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Normalization of Impact Energy by Laminate Thickness for Compression After Impact Testing

A.T. Nettles and S.M. Hromisin
Marshall Space Flight Center, Huntsville, Alabama

April 2013

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Marshall Space Flight Center • Huntsville, Alabama 35812

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LIST OF ACRONYMS

ASTM	American Society for Testing and Materials
CAI	compression after impact
IE	impact energy
IRT	infrared thermography
NDE	nondestructive evaluation
OHC	open hole compression
TP	Technical Publication

NOMENCLATURE

a	thickness exponent for damage resistance
b	thickness exponent for damage tolerance
C	arbitrary constant
DW	damage width/size
h_c	core thickness
IE_0	given impact energy
i	free index in indicial notation
L_m	length of moment arm
m	thickness exponent
P	applied load
R	correlation coefficient
t	laminate thickness
t_f	thickness of the top fact sheet
w	specimen width
y	vertical axis value
σ_f	compressive stress

TECHNICAL PUBLICATION

NORMALIZATION OF IMPACT ENERGY BY LAMINATE THICKNESS FOR COMPRESSION AFTER IMPACT TESTING

1. INTRODUCTION

Compression after impact (CAI) strength can be a critical design parameter in many structures and thus the test method used to ascertain this value is important. CAI testing is so widely used that a standard was developed by the American Society of Testing and Materials (ASTM)[1] in 2005. In this standard the suggested impact energy is dependent on the specimen thickness by a specified ratio of impact energy (IE) to specimen thickness (t) which is given as 6.7 J/mm.[2] Thus, the suggested impact energy level used for a laminate is linearly dependent on the laminate's thickness (i.e., if the laminate thickness doubles, then the impact energy used also doubles). In damage tolerance studies, it has not been uncommon to divide the impact energy by the laminate thickness to 'normalize' data.[3–17] While simplistic, this normalization of the impact energy data will certainly result in more comparable damage tolerance data across different laminate thicknesses. For example, 16- and 32-ply quasi-isotropic laminates of the same fiber-resin system were impacted with 31.5 J of energy under the same boundary conditions.[15] The residual compression strength of the 16-ply laminate was 165 MPa and the residual compressive strength of the 32-ply laminate was 275 MPa, a difference of 67% more strength for the thicker laminate. This is not unexpected since the thicker laminate should have more damage resistance for a given impact energy. However, when the thinner laminate was impacted with one-half the impact energy (15.7 J), both specimens had been impacted with 6.7 J/mm of impact energy and the residual strength of the thin laminate increased to 236 MPa. This resulted in a difference of 14% more strength (rather than 67%) for the thicker specimen which is more comparable.

A simple linear correlation of impact energy with specimen thickness may cause damage tolerance data to be qualitatively more comparable, but a physical basis for doing so is not readily apparent. In a test for damage resistance (perforation) of plastic film (ASTM D 1709-09)[18] it is cautioned that, "The impact resistance of plastic film while partly dependent on thickness, has no simple correlation with sample thickness. Hence, impact values cannot be normalized over a range of thickness without producing misleading data as to the actual impact resistance of the material. Data from these test methods are comparable only for specimens that vary by no more than ±25% from the nominal or average thickness of the specimens tested."

It is known that damage resistance (and thus damage tolerance) may not be similar for laminates of equal thickness made of the same material because the stacking sequence (lay-up) of the laminate can alter the damage resistance of a laminate despite the laminate having the same in-plane stiffnesses and equal number of plies oriented at 0°, ±45°, and 90°. For a quasi-isotropic laminate (25% 0°-plies, 50% ±45°-plies, and 25% 90°-plies), it has been demonstrated that the stacking sequence can influence a laminate's damage resistance and damage tolerance. Avery and Grande[19] presented data for 24-ply quasi-isotropic laminates with two different stacking sequences and found that less grouping of plies resulted in larger planar areas of damage, especially at high impact levels. When based on planar area of damage, the residual compression strength was similar for both laminates. Guynn and O'Brien[4] came to similar conclusions based on 16-ply laminates. Hitchen and Kemp[20] tested laminates of the same thickness containing 50% 0°-plies and 50% ±45°-plies (no 90°-plies), with six different lay-ups for damage resistance and damage tolerance at an impact energy of 7 J. The planar damage size and shape was not always similar and the CAI strengths showed some variation, but this variation became less when the CAI strength was plotted versus damage size.

Thus, if a comparison of CAI strength between laminates of different thicknesses is to be made, similar material and stacking sequence is required. Once these parameters are satisfied, the question of how to normalize the CAI strength as a function of specimen thickness needs to be established since linear correlation may not give the most comparable results.

This correlation is important as it would be of great benefit to be able to quantitatively compare CAI data for a launch vehicle interstage structure (thick laminate) to a launch vehicle fairing structure (thin laminate), for example.

1.1 Experimental Observations of Laminate Thickness on Damage Tolerance

In a study by Caprino[21] the effects of specimen thickness on impact resistance of laminated composites showed that the energy absorbed by specimens of different thicknesses at an impact level that produced initial damage (delamination) is proportional to the laminate thickness to the 2.5 power. Physical reasons based on the Hertzian contact law and simple mechanics of materials are given that show this is not an unexpected result. In the same study it was shown that energy of penetration of a laminate was proportional to the thickness to the 1.5 power.

The results from reference 21 along with the general observation of the authors was the inspiration of the current study; for given boundary conditions, thicker specimens appear to have higher CAI strengths, even when the impact energy is normalized (divided) by the specimen thickness. It was reasoned that if incident delamination damage energy is proportional to the 2.5 power of the thickness and the energy of penetration is proportional to the 1.5 power of the thickness, then rather than normalizing impact energy by the specimen thickness into the –1 power to obtain similar CAI strength data for specimens with the same boundary conditions, normalization of impact energy should be to the specimen thickness to an exponent between –2.5 and –1.5 with lower impact damage levels, perhaps having CAI strength data scaling closer to the –2.5 power of thickness and severe impact damage levels having CAI strength data scaling closer to the –1.5 power of thickness.

In reference 21, only the damage resistance in the form of delamination size and/or energy absorbed by the laminate has been considered. By attempting to relate residual compression strength to impact energy, the specimens' thicknesses add yet more complexity to the problem.

Data from the open literature were examined for specimen thickness effects on CAI strength. Due to the many variables used throughout the different studies (different fiber/resin systems, lay-ups, impact boundary conditions, and not enough data), only one set of existing data was deemed suitable for analysis. CAI strength data from Aoki et al.[15] were reanalyzed by normalizing the impact energy by the thickness of the specimen to powers of –1, –1.5, –2, and –2.5. Data from reference 15 for quasi-isotropic laminates are presented in table 1. These specimens were of the stacking sequence $(45, 0, -45, 90)_{ns}$, where $n=2$, 3, 4, and 8. The diameter of the impactor was 15.9 mm and the specimens were clamped over a 6.35-cm circular opening during impact conforming to ASTM Standard D 7137-07.[1] The residual strength testing also conformed to ASTM Standard D 7137-07.[1]

Table 1. CAI data from reference 15.

Specimen	Impact Energy (J)	Specimen Thickness (mm)	IE/t (J/mm)	IE/$t^{1.5}$ (J/mm$^{1.5}$)	IE/t^2 (J/mm^2)	IE/$t^{2.5}$ (J/mm$^{2.5}$)	Failure Stress (MPa)
16-ply	7.5	2.3	3.3	2.2	1.4	0.9	245
16-ply	15.4	2.3	6.7	4.4	2.9	1.9	230
16-ply	19.5	2.3	8.5	5.6	3.7	2.4	230
16-ply	22.8	2.3	9.9	6.5	4.1	2.9	200
16-ply	31.5	2.3	13.7	9	6	3.9	165
24-ply	11	3.4	3.2	1.8	1	0.5	315
24-ply	15.4	3.4	4.5	2.5	1.3	0.7	305
24-ply	22.8	3.4	6.7	3.6	2	1.1	275
24-ply	31.5	3.4	9.3	5	2.7	1.5	235
24-ply	38	3.4	11.2	6.1	3.3	1.8	226
32-ply	15.4	4.7	3.3	1.5	0.7	0.3	340
32-ply	31.5	4.7	6.7	3.1	1.4	0.7	280
32-ply	34.5	4.7	7.3	3.4	1.6	0.7	305
32-ply	38	4.7	8.1	3.7	1.7	0.8	242
32-ply	45	4.7	9.6	4.4	2	0.9	240
64-ply	62.3	9.3	6.7	2.2	0.7	0.2	340

Figure 1 plots the CAI strength versus the unnormalized impact energy and, as expected, the thicker specimens have more strength for a given impact severity level. Each set of data for a given thickness has a best fit power curve applied to it so a comparison between laminates of different thicknesses at any given impact severity level can be made. In figure 1, low, medium, and high impact severity levels are noted. While rather arbitrary in nature, these levels may help give information about how impact severity affects the CAI strength results to be compared. The three levels were chosen such that little extrapolation of the best fit curves would be needed (i.e., the levels included most of the experimentally measured data). For a quantitative assessment, the differences in CAI strengths for the three thicknesses are compared at low, medium, and high impact severity levels. The 64-ply specimen has only one data point and thus will not be included here.

