

IMPACT TESTING OF TEXTILE
COMPOSITE MATERIALS

by

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OUTLINE

Objective

Approach

Description of Materials

Test Specimen Configurations

Test Methods

Results

Damage Resistance

C-Scan Damage Area

Impact Force

Damage Tolerance

Compression & Tension After Impact

Residual Strength

Summary of Findings

Objectives:

To evaluate the Impact Damage Resistance & Damage Tolerance of various Textile Composite Materials.

Program Methodology

Static Indentation Tests

- Perform Repeated Static Indentation tests to obtain various amounts of damage.
- Document the Damage Resistance of each of the material forms.
- Calculate the falling weight impact energies to produce the same amounts of damage.

Falling Weight Impact Tests

- Impact coupons at the energy levels calculated from the Static Indentation tests.
- Document the Damage Resistance of each of the material forms.

Compression & Tension After Impact Tests

- Measure and compare the residual strength after impact of these materials.
- Document the Damage Tolerance of each of the material forms.

Stitched & Unstitched Uniweaves

Stitched & Unstitched Uniweave Constructed From
AS4/3501-6 Carbon/Epoxy.

A 225 denier fiberglass yarn was woven in the fill direction to hold the fibers together while stitching.

Stitching was done with a 1250 yd/lb fiberglass yarn at 8 penetrations per inch, each spaced 1/8 inch apart.

Four quasi-isotropic layups:

	Layup	Avg. Thickness, in.	
		Stitched	Unstitched
48 ply	[45°/0°/-45°/90°]6s	0.297	0.262
32 ply	[45°/0°/-45°/90°]4s	0.203	0.178
24 ply	[45°/0°/-45°/90°]3s	0.155	0.135
16 ply	[45°/0°/-45°/90°]2s	0.102	0.091

2-D Triaxial Braid Configurations

Material	Braid Code	Braid Yarn Size	Percent 0° Yarns	Braid Pattern	0° Yarn Size	Avg. Thickness, in.
SLL	[030K/±706K]46	6K	46	0±70	30K	0.225
LLL	[075K/±7015K]46	15K	46	0±70	75K	0.220
LLS	[036K/±4515K]46	15K	46	0±45	36K	0.251
LSS	[06K/±4515K]12	15K	12	0±45	6K	0.220

[0XXX / ±TXXX] Y % Axial

Where: XX indicates the yarn size, K indicates thousands
Y indicates the percentage of axial yarns in the preform.

3-D Woven Preform Configurations

TS1 & TS2	Through-the-Thickness	Angle	Interlock
LS1 & LS2	Layer-to-Layer	Angle	Interlock
OS1 & OS2	Through-the-Thickness	Orthogonal	Interlock

Avg. Specimen Thicknesses, in.

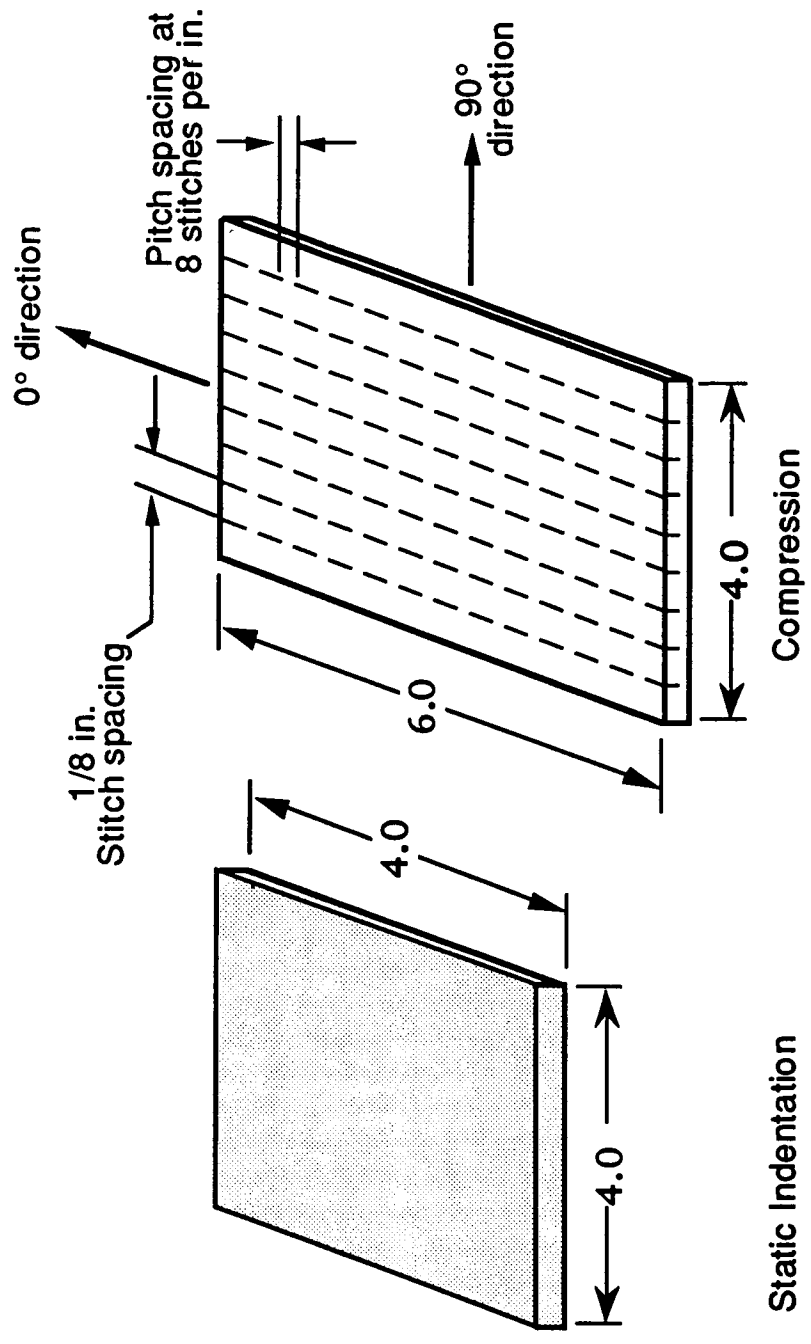
TS1	0.229	LS1	0.223	OS1	0.225
TS2	0.222	LS2	0.227	OS2	0.231

Basically:

"1" have Larger Yarns with Fewer Yarns/in. and Fewer Layers Than "2".
Yarn % Areal Wt. was about equal between the 1 & 2 configurations.

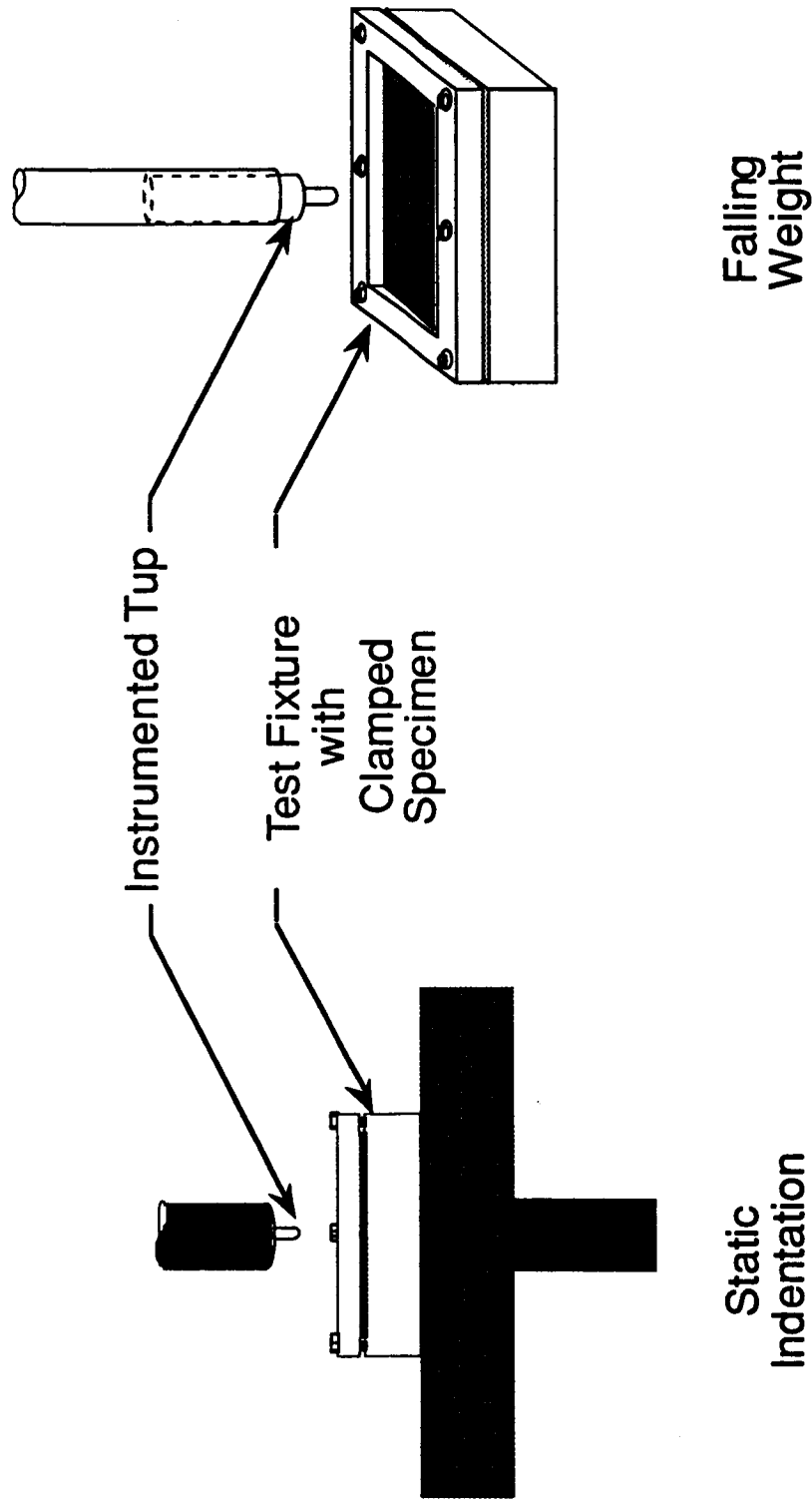
SPECIMEN CONFIGURATIONS

Static Indentation & Falling Weight Coupons



Test Specimen Configurations were as shown. The static indentation coupons were 4.0 in. square. The CAI & TAI were 4.0 in. wide and 6.0 or 10.0 inch long, respectively.

