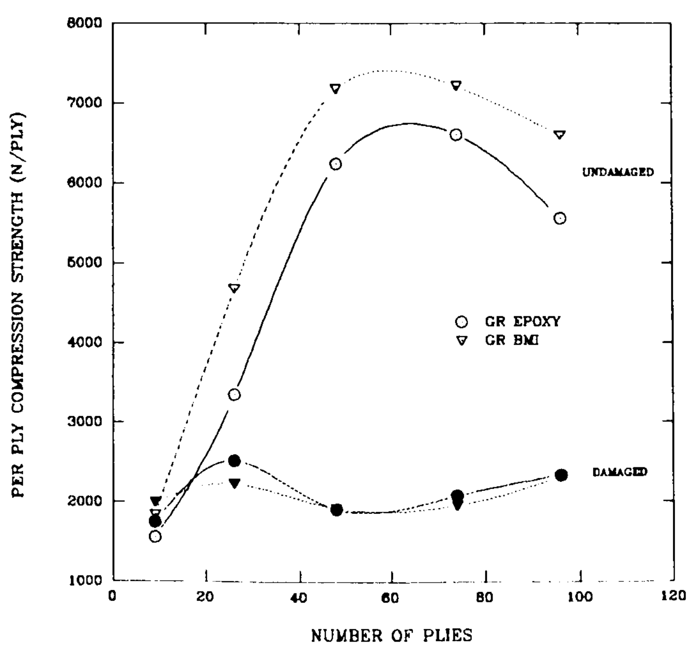


Figure 3. Laminate Compression Strengths - Undamaged and PICS