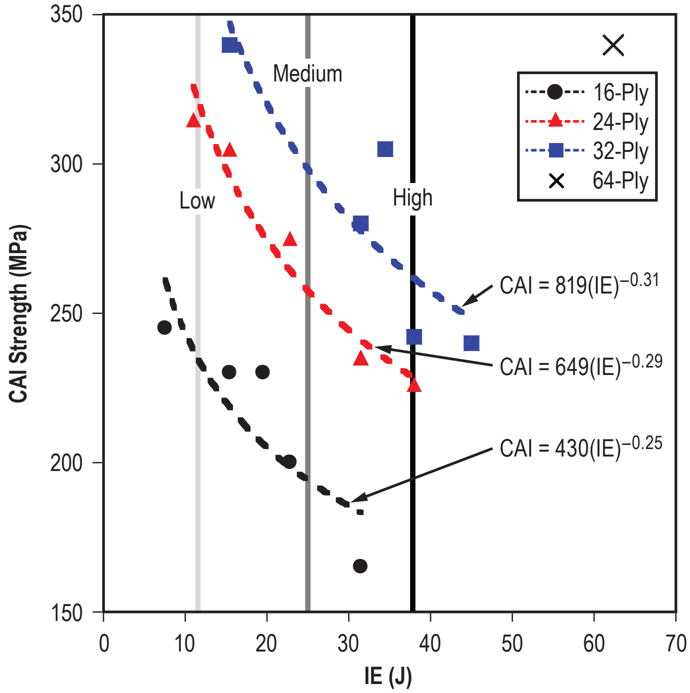

Figure 1. Plot of CAI strength versus unnormalized impact energy from table 1.

In figure 1 the low impact severity level will require extrapolation of the 32-ply data and the high impact severity level will require extrapolation of the 16-ply data. It should be noted that extrapolation of the curves in figure 1 need to be used with caution as the best fit equations are only valid for the strength degradation portion of the CAI strength versus damage severity curve. Using the three damage severity levels and the equations shown in figure 1 yields the results presented in table 2.

Table 2. Difference in CAI strength values at three damage severity levels in figure 1.

Impact Severity Level = IE (J)	16-Ply CAI Strength (MPa)	24-Ply CAI Strength (MPa)	% Increase Over 16-Ply	32-Ply CAI Strength (MPa)	% Increase Over 16-Ply	% Increase Over 24-Ply
11	236	323	37	389	65	20
25	192	255	33	302	57	18
38	173	226	31	265	53	17

As the impact severity level increases, the percent difference in CAI strength between the laminates of different thicknesses decreases slightly. Extrapolating this trend indicates that, at very severe impact damage levels, the CAI strengths of the different thickness specimens begin to converge. This makes physical sense as a very severe impact level will be akin to an open hole compression (OHC) test.

By normalizing the impact energy by the laminate thickness, the percent difference of the CAI strength values of the thicker laminates compared to the thinner laminates should be lessened. Figure 2 plots the CAI strength data versus impact energy normalized by specimen thickness to the –1 power from table 1 and each of the curves (one for each thickness) has a best fit power law applied (dashed lines).

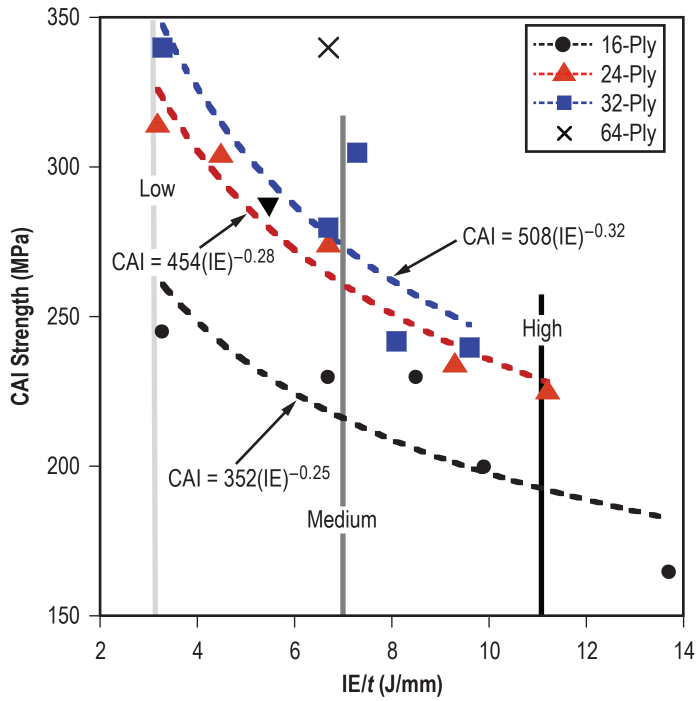

Figure 2. Plot of CAI strength versus normalized thickness ($m = -1$) from table 1.

For ease of notation, the power to which the thickness of the laminate is raised to will be denoted by m. For example, IE/t^2 implies that $m = -2$.

In figure 2 low, medium, and high impact severity levels are arbitrarily chosen as explained earlier and are noted (excluding the 64-ply laminate). Using these three impact severity levels with the equations in figure 2 yields the results presented in table 3.

Table 3. Difference in CAI strength values at three impact severity levels in figure 2.

Impact Severity Level = IE/*t* (J/mm)	16-Ply CAI Strength (MPa)	24-Ply CAI Strength (MPa)	% Increase Over 16-Ply	32-Ply CAI Strength (MPa)	% Increase Over 16-Ply	% Increase Over 24-Ply
3	267	334	25	357	34	7
7	216	263	22	273	26	4
11	193	232	20	236	22	2

Table 4 shows the percent difference in CAI strength for the unnormalized and normalized data from tables 2 and 3 for comparisons between the thicknesses tested at low, medium, and high impact damage severity levels.

Table 4. Percent difference in CAI strength values for unnormalized and normalized data.

Comparison of Percent Difference in CAI Strength for Different Thicknesses (Unnormalized→Normalized)			
Impact Severity Level	**24- and 16-Ply**	**32- and 16-Ply**	**32- and 24-Ply**
Low	37→25	65→34	20→7
Medium	33→22	57→26	18→4
High	31→20	53→22	17→2

With normalization the thicker laminates still have more CAI strength, but the magnitude of these differences is lessened, with the 32- and 24-ply laminate comparison being within 10% across all damage severity levels (less at the higher levels, as mentioned previously).

When the impact energy is normalized by t^m, $m = -1$, the thicker specimens still have a higher CAI strength for a given impact severity level. This indicates that if a similar CAI strength is to be obtained for a given impact severity level, the thicker specimens need to be impacted with more energy than what is calculated from a linear correlation (i.e., $m < -1$).

Figure 3 plots the CAI strength versus the impact energy to the m power for $m = -1.5$, –2, and –2.5 as presented in table 1. In order to more quantitatively assess the effects of normalizing the impact energy by the various t^m examined, each plot contains a power curve to *all* of the data *pooled* (solid line) with the corresponding correlation coefficient R. The closer R is to 1 the better the data fit the applied power curve and the more comparable the CAI strength data are for the different thicknesses across all impact severity levels. As with figures 1 and 2, low, medium, and high damage severity levels are arbitrarily chosen to include most of the experimentally measured data and are noted in each figure.