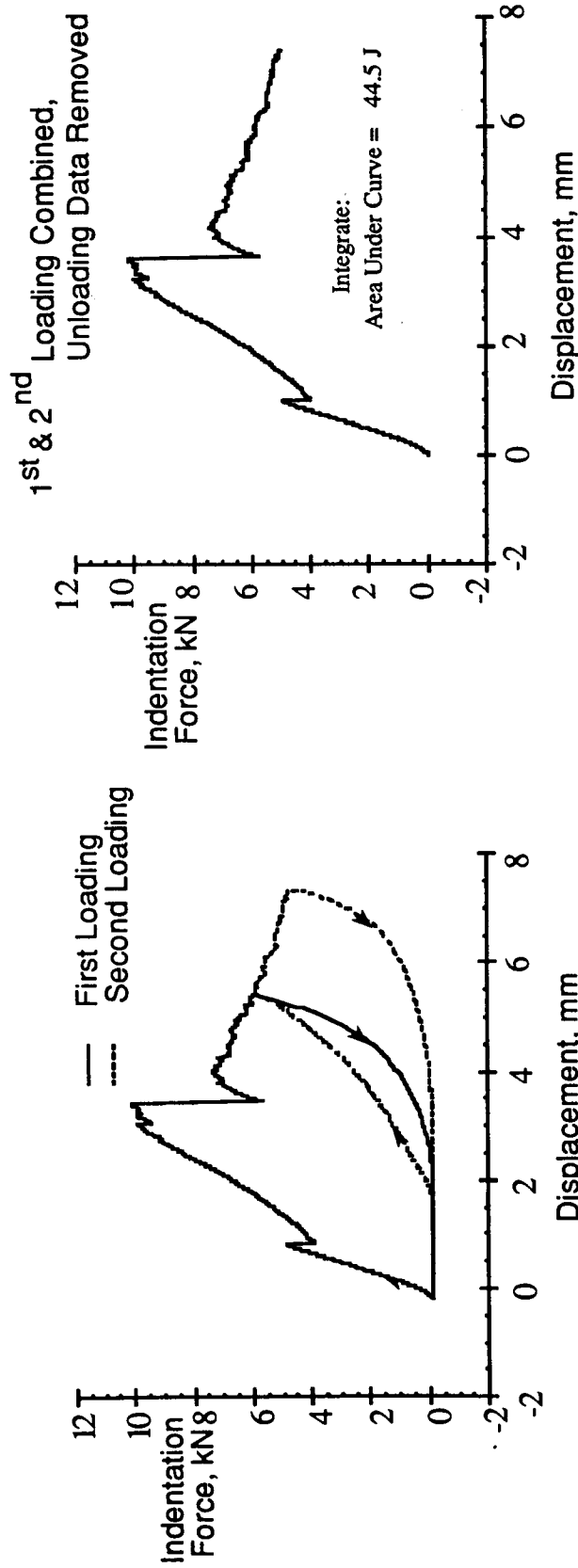
Impact Methods



Both Static Indentation and Falling Weight Impacts were performed. Both testing methods used the same instrumented tip, 1/2" diameter tip, and clamped aluminum test frames.

Static Indentation Tests

32 ply Unstitched Uniweave



Data, taken from static indentation tests such as these, were used to determine the falling weight energies required to produce pre-determined amounts of damage in the Uniwoven materials. Energies were calculated to produce on average both 0.10 inch dent depths and a barely measurable surface dent, dents on the order of a few thousands of an inch. For the purpose of this presentation, the terms "Severe Impact Damage" refers to impacts sufficient to produce average dent depth in the uniweaves of 0.10 inch. The term "Barely Visible Damage" refers to impact energies sufficient to produce damage barely measurable by C-Scan. The average dent depths for each of the impact energies used on each of the various material architecture's are given elsewhere.

Falling Weight Impact Energies For Uniweaves

	<u>BVD</u>	<u>Mean</u>	<u>SID</u>
48 ply Stitched	15.39 ft•lbs	39.12 ft•lbs	62.86 ft•lbs
48 ply Unstitched			
32 ply Stitched	7.29 ft•lbs	18.77 ft•lbs	30.26 ft•lbs
32 ply Unstitched			
24 ply Stitched	5.48 ft•lbs	13.29 ft•lbs	21.11 ft•lbs
24 ply Unstitched			
16 ply Stitched	3.00 ft•lbs	7.43 ft•lbs	11.87 ft•lbs
16 ply Unstitched			

BVD : Barely Visible Damage, Dent depths \approx 0.005 in.
Mean : Mean Impact Damage, Dent depths \approx 0.04 in.
SID : Severe Impact Damage, Dent depths \approx 0.10 in.

In order to isolate the effect of stitching, impact energies were kept constant between the stitched and unstitched specimens for each of the different ply counts.

Falling Weight Impact Energies For Braids & Weaves

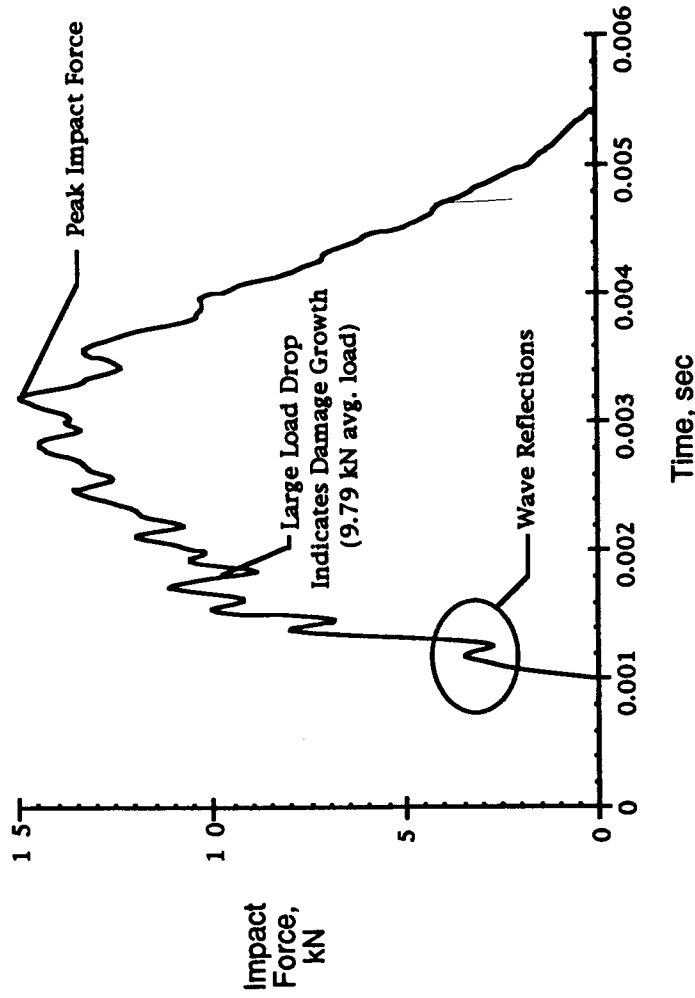
	<u>BVD</u>	<u>SID</u>	
2-D Braids	15.39 ft•lbs	62.86	ft•lbs
3-D Weaves	15.39 ft•lbs	62.86	ft•lbs

BVD: Barely Visible Damage, Dent depths \approx 0.009 in.
SID: Severe Impact Damage, Dent depths \approx Penetration.

The 2-D Braids and 3-D Weaves had an average plate thickness only slightly thinner than that of the 48 ply Unstitched Uniweaves. In order to make a comparison of the Impact Damage Resistance & Impact Damage Tolerance of these materials with that of the Uniweaves, impact energies were kept the same as what was used on the 48 ply Uniweaves. The "Barely Visible Damage" energy level resulted in average dent depths slightly larger than that obtained with the Uniweaves. The "Severe Impact Damage" energy level resulted in plate penetration in most cases.