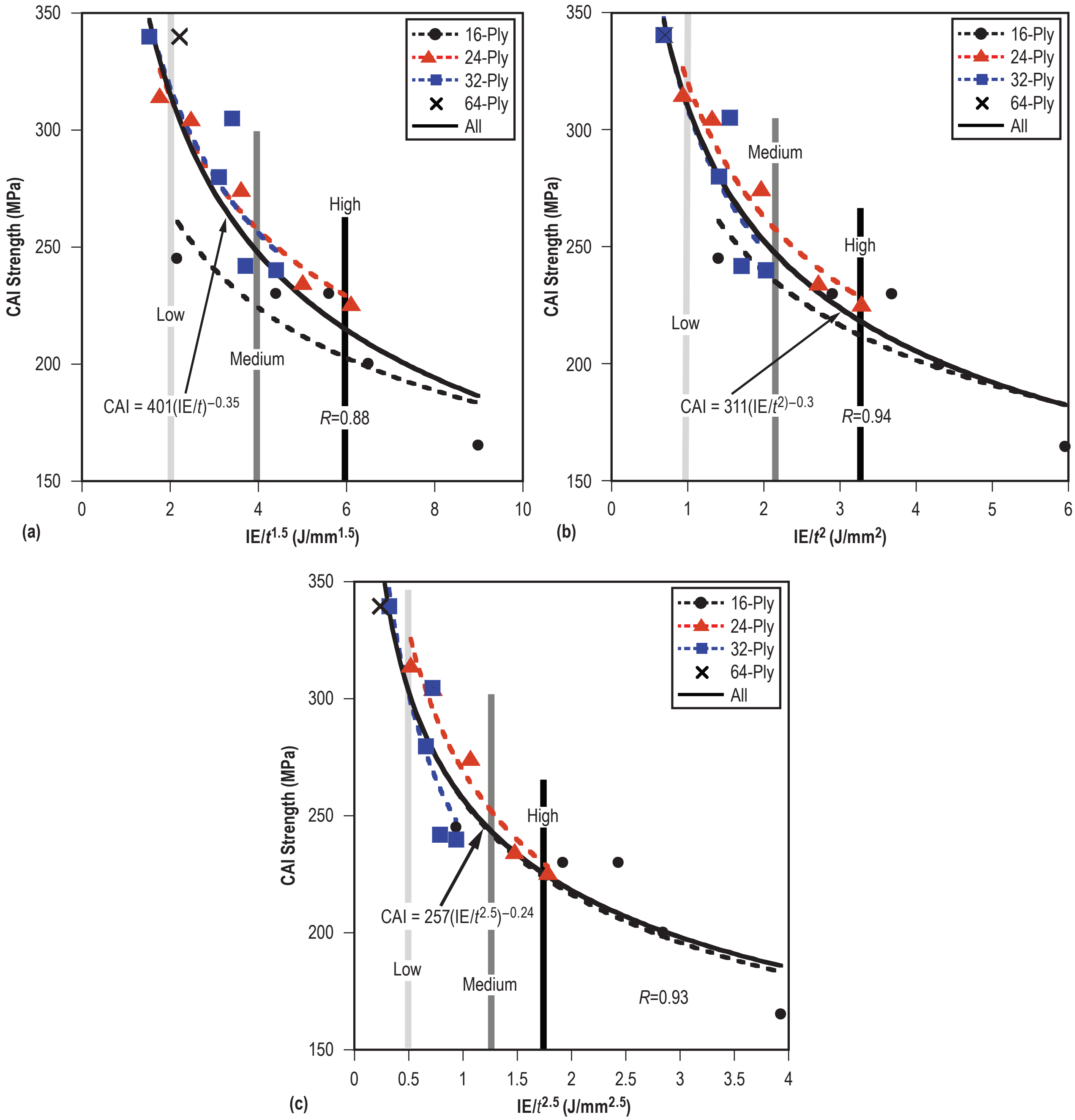

Figure 3. Plots of data presented in table 1 along with a best fit power curve (solid line) of data from all four thicknesses pooled: (a) $m = -1.5$, (b) $m = -2$, and (c) $m = -2.5$.

It appears that the data correlate well across all impact severity levels at $m = -2$. As m increases to –2.5, the data for the 32-ply specimens tend to be 'overcorrected' at high impact levels as the CAI strength results fall more below the other specimens.

A quantitative comparison of the various exponents that the specimen thickness is raised to can be conducted. A best fit power law for each of the three curves (representing the three thicknesses) at $m = -1.5$, –2, and –2.5 is applied (dashed lines in fig. 3), and then the low, medium, and high impact severity levels of each are used to find CAI strengths. The results are given in tables 5a–5c.

Table 5a. Difference in CAI strength values in figure 3 with $m = -1.5$.

Impact Severity Level $= IE/t^{1.5}$ (J/mm$^{1.5}$)	16-Ply CAI Strength (MPa)	24-Ply CAI Strength (MPa)	% Increase Over 16-Ply	32-Ply CAI Strength (MPa)	% Increase Over 16-Ply	% Increase Over 24-Ply
2	265	313	18	319	20	2
4	223	256	15	257	15	–
6	201	228	13	227	13	–

Table 5b. Difference in CAI strength values in figure 3 with $m = -2$.

Impact Severity Level $= IE/t^{2}$ (J/mm^{2})	16-Ply CAI Strength (MPa)	24-Ply CAI Strength (MPa)	% Increase Over 16-Ply	32-Ply CAI Strength (MPa)	% Increase Over 16-Ply	% Increase Over 24-Ply
1	285	321	13	310	9	–3
2.1	237	259	9	246	4	–5
3.25	212	228	8	215	1	–6

Table 5c. Difference in CAI strength values in figure 3 with $m = -2.5$.

Impact Severity Level $= IE/t^{2.5}$ (J/mm$^{2.5}$)	16-Ply CAI Strength (MPa)	24-Ply CAI Strength (MPa)	% Increase Over 16-Ply	32-Ply CAI Strength (MPa)	% Increase Over 16-Ply	% Increase Over 24-Ply
0.5	306	330	8	301	–2	–9
1.25	243	253	4	227	–7	–10
1.75	223	230	3	204	–9	–11

For each pair of laminate thicknesses (24–32, 16–24, and 16–32 plies), the percent difference in CAI strength with respect to the normalization of the impact energy to the five thickness exponents evaluated, m, are summarized in tables 6a–6c.

Table 6a. Percent difference in CAI strength values between 24- and 32-ply specimens for various IE/t^m values.

Comparison of Percent Difference in CAI Strength for 24- and 32-Ply Laminates (33% Increase in Thickness)					
Impact Severity Level	Unnormalized	m=–1	m=–1.5	m=–2	m=–2.5
Low	20	7	2	–3	–9
Medium	18	4	–	–5	–10
High	17	2	–	–6	–11

Table 6b. Percent difference in CAI strength values between 16- and 24-ply specimens for various IE/t^m values.

Comparison of Percent Difference in CAI Strength for 16- and 24-Ply Laminates (50% Increase in Thickness)					
Impact Severity Level	Unnormalized	m=–1	m=–1.5	m=–2	m=–2.5
Low	37	25	18	13	8
Medium	33	22	15	9	4
High	31	20	13	8	3

Table 6c. Percent difference in CAI strength values between 16- and 32-ply specimens for various IE/t^m values.

Comparison of Percent Difference in CAI Strength for 16- and 32-Ply Laminates (100% Increase in Thickness)					
Impact Severity Level	Unnormalized	m=–1	m=–1.5	m=–2	m=–2.5
Low	65	34	20	9	–2
Medium	57	26	15	4	–7
High	53	22	13	1	–9

A cursory examination of tables 6a–6c shows that the exponent, m, that gives the most comparable CAI strength data is dependent mainly upon the difference in thicknesses of the specimens to be compared. The impact severity level shows a smaller effect on the comparability of the CAI strength data, although it should be noted that for comparison of the two thickest laminates at the high impact severity level (table 6a, last row), the commonly used $m=-1$ appears to fit well.

According to tables 6a–6c for the CAI strength data given in table 1, the impact energy data should be normalized by the specimen thickness to the –1.5 power for comparing 24- and 32-ply CAI strength data, to the –2.5 power for comparing 16- and 24-ply CAI strength data, and to the –2 power for comparing 16- and 32-ply CAI strength data. It thus appears that normalizing the impact energy by the specimen thickness raised to a power to compare CAI strength results will not be a 'one size fits all' proposition for various increases in laminate thicknesses. Figure 4 is a plot of the average of all the percent differences for any given value of m as a function of m. Note the large standard deviation values since data across all impact severity levels and thicknesses are being considered (i.e., tables 6a–6c are combined).

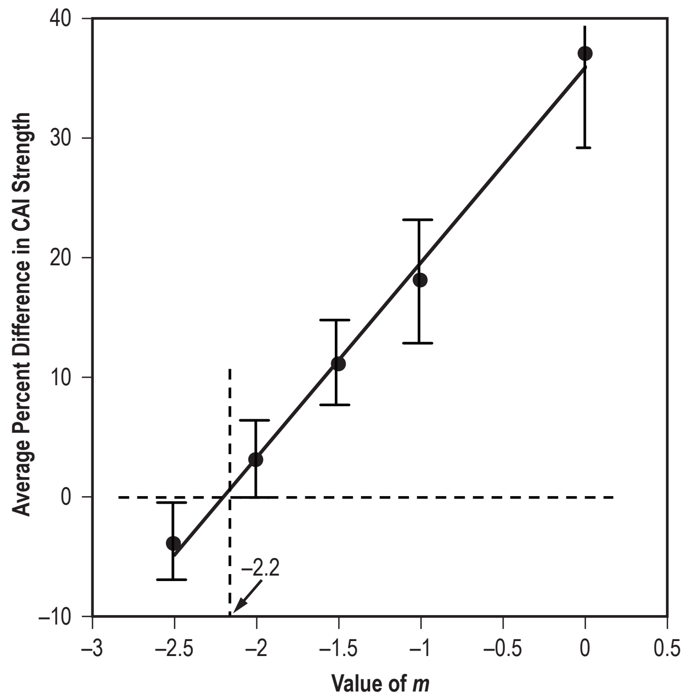

Figure 4. Plot of percent difference in CAI strengths across all three laminate thicknesses and all three impact severity levels as a function of *m*.

From a least squares linear fit of the data in figure 4, the percent difference in CAI strengths is zero at $m = -2.2$. This value is close to that found by a visual assessment of the three plots in figure 3 in which $m = -2$ appeared to give the most comparable CAI strength data across all impact severity levels.

This experimental data, while limited, demonstrates that in order to correlate CAI strength of laminates that are similar, differing only in thickness, that the impact energy used needs to be higher for thicker specimens by more than just a linear correlation.

A systematic study was performed to compliment the data shown thus far to support or refute the premise that normalizing impact energy by the specimen thickness to a power between –1.5 and –2.5 gives more uniform results for the CAI strength data of specimens of similar lay-ups but different thicknesses under the same impact boundary conditions.

It should be noted that detailed information about failure mechanisms due to the impact event and during compression to failure testing are not presented in this study and only the impact energies and associated compression after impact strengths are presented since these are the values of interest for the premise of this Technical Publication (TP).

2. EXPERIMENTATION

2.1 Laminates

CAI testing was performed on two groups of specimens. The first group had laminates of 8 and 16 plies composed of IM7/8551-7 carbon/epoxy. The second group had laminates of 8, 16, and 24 plies composed of IM7/MTM-45 carbon/epoxy. Table 7 gives the specific lay-up and nominal thicknesses of the laminates manufactured.

Table 7. Lay-up of laminates used in this study.

Material	Lay-Up	Number of Plies	Nominal Laminate Thickness (mm)
IM7/8551-7	$(45,0,-45,90)_S$	8	1.07
IM7/8551-7	$(45,0,-45,90)_{2S}$	16	2.14
IM7/MTM-45	$(45,0,-45,90)_S$	8	1.09
IM7/MTM-45	$(45,0,-45,90)_{2S}$	16	2.18
IM7/MTM-45	$(45,0,-45,90)_{3S}$	24	3.28

Laminates were manufactured by curing 3,721-cm square sections of prepreg in a heated platen press according to the manufacturer's recommended cure cycle. After cure, these panels had one side prepared for bonding to honeycomb core since the four-point-bend method was to be utilized to assess CAI strength.[22] This was achieved by sanding the surface to be bonded with 120 grit abrasive paper followed by an alcohol wipe. This was repeated until water would remain on the entire surface without beading after being removed from immersion. The bottom (tensile) face sheet was identical to the top face sheet. The core density used for these specimens was 192 kg/m^3 and the core thickness was 3.81 cm. The top and bottom face sheets were bonded to the honeycomb with FM-300 film adhesive. Once these bonds had cured, the panels were cut into 5.1-cm-wide test specimens (fig. 5).

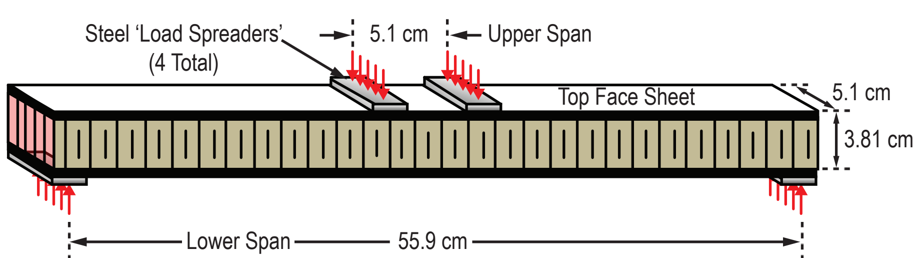

Figure 5. Schematic of the type of test specimen used in this study to assess CAI strength. The face sheets were cured before bonding to honeycomb in a second process to manufacture the test specimens.

2.2 Impact Testing

Each sandwich specimen was impacted at its geometric center on the top (compression) face sheet. The impactor had a diameter of 6.4 mm and the specimen was placed on a solid steel plate during impact to give the highest rigidity, and thus most damage possible for a given impact energy.[23,24] This also ensured similar boundary conditions for all impacts.

An instrumented drop-weight impact apparatus was used to inflict damage to the specimens. The impact energy was measured by measuring the velocity of the impactor at the point of contact with the specimen since some of the initial potential energy of the drop weight was lost due to friction with the guide posts.

As mentioned previously, the sandwich four-point-bend method[22] was utilized to generate compressive forces in the damaged laminate. This methodology was chosen over end loading since an abundance of prepreg, film adhesive, and honeycomb core was available while strain gauges were not and the end loading method requires four strain gauges per specimen.[1] The compressive stress in the face sheet between the upper span was calculated from:

$$\sigma_f = \frac{P}{w}\left(L_m\right)\left[\frac{\frac{h_c}{2} + t_f}{\left[t_f\left(h_c + t_f\right)^2\right]}\right] , \tag{1}$$

where σ_f is the compressive stress, w is the specimen width, P is the applied load, L_m is the length of moment arm (25.4 cm), t_f is the thickness of the top face sheet, and h_c is the core thickness (3.81 cm).

The cross head rate used was 2.5 mm/min which caused the typical test to last approximately 1–2 min. All failures were similar in that fiber fracture occurred across the width of the specimen through the point of impact.

2.3 Results

2.3.1 IM7/8551-7 Material

The results from the residual compression strength testing for the IM7/8551-7 material are given in table 8 and are plotted in figure 6.

Table 8. Results from CAI testing of IM7/8551-7 laminates.

Number of Plies	Thickness (mm)	Impact Energy (J)	Number of Specimens	CAI Strength (MPa)
8	1.14	0.9	5	377 ± 22
8	1.14	1.5	6	344 ± 16
8	1.14	2.6	5	311 ± 8
8	1.14	3.8	5	294 ± 20
16	2.29	3.8	3	438 ± 24
16	2.29	6.2	7	372 ± 16
16	2.29	8	3	348 ± 15

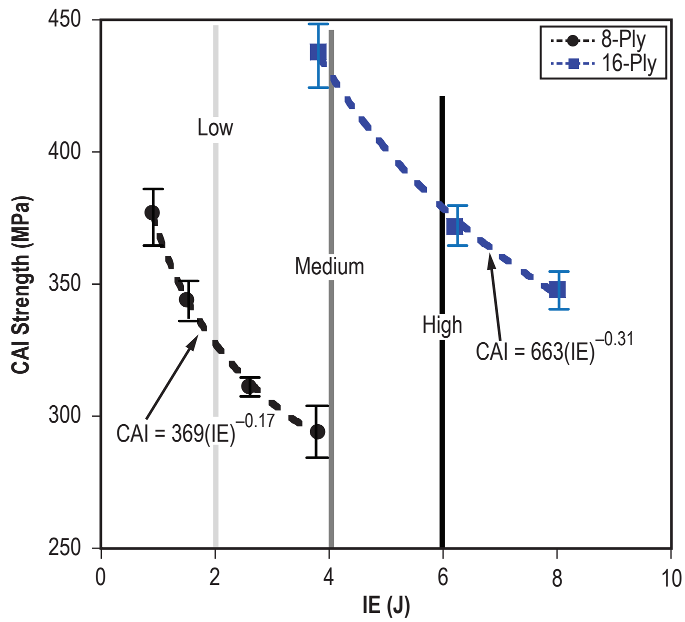

Figure 6. Unnormalized data from table 8.

Using the three damage severity levels shown in figure 6 with the equations in figure 6 yields the results presented in table 9. The undamaged compression strength of this laminate was measured as 684 MPa, thus the extrapolated 16-ply data should not be above this value. The OHC strength of this laminate was measured at 270 MPa, thus the extrapolated 8-ply data should not be below this value.

Table 9. Difference in CAI strength values at three damage severity levels from figure 6.

Impact Severity Level = IE (J)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply
2	328	535	63
4	292	431	48
6	272	380	40

Without normalization, the 16-ply laminate has between 40% and 63% more strength than the 8-ply laminate, depending on the impact severity level. As the impact severity level increases, the percent difference in CAI strength values between the two different thicknesses used is lessened.

If the impact energy is normalized by the specimen thickness raised to a power between –1 and –2.5, the data will result as shown in figure 7. In figure 7, all of the data are pooled and a best fit power curve is applied for impact energy normalized by the specimen thickness to powers of –1, –1.5, –2, and –2.5.

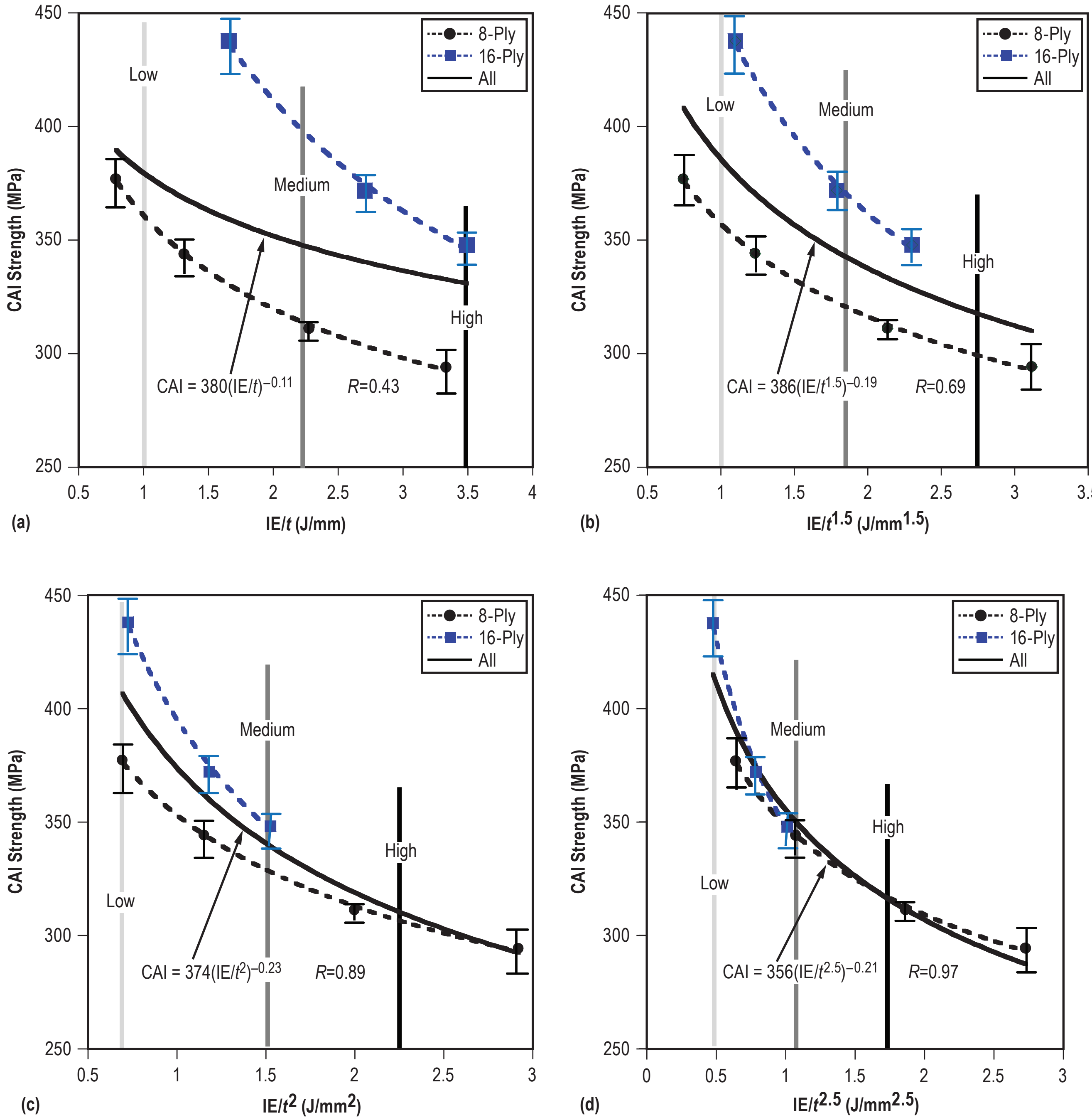

Figure 7. IM7/8551-7 CAI data from table 8 normalized by specimen thickness to powers of (a) –1, (b) –1.5, (c) –2, and (d) –2.5.