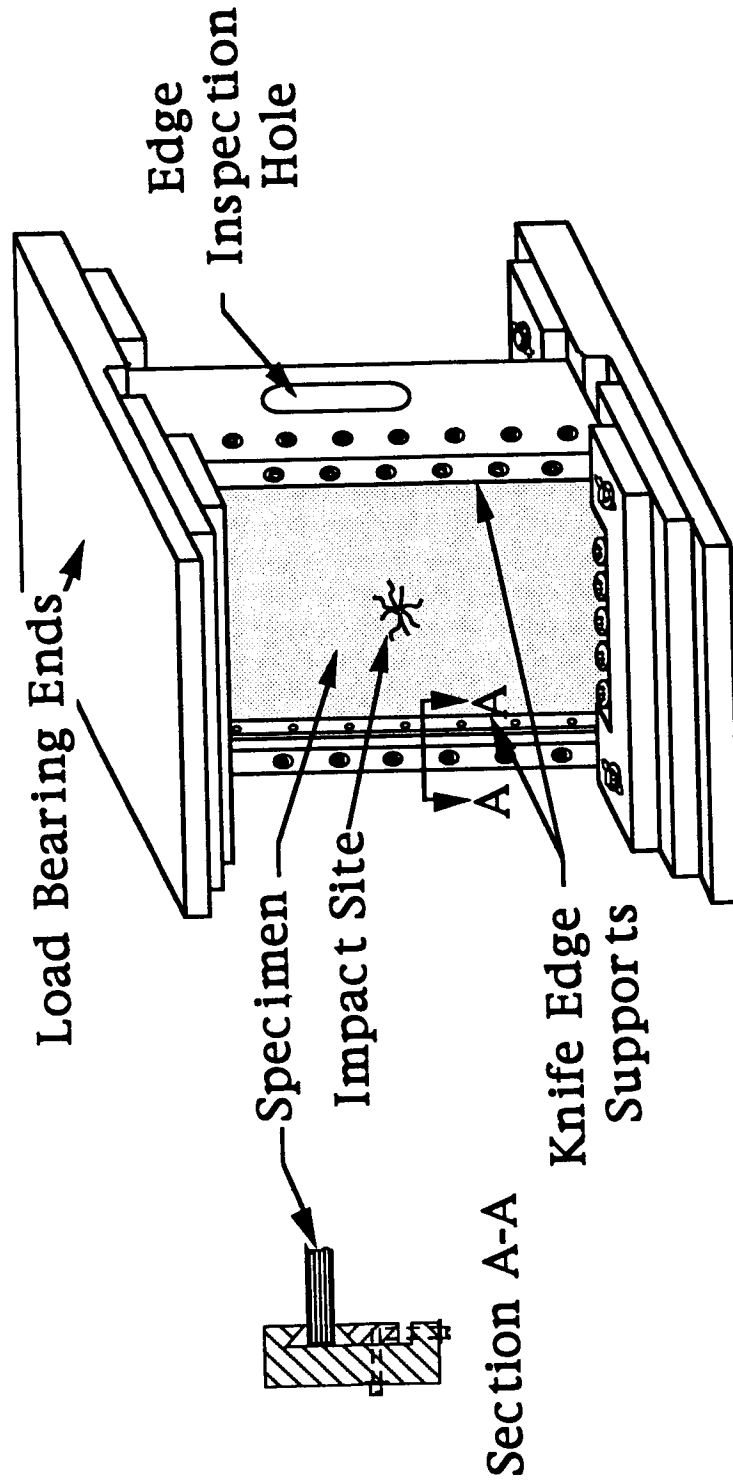
FALLING WEIGHT IMPACT

48 ply Stitched Uniweave, 15.39 ft·lbs Impact Energy



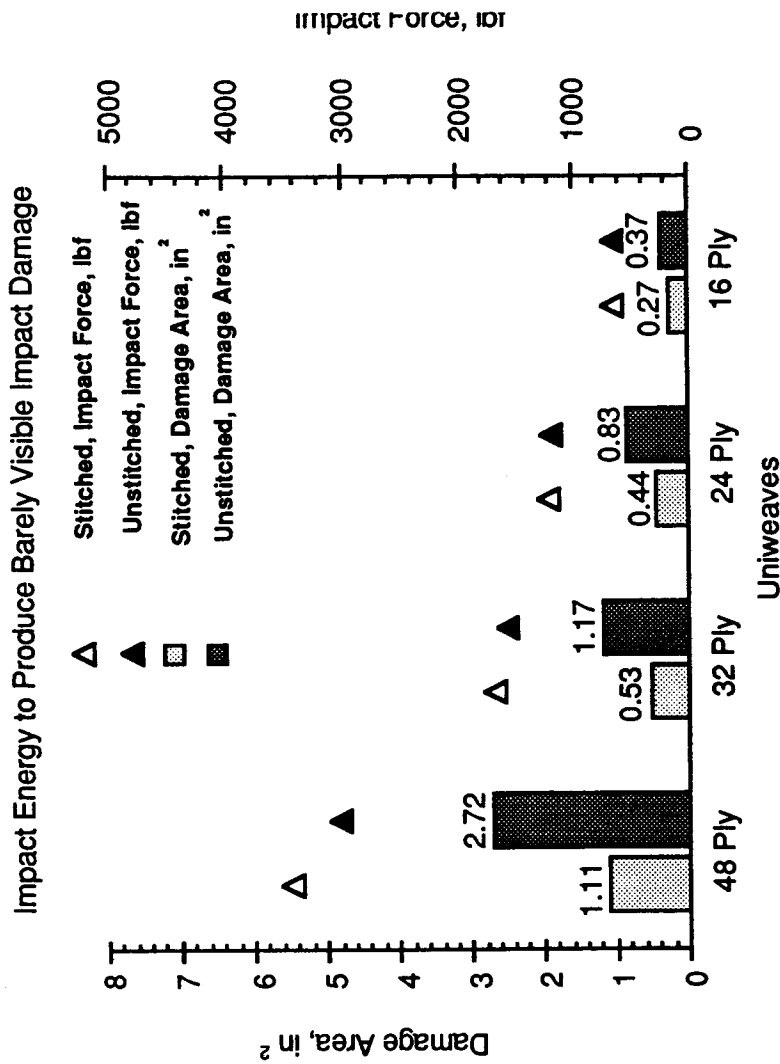
This is a plot of Impact Force -vs- Time for a typical stitched uniweave. The amount of peak force obtained is a function of the extent of damage to the test coupon from the impact event. Lower peak energies imply that energy was absorbed by damage growth.

Compression After Impact Test Fixture



This standard NASA compression after impact test fixture was used to prevent buckling in the test coupon during loading. Obvious buckling was observed in the 16 ply coupons and some of the 24 ply coupons. Thus, the reported failure strengths will be lower than expected.

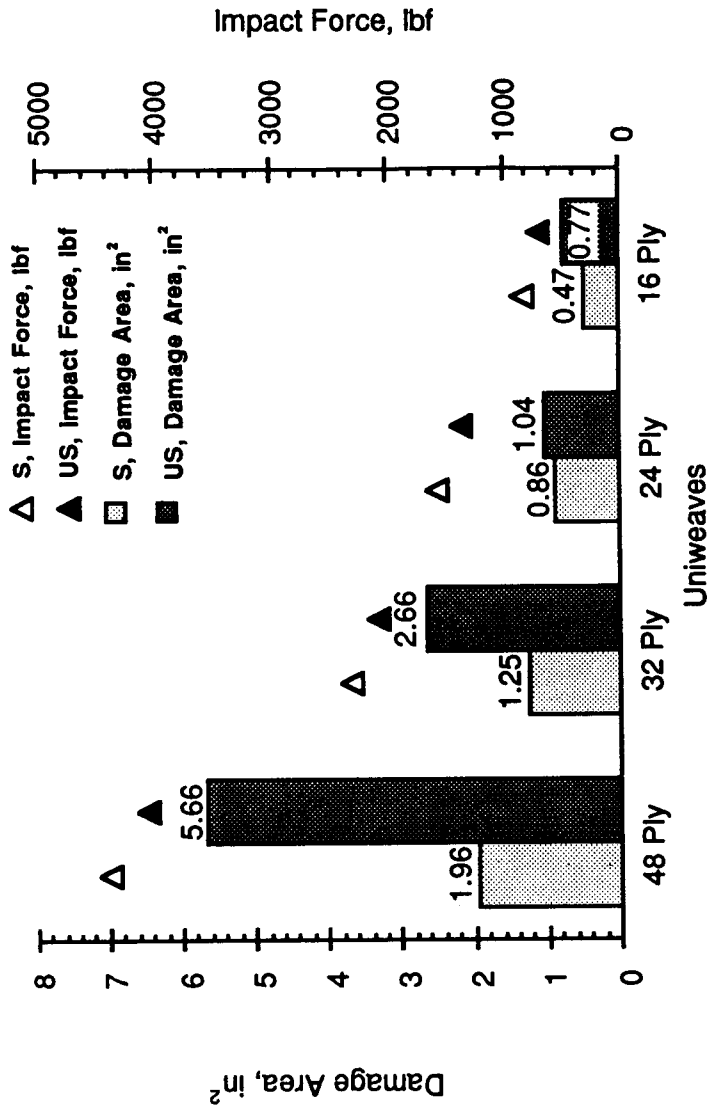
Damage Resistance of Uniweaves



This is a plot of Damage Area and Impact Force versus each material type for both stitched and unstitched uniweaves impacted at an energy sufficient to produce "Barely Visible Impact Damage". Four different thicknesses are shown. Investigation of this figure shows that damage area was always larger without stitching. It is also observed that the peak impact force, obtained during the actual impact event, is always lower for the unstitched materials. Implying that damage growth increases with decreasing peak force. Thus, stitching has improved the materials Damage Resistance.