The thickness exponent m appears to fit the data for both thicknesses across all impact severity levels best at a value of $m = -2.5$. A best fit power law for each of the two curves at each of the four values of m is applied; then, arbitrarily selected low, medium, and high impact severity levels (as noted in figs. 8 and 9) are used to find CAI strengths. The results are given in tables 10a–10d.

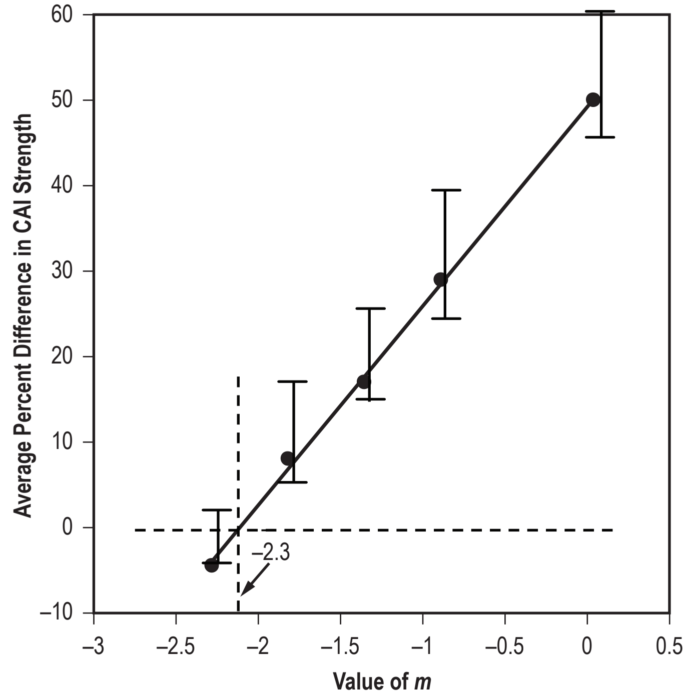

Figure 8. Plot of percent difference in CAI strengths across both laminate thicknesses and all three damage severity levels for IM7/8551-7 laminates.

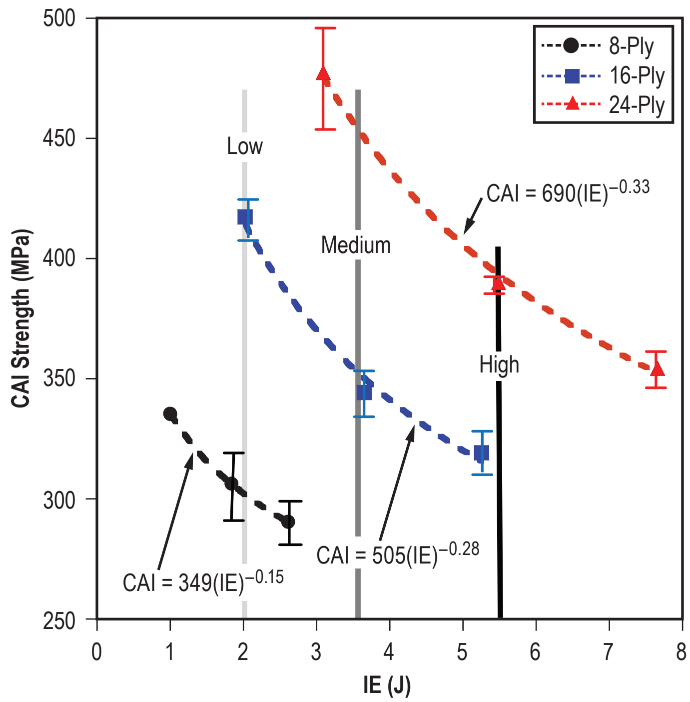

Figure 9. Unnormalized data from table 12.

Table 10a. Difference in CAI strength values in figure 7 with $m = -1$.

Impact Severity Level = IE/*t* (J/mm)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply
1	361	512	42
2.25	315	398	26
3.5	292	347	19

Table 10b. Difference in CAI strength values in figure 7 with $m = -1.5$.

Impact Severity Level = $IE/t^{1.5}$ ($J/mm^{1.5}$)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply
1	357	449	26
1.8	323	374	16
2.75	301	328	9

Table 10c. Difference in CAI strength values in figure 7 with $m = -2$.

Impact Severity Level = IE/t^{2} (J/mm^{2})	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply
0.7	375	441	18
1.5	329	348	6
2.25	308	307	–

Table 10d. Difference in CAI strength values in figure 7 with $m = -2.5$.

Impact Severity Level = $IE/t^{2.5}$ ($J/mm^{2.5}$)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply
0.5	393	431	10
1.1	343	338	–1
1.75	317	293	–8

For the two laminate thicknesses, the percent difference in CAI strength with respect to the thickness exponent, *m*, are summarized in table 11.

Table 11. Percent difference in CAI strength values between 8- and 16-ply specimens for various IE/t^m values.

Comparison of Percent Difference in CAI Strength for 8- and 16-Ply Laminates (100% Increase in Thickness)					
Impact Severity Level	Unnormalized	m=–1	m=–1.5	m=–2	m=–2.5
Low	63	42	26	18	10
Medium	48	26	16	6	–1
High	40	19	9	–	–8

A cursory examination of table 11 shows that the exponent that gives the most comparable CAI strength data across all impact severity levels is m=–2.5 and that the impact severity level shows a larger effect on the comparability of the CAI strength data than for the data examined in tables 6a–6c. This may be due to the thinner specimens for these data, having one-half the thickness of the thinnest specimens from the previous data set.

Figure 8 is a plot of the average of all the percent differences in CAI strength across all three impact severity levels for any given value of m as a function of m. From a least squares linear fit of the data in figure 8, the percent difference in CAI strengths is zero at m=–2.3. This value is close to that found by a visual assessment of the plots in figure 7 where m=–2.5 appeared to give the most comparable CAI strength data across all impact severity levels.

2.3.2 IM7/MTM-45 Material

The results from the residual compression strength testing for the IM7/MTM-45 material are given in table 12 and the results plotted in figure 9.

Table 12. Results from CAI testing of IM7/MTM-45 laminates.

Number of Plies	Thickness (mm)	Impact Energy (J)	Number of Specimens	CAI Strength (MPa)
8	1.11	1.5	1	350
8	1.11	2.7	3	306 ± 29
8	1.11	3.8	4	290 ± 19
16	2.18	2.9	4	425 ± 17
16	2.18	5.3	3	344 ± 19
16	2.18	7.7	3	319 ± 18
24	3.28	4.5	4	477 ± 43
24	3.28	8	3	390 ± 7.3
24	3.28	11.2	3	354 ± 16

In figure 9 each severity level chosen will require extrapolation of some of the data. The undamaged compression strength of this laminate was measured as 690 MPa and the OHC strength measured as 270 MPa. These are the approximate upper and lower compression strength limits to curve extrapolation. Using the three damage severity levels shown in figure 9 with the equations in figure 9 yields the results presented in table 13.

Table 13. Difference in CAI strength values of unnormalized data.

Impact Severity Level = IE (J)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply	24-Ply CAI Strength (MPa)	% Increase Over 8-Ply	% Increase Over 16-Ply
2	315	414	31	549	74	33
3.5	289	354	22	456	58	29
5.5	270	312	16	393	46	26

As the impact severity level increases, the percent difference in CAI strength between the laminates of different thicknesses decreases.

By normalizing the impact energy by the specimen thickness to a power between –1 and –2.5, the data fall as shown in figure 10. In figure 10, all of the data are pooled and a best fit power curve is applied for impact energy normalized by the specimen thickness to powers of –1, –1.5, –2, and –2.5.

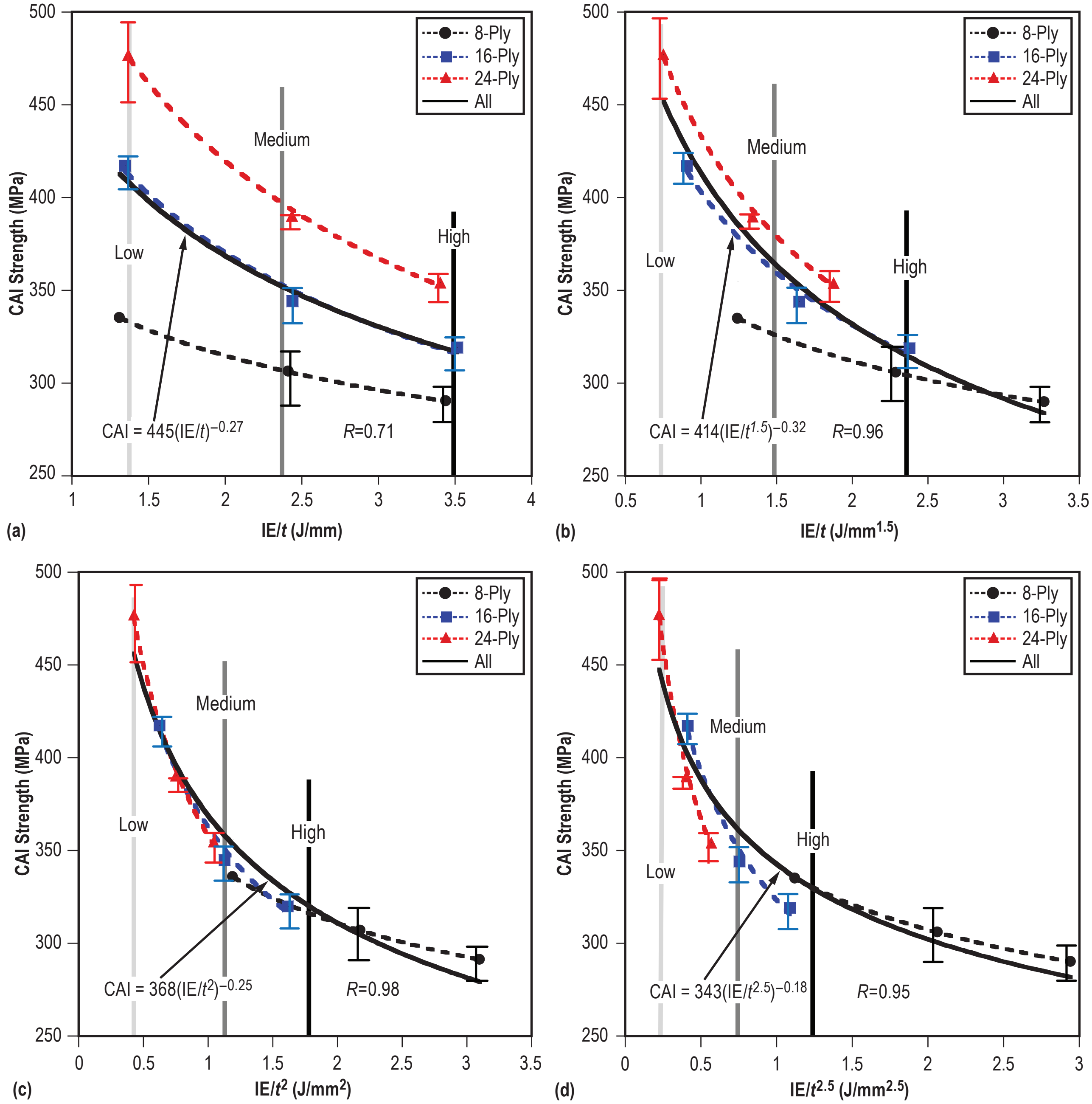

Figure 10. IM7/MTM-45 CAI strength data from table 12 normalized by specimen thickness to powers of (a) –1, (b) –1.5, (c) –2, and (d) –2.5.

The thickness exponent m appears to fit the data for all three thicknesses across all impact severity levels best at a value of $m = –2$. Using $m = –2.5$ results in overcorrection of the CAI strength data for high impact severity levels.

A best fit power law for each of the three curves at each of the four values of m is applied; then low, medium, and high impact severity levels are used to find CAI strengths. The results are given in tables 14a–14d.

Table 14a. Difference in CAI strength values in figure 10 with $m = -1$.

Impact Severity Level = IE/t (J/mm)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply	24-Ply CAI Strength (MPa)	% Increase Over 8-Ply	% Increase Over 16-Ply
1.4	332	410	23	473	42	15
2.4	306	353	15	396	29	12
3.5	289	318	10	349	21	10

Table 14b. Difference in CAI strength values in figure 10 with $m = -1.5$.

Impact Severity Level = IE/$t^{1.5}$ (J/mm$^{1.5}$)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply	24-Ply CAI Strength (MPa)	% Increase Over 8-Ply	% Increase Over 16-Ply
0.75	361	438	21	477	32	9
1.5	326	361	11	380	17	5
2.4	303	316	4	325	7	3

Table 14c. Difference in CAI strength values in figure 10 with $m = -2$.

Impact Severity Level = IE/t^2 (J/mm^2)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply	24-Ply CAI Strength (MPa)	% Increase Over 8-Ply	% Increase Over 16-Ply
0.4	395	467	18	483	22	3
1.1	339	351	4	346	2	–1
1.75	316	309	–2	297	–6	–4

Table 14d. Difference in CAI strength values in figure 10 with $m = -2.5$.

Impact Severity Level = IE/$t^{2.5}$ (J/mm$^{2.5}$)	8-Ply CAI Strength (MPa)	16-Ply CAI Strength (MPa)	% Increase Over 8-Ply	24-Ply CAI Strength (MPa)	% Increase Over 8-Ply	% Increase Over 16-Ply
0.25	420	478	14	463	10	–3
0.75	356	351	–1	322	–10	–8
1.25	330	304	–8	272	–18	–11

For each pair of laminate thicknesses, the percent difference with respect to the thickness exponent, *m*, are summarized in tables 15a–15c.

Table 15a. Percent difference in CAI strength values between 8- and 16-ply specimens for various IE/t^m values.

Comparison of Percent Difference in CAI Strength for 8- and 16-Ply Laminates (100% Increase in Thickness)					
Impact Severity Level	Unnormalized	*m* = –1	*m* = –1.5	*m* = –2	*m* = –2.5
Low	31	23	21	18	14
Medium	22	15	11	4	–1
High	16	10	4	–2	–8

Table 15b. Percent difference in CAI strength values between 8- and 24-ply specimens for various IE/tm values.

Comparison of Percent Difference in CAI Strength for 8- and 24-Ply Laminates (200% Increase in Thickness)					
Impact Severity Level	Unnormalized	*m* = –1	*m* = –1.5	*m* = –2	*m* = –2.5
Low	74	42	32	22	10
Medium	58	29	17	2	–10
High	46	21	7	–6	–18

Table 15c. Percent difference in CAI strength values between 16- and 24-ply specimens for various IE/tm values.

Comparison of Percent Difference in CAI Strength for 16- and 24-Ply Laminates (50% Increase in Thickness)					
Impact Severity Level	Unnormalized	*m* = –1	*m* = –1.5	*m* = –2	*m* = –2.5
Low	33	15	9	3	–3
Medium	29	12	5	–1	–8
High	26	10	3	–4	–11

A cursory examination of tables 15a–15c shows that the exponent that gives the most comparable CAI strength data is dependent mainly upon the difference in thicknesses of the specimens to be compared. The impact severity level shows a smaller effect on the comparability of the CAI strength data.

For the data given, the impact energy data should be normalized by the specimen thickness to the –2.5 power for comparing 8- and 16-ply CAI data, to the –2 power for comparing 16- and 24-ply data, and to the –2 power for comparing 16- and 24-ply data. Figure 11 is a plot of the average of all the percent differences across all thicknesses and impact severity levels for any given value of *m* as a function of *m*. From the least squares linear fit of the data in figure 11, the percent difference in CAI strengths is zero at $m = -2.2$, which is close to the value of $m = -2$ as determined by the visual examination of figure 10.

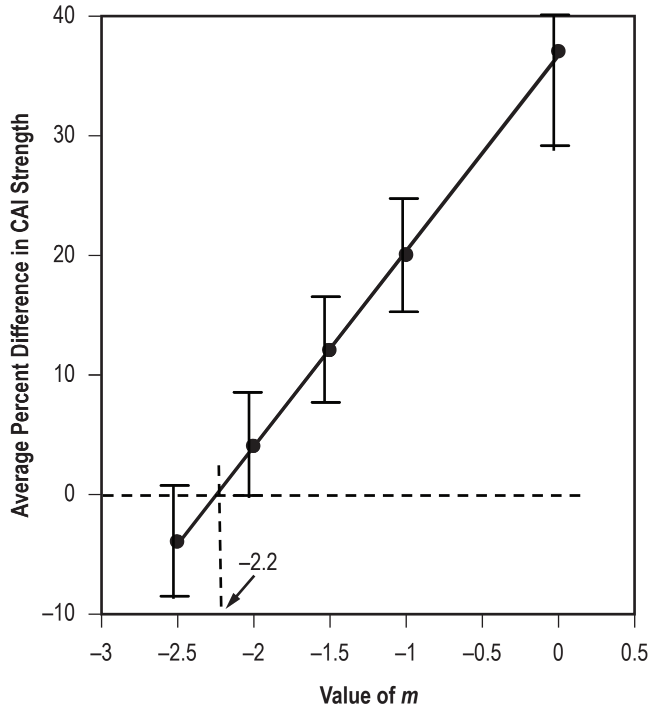

Figure 11. Plot of percent difference in CAI strengths combined across all three laminate thicknesses.

Thus, from three sets of data (one from the literature and two produced in this study), normalizing the impact energy by the specimen thickness raised to a power will result in more comparable CAI strength results for different laminate thicknesses tested. It is apparent that, depending on the severity of impact and the difference in thickness, the exponent of thickness that gives the best fit of the CAI strength data will differ. However, for the range of impact energies examined thus far, a cursory examination of the data shows that despite this difference, CAI strength can be better compared by normalizing the impact energy to a specimen thickness raised to a power between –2.2 and –2.3.