Damage Resistance of Uniweaves

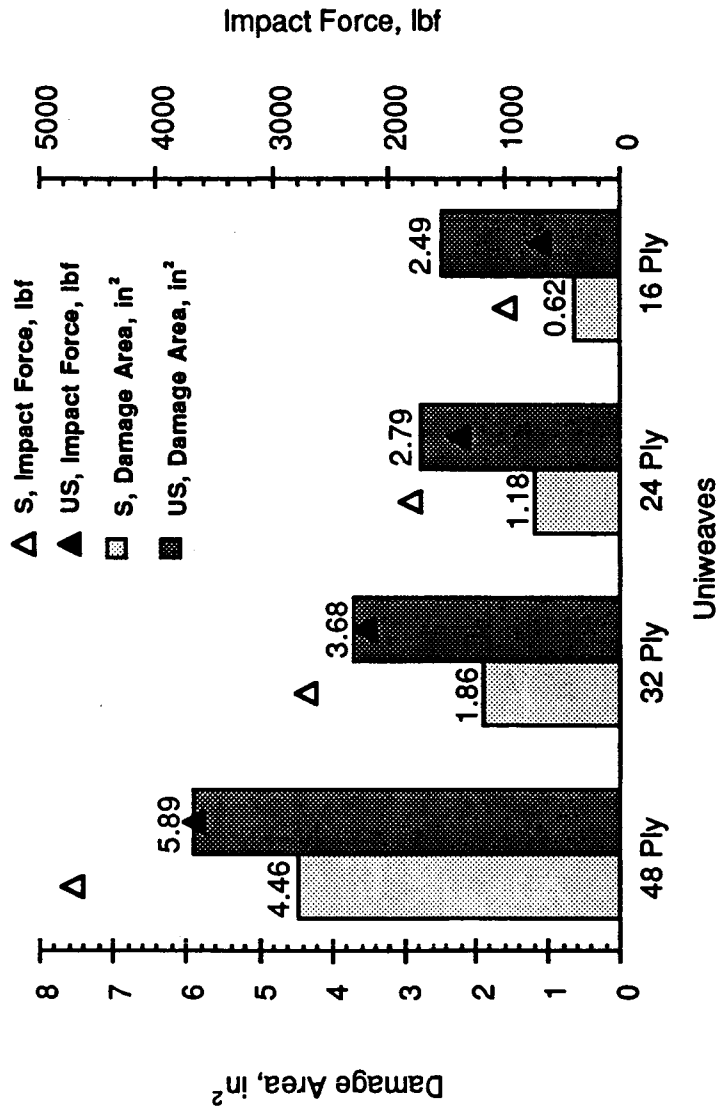
Impact Energy to Produce Mean Impact Damage



This is a plot of Damage Area and Impact Force versus each material type for both stitched and unstitched uniweaves impacted at an energy sufficient to produce "Mean Impact Damage". All four ply thicknesses are shown. Again the damage resistance is improved by stitching. Damage areas are smaller and peak impact energies are higher in all cases. In this figure there is also a plate thickness effect shown. As the plate thickness increases, so does the improvement in damage resistance.

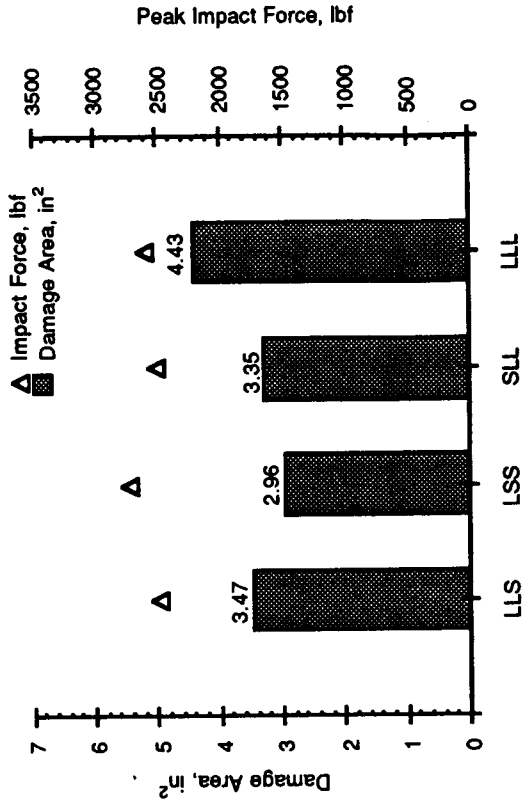
Damage Resistance of Uniweaves

Impact Energy to Produce Severe Impact Damage

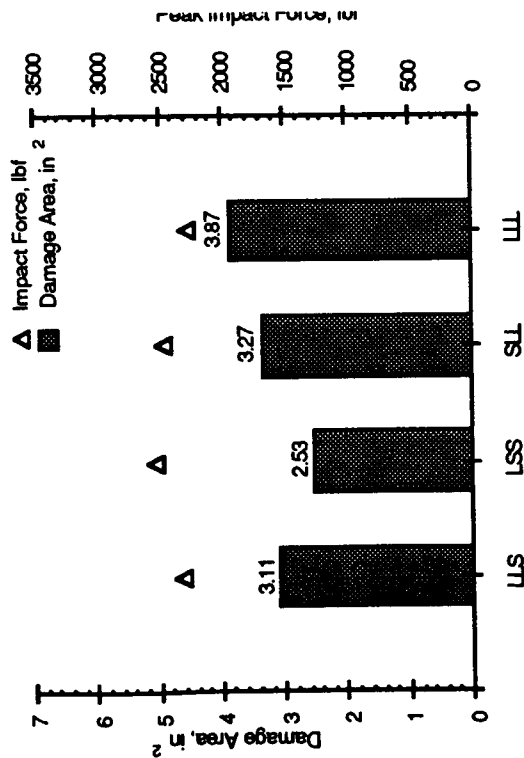


This is a plot of Damage Area and Impact Force versus each material type for both stitched and unstitched uniweaves impacted at an energy sufficient to produce "Severe Impact Damage". All four ply thicknesses are shown. Damage resistance is again improved by stitching. Damage areas are smaller and peak impact energies are higher for the stitched materials in all cases. Comparing this figure to the "Barely Visible Impact" energy level you will find that damage area increased almost 300% in the unstitched materials but only about 200% with the stitched uniweaves.

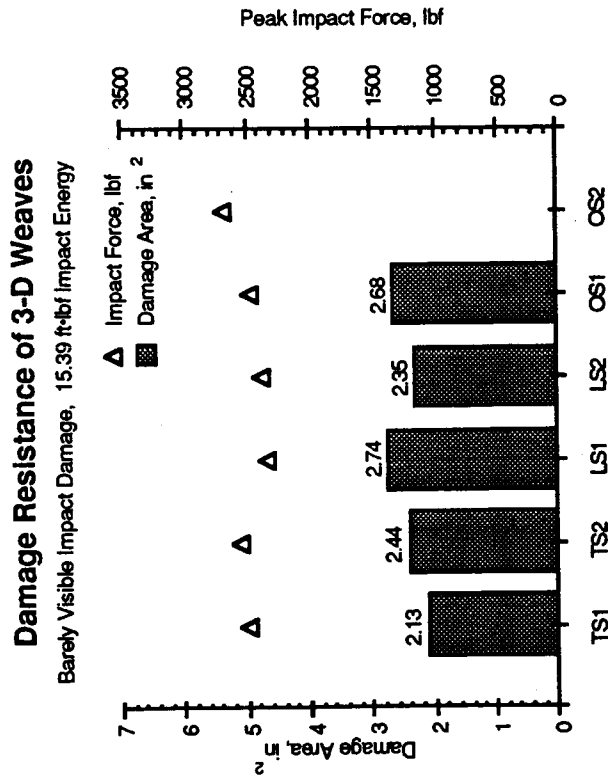
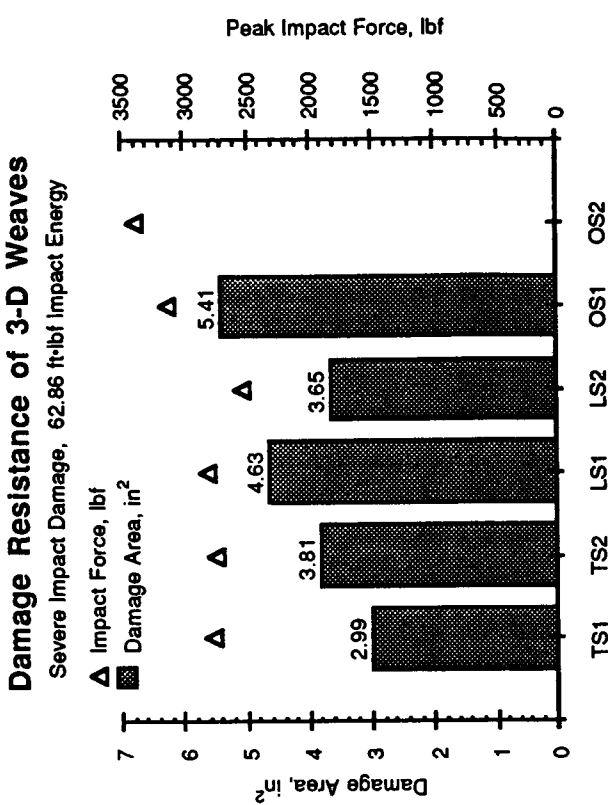
Damage Resistance of 2-D Braids Severe Impact Damage, 62.86 ft·lbf Impact Energy



Damage Resistance of 2-D Braids Barely Visible Impact Damage, 15.39 ft·lbf Impact Energy



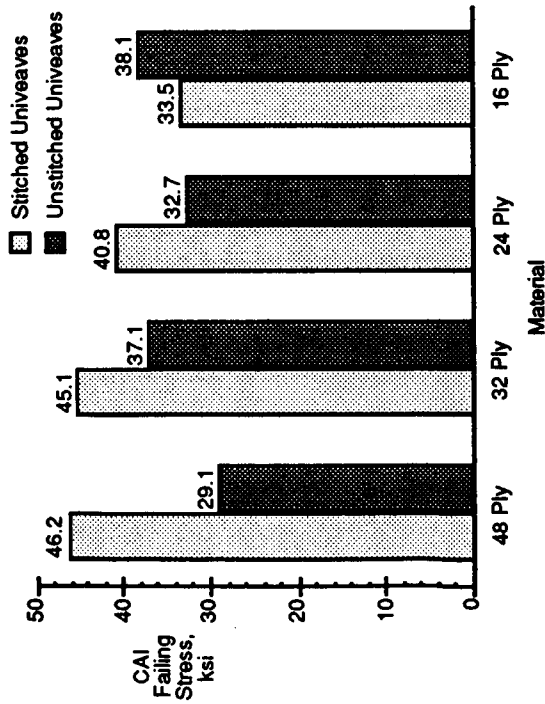
The figure on the left is a plot of Damage Area and Impact Force versus each material type for the 2-D Braids impacted at an energy sufficient to produce "Barely Visible Impact Damage". The figure on the right is the same as the first figure but at the elevated impact level to produce "Severe Impact Damage". All four braid types are compared. Damage areas were large as compared with the other material forms at the lower impact level but damage area only increased 11% between the BVD and SID energy levels. There were no obvious improvements in Damage Resistance by varying the braiding perimeters. The LSS architecture, which contained the smaller sized tows, did show the most resistance to damage growth but the extent of damage was still fairly severe.



These are plots of Damage Area and Impact Force versus each material type for the 3-D Weaves impacted at the "Barely Visible Impact Damage" level on the left and the "Severe Impact Damage" level on the right. Five of the six weave types are compared. The OS2 material is absent due to the inability to acquire c-scan data on this material form. Damage resistance was improved over the Braids and Unstitched Uniweaves but not over the Stitched Uniweaves. There was a 64% increase in damage area between these two figures on the average. There appears to be an improvement in Damage Resistance with the TS# materials while the OS1 displays the worst response. It will later be shown that this trend reverses itself in a comparison of Damage Tolerance between these same two architecture's.

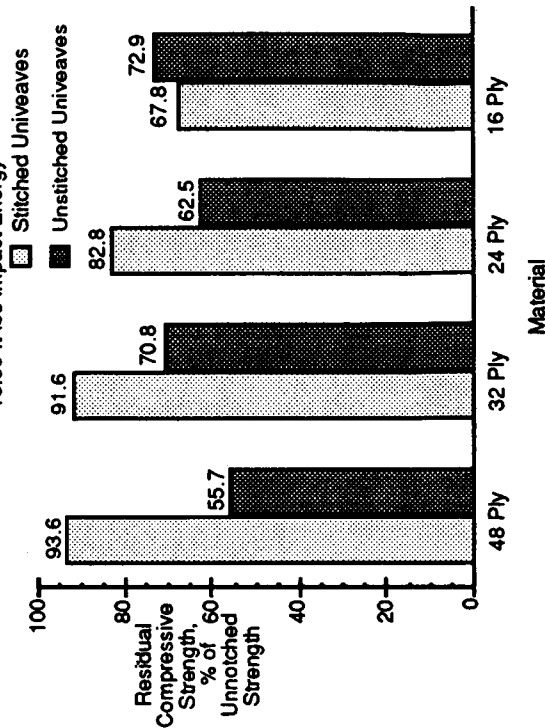
Compression After Impact of Uniweaves

Barely Visible Impact Damage, 15.39 ft-lbs Impact Energy



Damage Tolerance of Uniweaves

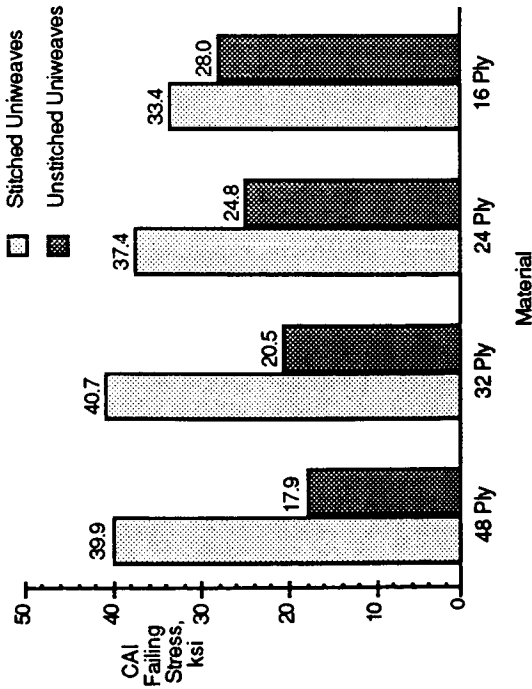
Compression After Impact, Barely Visible Impact Damage
15.39 ft-lbs Impact Energy



These two figures show an evaluation of the Compression Response of the Stitched & Unstitched Uniweaves, impacted at the lower "Barely Visible Impact Damage" energy level. On the left is a plot of the Compression after Impact (CAI) Strength versus each of the material forms and on the right is a plot of the residual strength where the CAI data has been normalized by it's unnotched strength. Noticeable bending was present in the 16 ply and some 24 ply specimens during loading thus, the failure strengths for these tests are low. Stitching appears to enhance this materials damage tolerance. An average of better than 91% retention in strength was had with the 48 ply materials. Compression strengths averaged better than 40 ksi demonstrating the ability to exceed current design criteria for commercial aircraft. Residual strength appears to improve with increasing plate thickness.

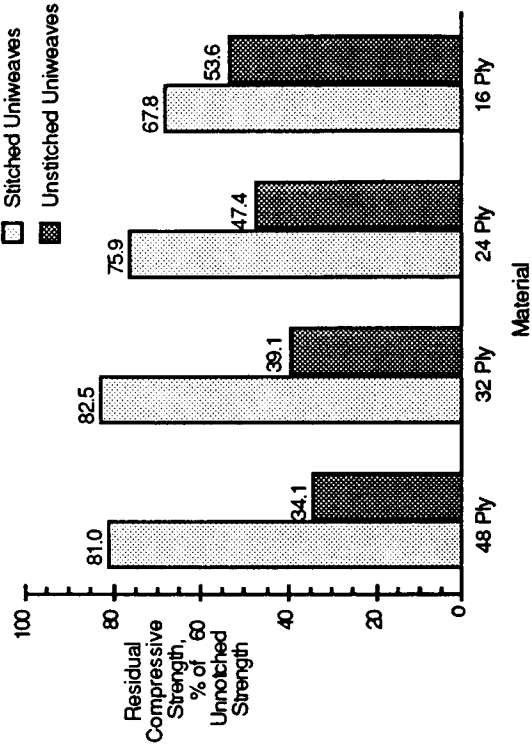
Compression After Impact of Uniweaves

Severe Impact Damage, 62.86 ft-lbs Impact Energy



Damage Tolerance of Uniweaves

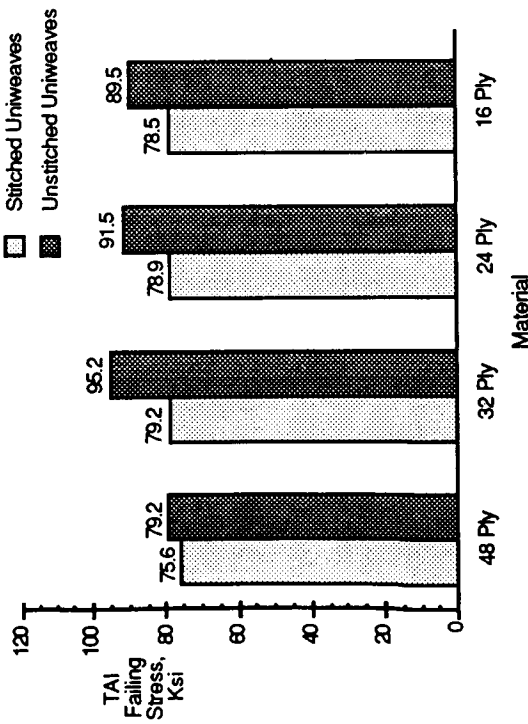
Compression After Impact, Severe Impact Damage
62.86 ft-lbs Impact Energy



These two figures allow an evaluation of the Compression Response of the Stitched & Unstitched Uniweaves, impacted at the higher "Severe Impact Damage" energy level. On the left is a plot of the Compression after Impact (CAI) Strength versus each of the material forms and on the right is a plot of the residual strength where the CAI data has been normalized by its unnotched strength. Stitching continues to enhance the damage tolerance capability of this material form. Even at this severe impact energy level, compression strengths were around the 40 Ksi threshold for design standards. Again, damage tolerance tended to improve with increasing plate thickness. Residual strengths were around 80% of the unnotched strength for the thicker 48 & 32 ply specimens but dropped with the thinner plates. The percent improvement in damage tolerance with stitching was greater at the higher impact energy level than that obtained at the lower impact energy.

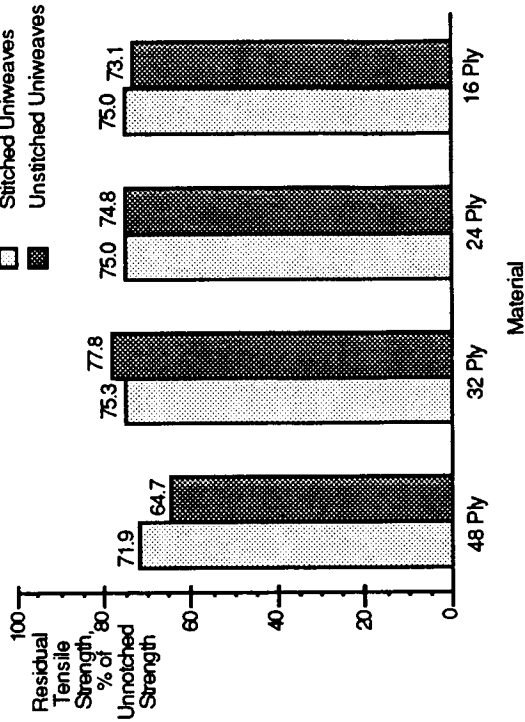
Tension After Impact of Uniweaves

Barely Visible Impact Damage, 15.39 ft-lbs Impact Energy



Damage Tolerance of Uniweaves

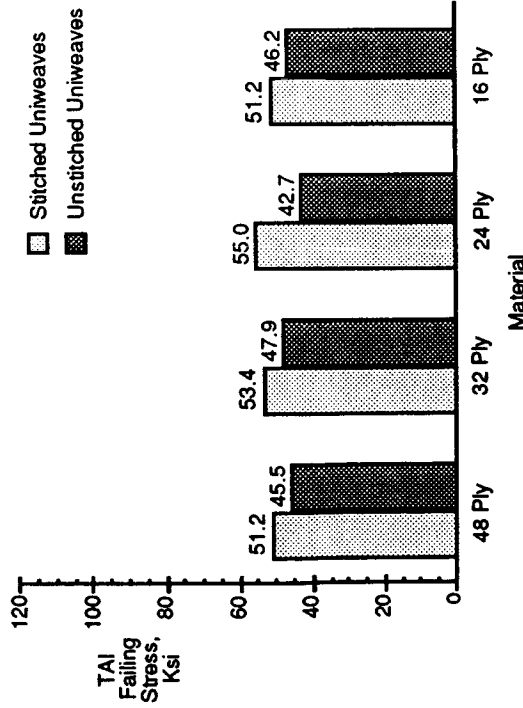
Tension After Impact, Barely Visible Impact Damage
15.39 ft-lbs Impact Energy



These two figures show an evaluation of the Tension Response of the Stitched & Unstitched Uniweaves impacted at the lower "Barely Visible Impact Damage" energy level. On the left is a plot of the Tension after Impact (TAI) Strength versus each of the material forms and on the right is a plot of the residual strength where the TAI data has been normalized by its unnotched strength. Stitching didn't appear to enhance the TAI strength but did tend to improve the strength retention. The unstitched uniweaves had an average failure strength of 78 ksi and an average of 74 % strength retention while the stitched averaged 89 ksi failure strength and only 73% retention of unnotched strength. Thus, even though the failure strengths were lower, the strength retention was equal or slightly better.