3. DISCUSSION

The CAI strength of a damaged laminate will depend upon the laminate's damage resistance and its damage tolerance. One example of the effect of specimen thickness on damage resistance will be that the planar damage size as measured by a nondestructive evaluation (NDE) technique may be different for different thicknesses at a given impact energy and with the same boundary conditions. Assuming a nonlinear relationship and a smaller damage size for thicker specimens,

$$DW \propto \mathrm{IE}_0/t^a \ , \tag{2}$$

where DW is damage size, IE_0 is a given impact energy, t is the laminate thickness, and a is the thickness exponent for damage resistance. (If the damage size increases with increasing specimen thickness, then the exponent, a, will be negative).

As the thickness of a specimen goes up, the CAI strength (damage tolerance) is assumed to go up for a given damage size. Assuming a nonlinear relationship and more strength for a thicker specimen,

$$\mathrm{CAI} \propto DW(t^b) \ , \tag{3}$$

where CAI is compression after impact strength, DW is a given planar damage size, t is the laminate thickness, and b is the thickness exponent for damage tolerance.

Combining equations (2) and (3),

$$\mathrm{CAI} \propto \mathrm{IE}_0(t)^{-a}(t^b) \propto \mathrm{IE}_0 t^{(b-a)} \ . \tag{4}$$

Examination of the data may help determine the exponents a and b for the laminates used in this study and thus the relative contribution of damage resistance and/or damage tolerance to cause thicker laminates to have a higher CAI strength for a given impact energy.

3.1 Damage Resistance

As mentioned previously, the CAI strength of a laminate consists of both the damage resistance and damage tolerance of the material. An examination of the damage resistance aspects of the IM7/MTM-45 laminates of three thicknesses will be presented in an effort to better understand the dependence of the CAI strength on the specimen thickness.

3.1.1 Size of Impact Damage

The width of the damage formed in the composite laminates due to impact was assessed with infrared thermography (IRT) techniques. The damage width as detected by IRT was used as a measure of damage size (*DW*) since this has been shown to be a good predictor of CAI strength.[24] A sample IRT image is shown in figure 12.

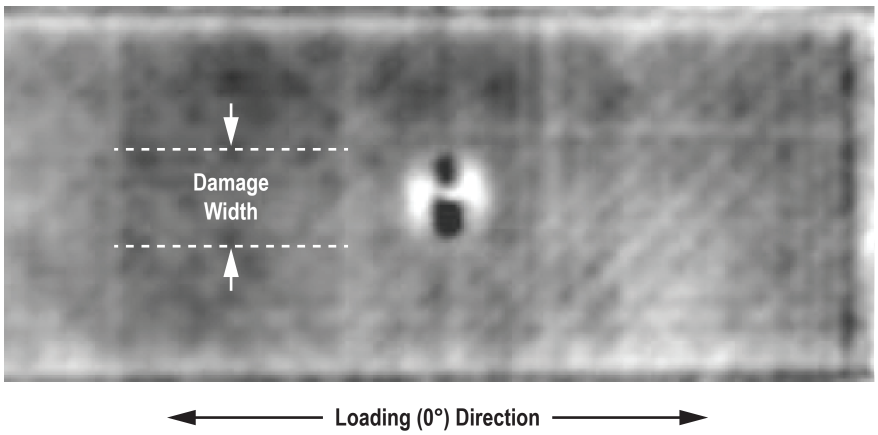

Figure 12. Sample infrared thermography image of 8-ply IM7/MTM-45 specimen impacted at 2.7 J.

The damage widths of impact observed for the IM7/MTM-45 specimens used in this study are presented in table 16 in the appendix. Each specimen thickness had four impacts at a given energy level and the width results were averaged. The impact energy versus damage width data from table 16 are plotted in figure 13 and a logarithmic curve fit of the form $y = C_0 + C_1 \log(x)$ applied. When plotting impact damage size versus impact energy, there typically is a critical impact energy at which damage begins, and as the impact energy increases, the damage size begins to level out as more severe damage is formed.[25] A plot of damage size versus impact energy can be represented well by a logarithmic curve fit.[26]

Table 16. Infared thermography results of impacted IM7/MTM-45 specimens.

Number of Plies	Thickness (mm)	Impact Energy (J)	Average Damage Width (mm)
8	1.11	1.5	11.8 ± 2.1
8	1.11	2.7	14.9 ± 1.8
8	1.11	3.8	16 ± 2.1
16	2.18	2.9	9 ± 0.7
16	2.18	5.3	13.3 ± 0.4
16	2.18	7.7	14.7 ± 1.1
24	3.28	4.5	8.9 ± 1.7
24	3.28	8	11.8 ± 0.6
24	3.28	11.2	13.5 ± 1

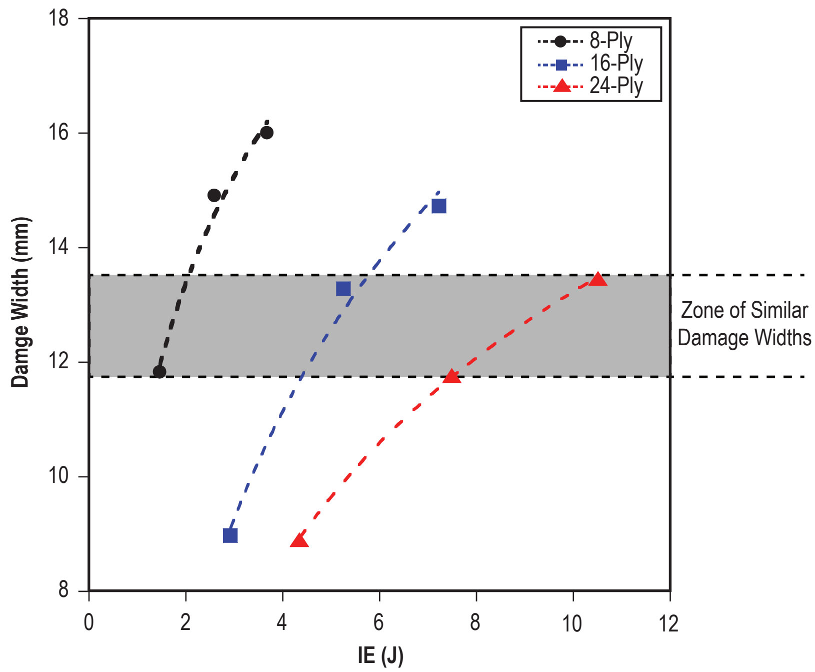

Figure 13. Plot of damage width versus impact energy for IM7/MTM-45 laminates.

The equations defining the curves in figure 13 are given by:

$$\text{8-ply:} \quad DW_1 = 10.2 + 10.6 \log(\text{IE}_1) \ , \tag{5}$$

$$\text{16-ply:} \quad DW_2 = 2.1 + 14.9 \log(\text{IE}_2) \ , \tag{6}$$

and

$$\text{24-ply:} \quad DW_3 = 1.3 + 11.9 \log(\text{IE}_3) \ , \tag{7}$$

where DW_i indicates damage width and IE_i is the impact energy. The subscripts 1, 2, and 3 correspond to the 8-, 16-, and 24-ply laminates, respectively.

3.1.2 Impact Energy to Produce a Given Damage Width

Now that a relation of damage width versus impact energy has been estimated from the best fit logarithmic curves in figure 13 and equations (5)–(7), the three energies needed to produce a given damage width for each of the three thicknesses of laminates can be deduced. To use a damage width outside the zone of damage widths common to all three thicknesses means reliance that extrapolation of the data beyond what was experimentally measured is required.

Table 17 shows a range of damage widths and the impact energy needed to produce the given damage width using equations (5)–(7).

Table 17. Impact levels needed to produce a range of damage widths for the three laminate thicknesses.

DW (mm)	IE_1 (J)	IE_2 (J)	IE_3 (J)
11	1.2	3.9	6.5
12	1.5	4.6	7.9
13	1.9	5.3	9.5
14	2.3	6.2	11.6

The data in table 17 are plotted in figure 14 as IE versus number of plies/8 plies. This gives the thinnest laminate a thickness value of unity and a specimen twice as thick a thickness value of 2 and a specimen three times as thick a thickness value of 3. A best fit power curve is applied to each of the damage widths plotted.

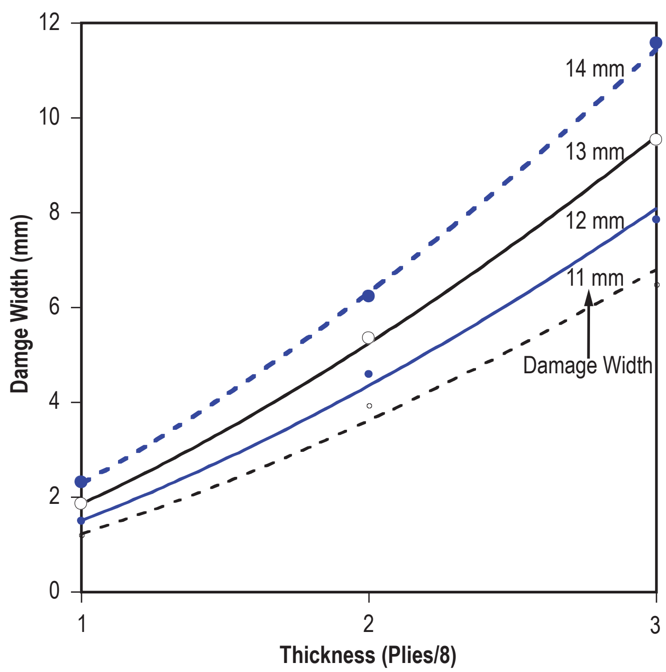

Figure 14. Impact energy needed to cause a given damage width as a function of specimen thickness for four different damage sizes.