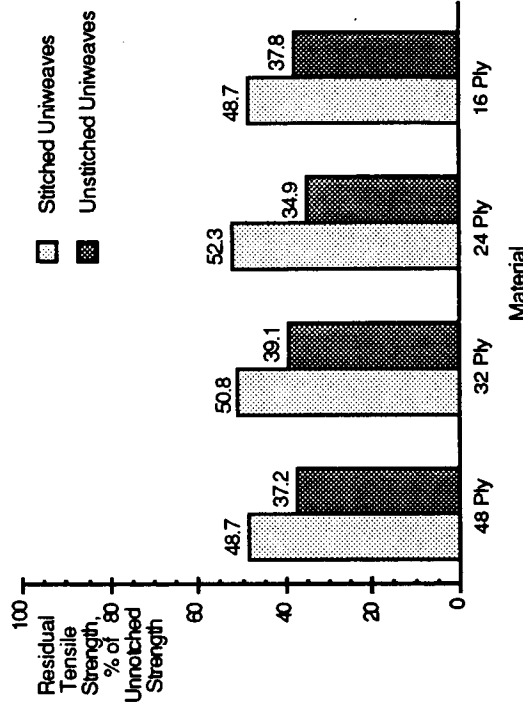
Tension After Impact of Uniweaves

Mean Impact Damage, 39.12 ft-lbs Impact Energy



Damage Tolerance of Uniweaves

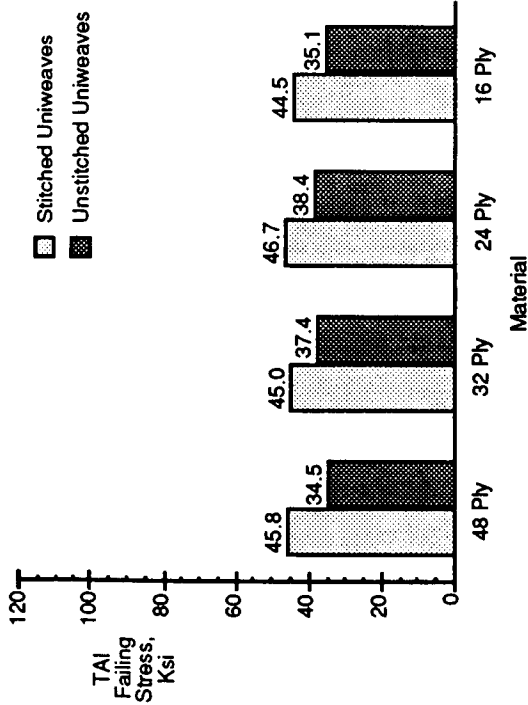
Tension After Impact, Mean Impact Damage
39.12 ft-lbs Impact Energy



These two figures show an evaluation of the Tension Response of the Stitched & Unstitched Uniweaves impact at the "Mean Impact Damage" energy level. On the left is a plot of the Tension after Impact (TAI) Strength versus each of the material forms and on the right is a plot of the residual strength where the TAI data has been normalized by its unnotched strength. At this median impact energy, stitching tended to improve both the TAI and residual strength of this material. With all ply counts, failing stresses were greater for the stitched uniweaves than the unstitched. In tension, these failure strengths were all well above the 40 ksi design allowable imposed by the commercial airframe manufactures. The percent residual strengths were also larger at this higher impact energy level. This implies that stitching may offer an improvement at the more extreme damage states while providing little or no improvement to specimens with little or no damage.

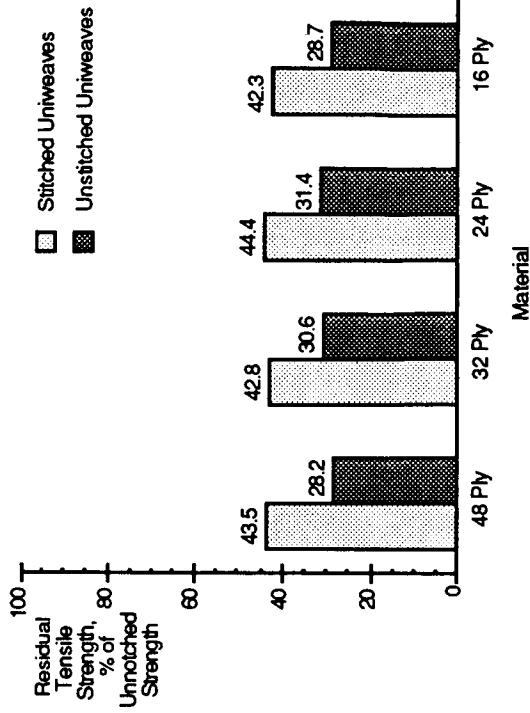
Tension After Impact of Uniweaves

Severe Impact Damage, 62.86 ft-lbs Impact Energy



Damage Tolerance of Uniweaves

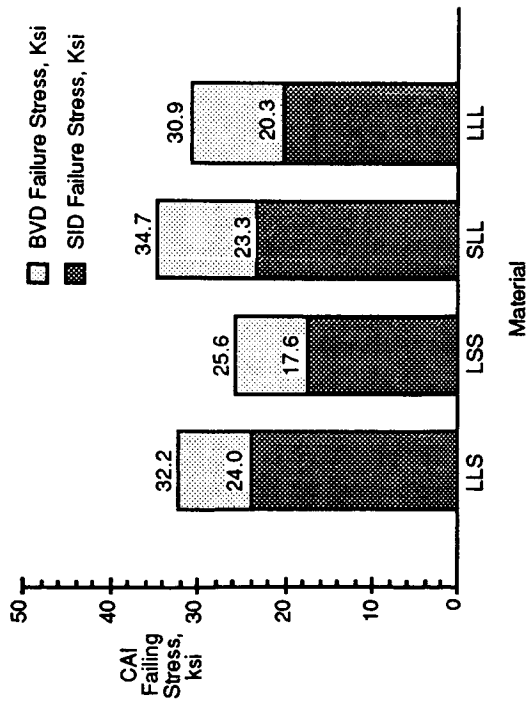
Tension After Impact, Severe Impact Damage
62.86 ft-lbs Impact Energy



These two figures show an evaluation of the Tension Response of the Stitched & Unstitched Uniweaves impacted at the higher "Severe Impact Damage" energy level. On the left is a plot of the Tension after Impact (TAI) Strength versus each of the material forms and on the right is a plot of the residual strength where the TAI data has been normalized by its unnotched strength. At the highest impact energy, stitching tended to improve both the TAI and residual strength of this material. Again failing stresses were greater for the stitched uniweaves than the unstitched. These failure strengths were all above the 40 ksi design allowable for the stitched materials. The percent of residual strength was also better with the stitched material. It is important to recall that stitching improved the CAI strength & compression Damage Resistance dramatically. In tension, stitching has not been shown to offer such improvements.

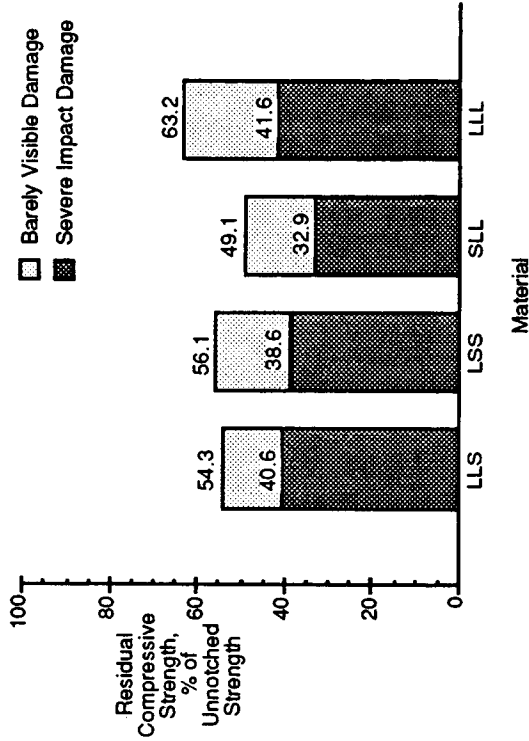
Compression After Impact of 2-D Braids

BVD, Barely Visible Damage, 15.39 ft-lbs Impact
 SID, Severe Impact Damage, 62.86 ft-lbs Impact



Damage Tolerance of 2-D Braids

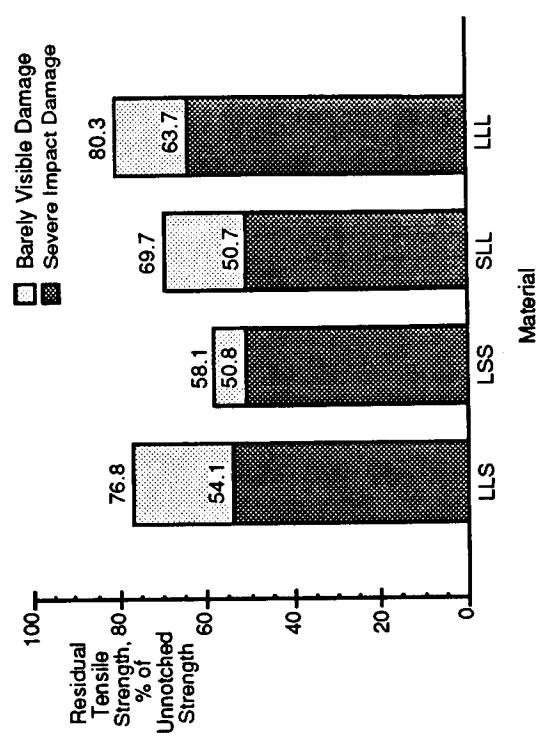
BVD, Barely Visible Damage, 15.39 ft-lbs Impact
 SID, Severe Impact Damage, 62.86 ft-lbs Impact



Compression After Impact (CAI) strength is plotted on the left while Residual Strength as a percent of unnotched strength is shown on the right for each of the four 2-D Braided architectures. Data for both the lower "Barely Visible Impact Damage" level and the upper "Severe Impact Damage" level are shown in each figure. Examination of these figures shows that the LSS architecture, which had the best Damage Resistance of the braids, has the least CAI strength. None of the 2-D Braids performed exemplary in either failing strength or percent of unnotched strength retention. Failing strengths, even at the lower impact energy, were all below the commercial airframe design allowable of 40 ksi. The residual strengths were also rather poor. The best residual strength performance was from the LLL architecture which coincidentally, had the worst Damage Resistance of the Braids. It retained only 63% of its unnotched strength.

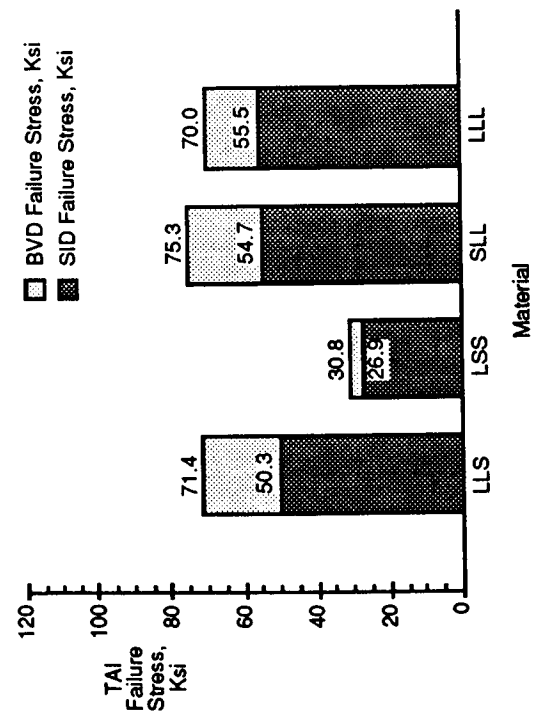
Damage Tolerance of 2-D Braids

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Tension After Impact of 2-D Braids

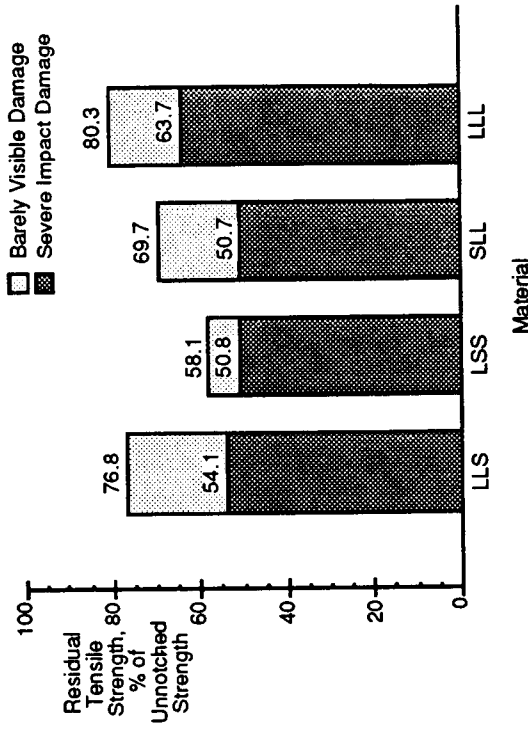
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Tension After Impact (TAI) strength is plotted on the left while Residual Strength as a percent of unnotched strength is shown on the right for each of the four 2-D Braided architectures. Data for both the lower "Barely Visible Impact Damage" level and the upper "Severe Impact Damage" level are shown in each figure. Again the LSS has the lowest TAI strength but recall that while the other three architecture's have 46% axial yarns, the LSS has only 12%, thus accounting for the significantly lower failing stress. Also, the LLL again has the greatest percent retention of unnotched strength. Although the 2-D Braids performed significantly better in tension that in compression, there overall strength is still rather low. At the "Severe Impact Damage" impact energy, the average percent residual strength is only 16% less than at the lower impact energy level.

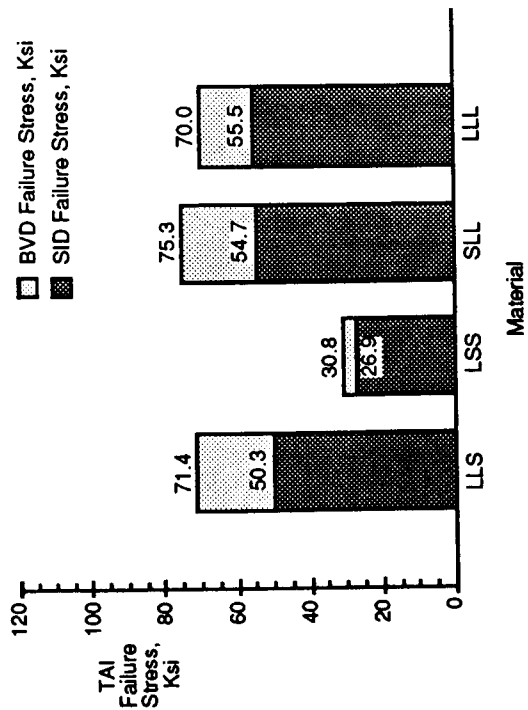
Damage Tolerance of 2-D Braids

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Tension After Impact of 2-D Braids

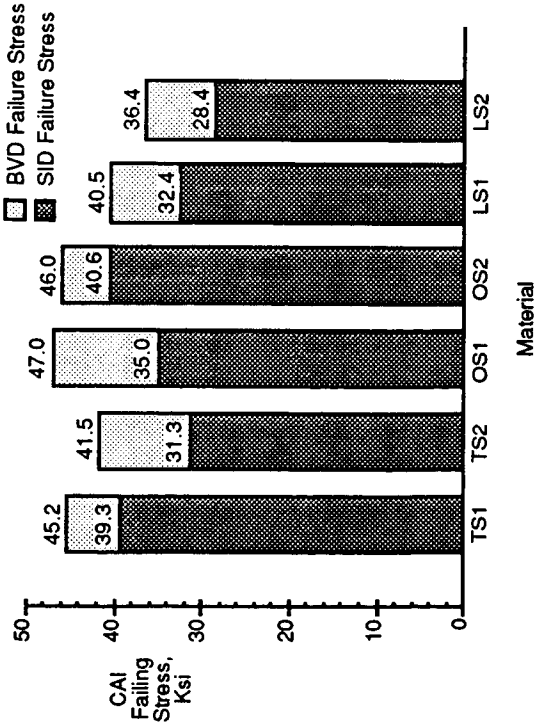
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Tension After Impact (TAI) strength is plotted on the left while Residual Strength as a percent of unnotched strength is shown on the right for each of the four 2-D Braided architectures. Data for both the lower "Barely Visible Impact Damage" level and the upper "Severe Impact Damage" level are shown in each figure. Again the LSS has the lowest TAI strength but recall that while the other three architecture's have 46% axial yarns, the LSS has only 12%, thus accounting for the significantly lower failing stress. Also, the LLL again has the greatest percent retention of unnotched strength. Although the 2-D Braids performed significantly better in tension than in compression, there overall strength is still rather low. At the "Severe Impact Damage" impact energy, the average percent residual strength is only 16% less than at the lower impact energy level.