The best fit power curves for the four damage widths are given by,

$$11\text{ mm:}\quad \mathrm{IE}=1.2(t)^{1.56}\ , \tag{8}$$

$$12\text{ mm:}\quad \mathrm{IE}=1.5(t)^{1.53}\ , \tag{9}$$

$$13\text{ mm:}\quad \mathrm{IE}=1.9(t)^{1.49}\ , \tag{10}$$

and

$$14\text{ mm:}\quad IE=2.3(t)^{1.46}\ . \tag{11}$$

The coefficients in each of the above equations are the impact energy needed to cause the associated damage width for the thinnest specimens (i.e., 1.2 J to cause a damage width of 11 mm in an 8-ply specimen, 1.5 J to cause a damage size of 12 mm in an 8-ply specimen, etc.). Notating these coefficients as IE_{DW} (impact energy to cause a certain damage width), equations (8)–(11) can be written in the form $\mathrm{IE}=\mathrm{IE}_{DW}\,t^{a}$; or rearranging,

$$\mathrm{IE}_{DW}=\mathrm{IE}/t^{a}\ . \tag{12}$$

The average of the exponents (denoted by a) for the four curve fits in figure 14 is $a=1.51$, which is close to the value of 1.5 as found in reference 21 for energy of penetration of an impacted laminate versus thickness. Thus, to obtain a given damage width, the impact energy must be divided by the specimen thickness to the 1.51 power and the exponent, a, in equation (2) is thus 1.51.

The next part of relating residual strength to specimen thickness is to determine the residual strength as a function of damage size for different specimen thicknesses.

3.2 Damage Tolerance

In order to gain insight into the relation of damage tolerance of the laminates examined in this study, the data from tables 12 and 16 can be used to plot CAI strength as a function of damage width for the IM7/MTM-45 specimens used in this study. The results for the three thicknesses are shown in figure 15.

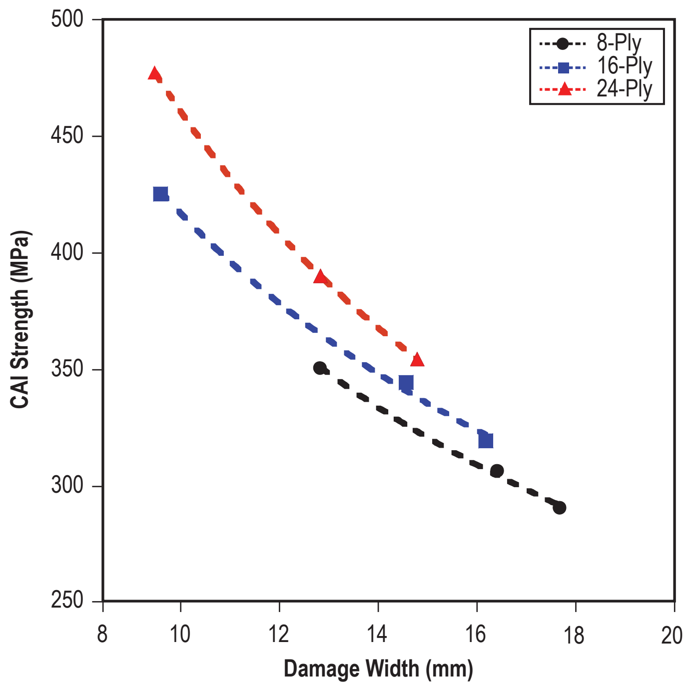

Figure 15. Plot of CAI strength versus damage width for IM7/MTM-45 laminates.

The equations defining the curves in figure 15 are given by:

$$\text{8-ply: } \mathrm{CAI}_1 = 1{,}569(DW_1)^{-0.607} \ , \tag{13}$$

$$\text{16-ply: } \mathrm{CAI}_2 = 1{,}499(DW_2)^{-0.573} \ , \tag{14}$$

and

$$\text{24-ply: } \mathrm{CAI}_3 = 2{,}280(DW_3)^{-0.716} \ , \tag{15}$$

where CAI_i indicates residual compression strength and DW_i is the damage width. The subscripts 1, 2, and 3 correspond to the 8-, 16-, and 24-ply laminates, respectively.

The average of the exponents in equations (13)–(15) is –0.63, thus $\mathrm{CAI} \propto DW(t)^{-0.63}$ and $b = -0.63$ in equation (3).

Thus, equation (4) gives $\mathrm{CAI} \propto \mathrm{IE}_0 t^{\,(-0.63-1.5)} \propto \mathrm{IE}_0/t^{2.13}$.

The data for the MTM-45 laminates are plotted in figure 16 for $m = -2.13$.

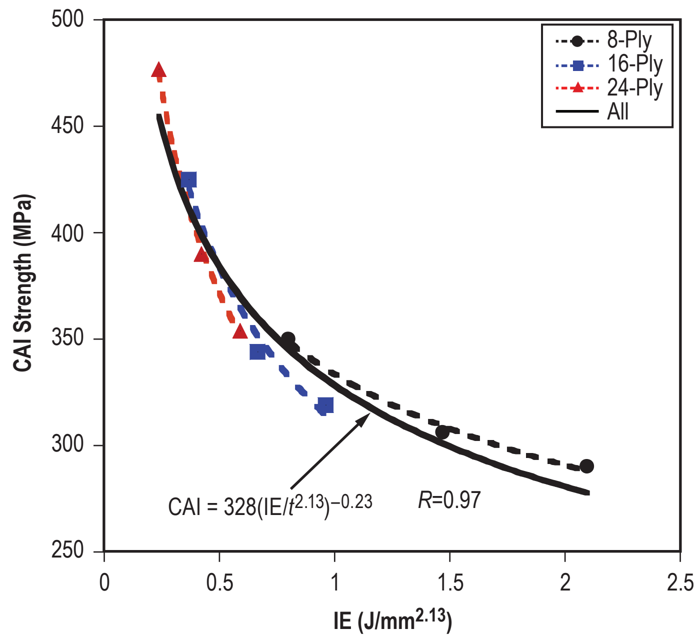

Figure 16. CAI strength data for IM7/MTM-45 specimens normalized by specimen thickness to the –2.13 power.

The data in figure 16 actually fit no better than the data for $m = -2$ (fig. 10). However, the relative contribution of the thickness on the CAI strength of a laminate is seen to be mostly comprised of the effects of damage resistance and less so on damage tolerance.

4. CONCLUSIONS

The conclusions are as follows:

- A definitive exponent that the specimen thickness must be raised to in order to normalize impact energy to give comparable CAI strength results across all impact damage severities probably cannot be achieved. An approximate exponent is the most that can be achieved in an attempt to compare CAI strength data across a range of impact damage severity levels.

- Care must be taken when comparing CAI strength data since the lay-up and material can have a large influence on results of laminates of the same thickness.

- As the impact severity level increases, the difference between the unnormalized CAI strengths becomes less, which makes physical sense as the specimens are essentially nearing the OHC strength of the laminate.

- For the data examined in this TP, an exponent of $m = -2.2$ appears to give the best overall comparison of CAI strength values across the range of thicknesses and impact severity levels used.

- Material type appears to play an important role as CAI strength data for IM7/8551-7 was much more dependent upon damage severity level than the CAI strength data of IM7/MTM-45.

- If only 'severe' impact severity levels are considered, then an exponent of $m = -1.5$ appears to give the best overall comparison of CAI strength data.

- Since ASTM D 7137 called for relatively thick specimens being impacted at a 'severe' level compared to the laminates and impact levels considered in this TP, no change is needed although normalization with $m = -1$ appears to favor the thicker laminate.

- For relatively thick laminates, normalizing impact energy by the specimen thickness gives fairly comparable CAI strength results, especially at high impact severity levels.

- For high impact severity levels, a lower value of m gives more comparable CAI strength data, and for low impact severity levels, a higher value of m gives more comparable CAI strength data.

- Most of the difference in CAI strength values for laminates of different thicknesses is due to a change in damage resistance.

- Once a given planar damage area forms, the CAI strength varies inversely by ≈0.63, although this value is quite dependent on specimen thickness.

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14. ABSTRACT
The amount of impact energy used to damage a composite laminate is a critical parameter when assessing residual strength properties. The compression after impact (CAI) strength of impacted laminates is dependent upon how thick the laminate is and this has traditionally been accounted for by normalizing (dividing) the impact energy by the laminate's thickness. However, when comparing CAI strength values for a given lay-up sequence and fiber/resin system, dividing the impact energy by the specimen thickness has been noted by the author to give higher CAI strength values for thicker laminates. A study was thus undertaken to assess the comparability of CAI strength data by normalizing the impact energy by the specimen thickness raised to a power to account for the higher strength of thicker laminates. One set of data from the literature and two generated in this study were analyzed by dividing the impact energy by the specimen thickness to the 1, 1.5, 2, and 2.5 powers. Results show that as laminate thickness and damage severity decreased, the value which the laminate thickness needs to be raised to in order to yield more comparable CAI data increases.

15. SUBJECT TERMS
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Huntsville, Alabama 35812