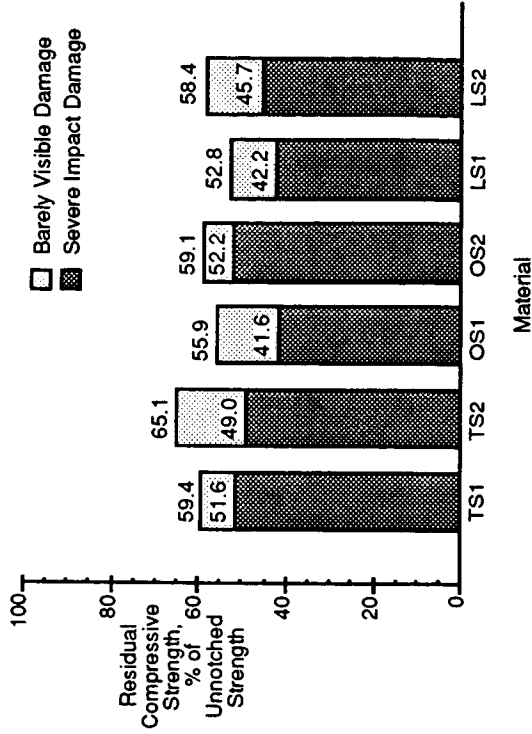
Compression After Impact of 3-D Weaves

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 SID, Severe Impact Damage, 62.86 ft-lbs Impact



Damage Tolerance of 3-D Weaves

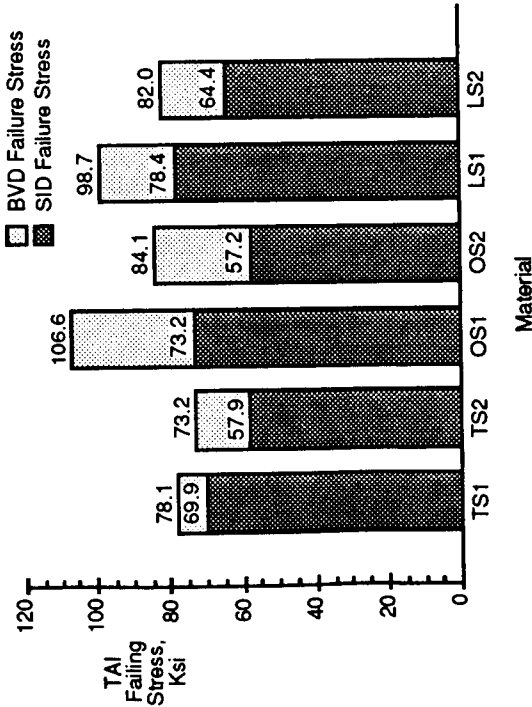
BVD, Barely Visible Damage, 15.39 ft-lbs Impact
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Compression After Impact (CAI) strength is plotted in the left figure and the right figure for each of the six 3-D Weaves. Data from both the lower "Barely Visible Impact Damage" level and the upper "Severe Impact Damage" level are shown in each figure. The weaves outperformed the 2-D Braids and the Unstitched Uniweaves at both impact energy levels in compression. They compared about equally with the Stitched Uniweaves, having an a failing stress of greater than 40 ksi with the OS1 architecture at the highest impact energy. Recall that the OS1 architecture also demonstrated the best Damage Resistance of the 3-D Weaves. Residual strengths were better than those of the 2-D Braids, regardless of the impact energy level. The Unstitched Uniweaves retained a higher percentage of their unnotched strength than the 3-D Weaves at the lower impact energy level but not at the more severe level. The Stitched Uniweaves outperformed the 3-D Weaves in compression, regardless of the impact energy level compared.

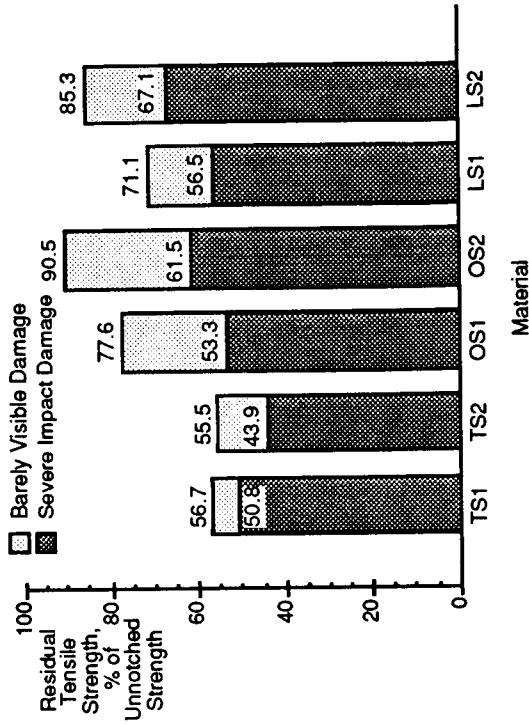
Tension After Impact of 3-D Weaves

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Damage Tolerance of 3-D Weaves

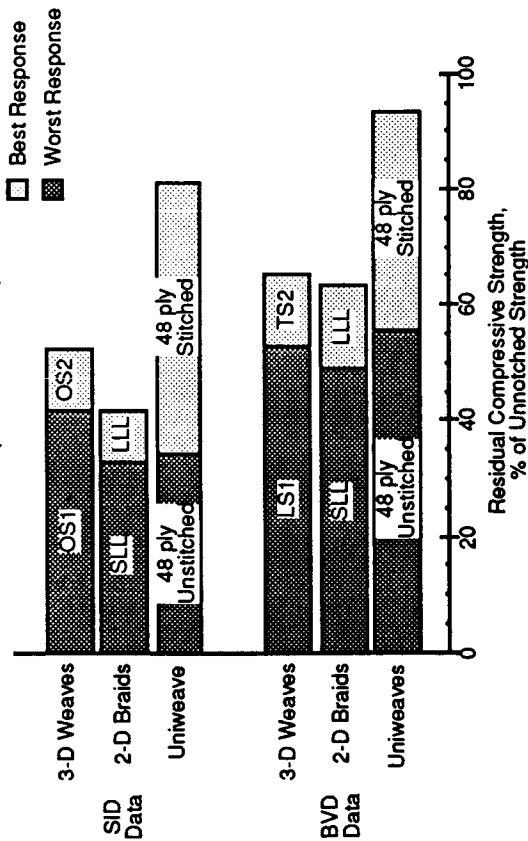
BVD, Barely Visible Damage, 15.39 ft-lbs Impact
 SID, Severe Impact Damage, 62.86 ft-lbs Impact



Tension After Impact (TAI) strength is plotted in the right left and Residual Strength as a percent of unnotched strength is shown on the right figure for each of the six 3-D Weaves. Data from both the lower "Barely Visible Impact Damage" level and the upper "Severe Impact Damage" level are shown in each figure. The 3-D Weaves tended to exhibit there best performance in tension. Although the extent of damage from impact was generally higher than that of many of the other material architectures, the failing stresses obtained from these materials were typically higher. Failing stresses for the OS1 specimens averaged 106.6 ksi, far better than any other material form. Only the 32 ply Stitched Uniweave came within 10% of this value. The best performing 2-D Braid offered 30% less load carrying capability at the "Barely Visible Damage" impact level. With the residual strength comparison, the OS2 material retained better than 90% of it's unnotched strength. Again, outperforming any other architecture evaluated in tension.

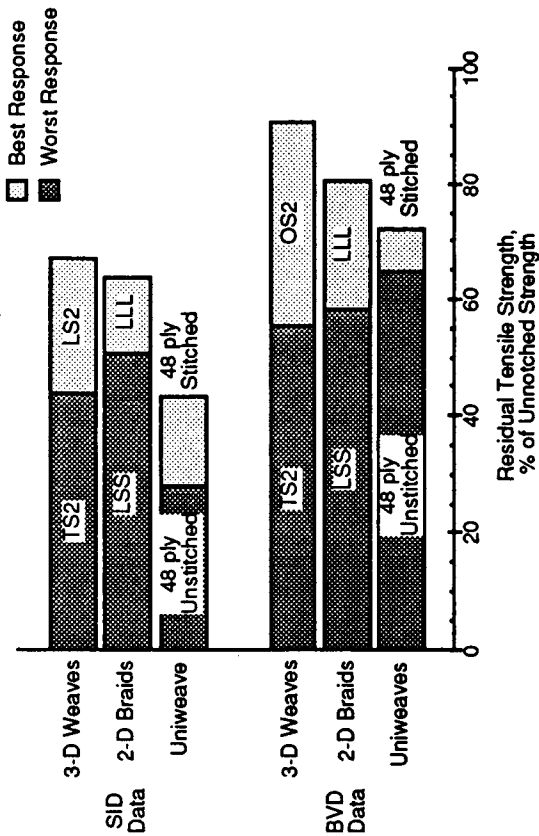
Damage Tolerance of Textiles in Compression

SID, Severe Impact Damage, 62.86 ft-lbs Impact
 BVD, Barely Visible Damage, 15.39 ft-lbs Impact
 Compression After Impact



Damage Tolerance of Textiles in Tension

SID, Severe Impact Damage, 62.86 ft-lbs Impact
 BVD, Barely Visible Damage, 15.39 ft-lbs Impact
 Tension After Impact



These two figures allow a comparison of the best and worst response to damage tolerance for all of the material architecture's in both tension and compression. The figure on the left shows the results from compression testing while the figure on the right is for the tension data. Both figures display results at both the "Severe Impact Damage" and "Barely Visible Damage" impact levels. Examination of these figures shows that stitching, which excels at reducing damage growth in compression, does not appear to enhance damage tolerance in tension. Overall, the 2-D Braids offer little tolerance to impact damage in compression but have moderately good response in tension. The 3-D Weaves, which offer reasonably good damage tolerance in compression, outperform all the other textile architecture's compared in tension. This result is surprising, given the poor damage resistance of these material forms.

Summary - Damage Resistance

Stitched & Unstitched Uniweaves

- Stitched Materials Had Less Damage Area and Higher peak Impact Force than Unstitched.
- Damage Resistance Increased with Plate Thickness.
- Unstitched 48 ply Had 189% More Damage Area Than Stitched 48 ply With Mean Impact Damage.

2-D Braids

- No Significant Difference Produced By Varying Any Of The Braiding Parameters.
- LLL Had 53% More Damage Area Than LSS with SID.

3-D Weaves

- No Significant Difference At Low Impact Energies.
- OS1 Had 53% More Damage Area Than TS1 with SID.

Summary - Damage Tolerance

Stitched & Unstitched Uniweaves

- **Stitching:** Improved CAI Strength at All Energy Levels.
Improved TAI strength at Mean & SID levels.
- **Stitching** Improved Damage Tolerance in All Cases.
- **Damage Tolerance** Increased with Plate Thickness.
- **Stitched 48 ply CAI** retained 94% of unnotched strength.
- **Stitched 48 ply TAI** retained 72% of unnotched strength.

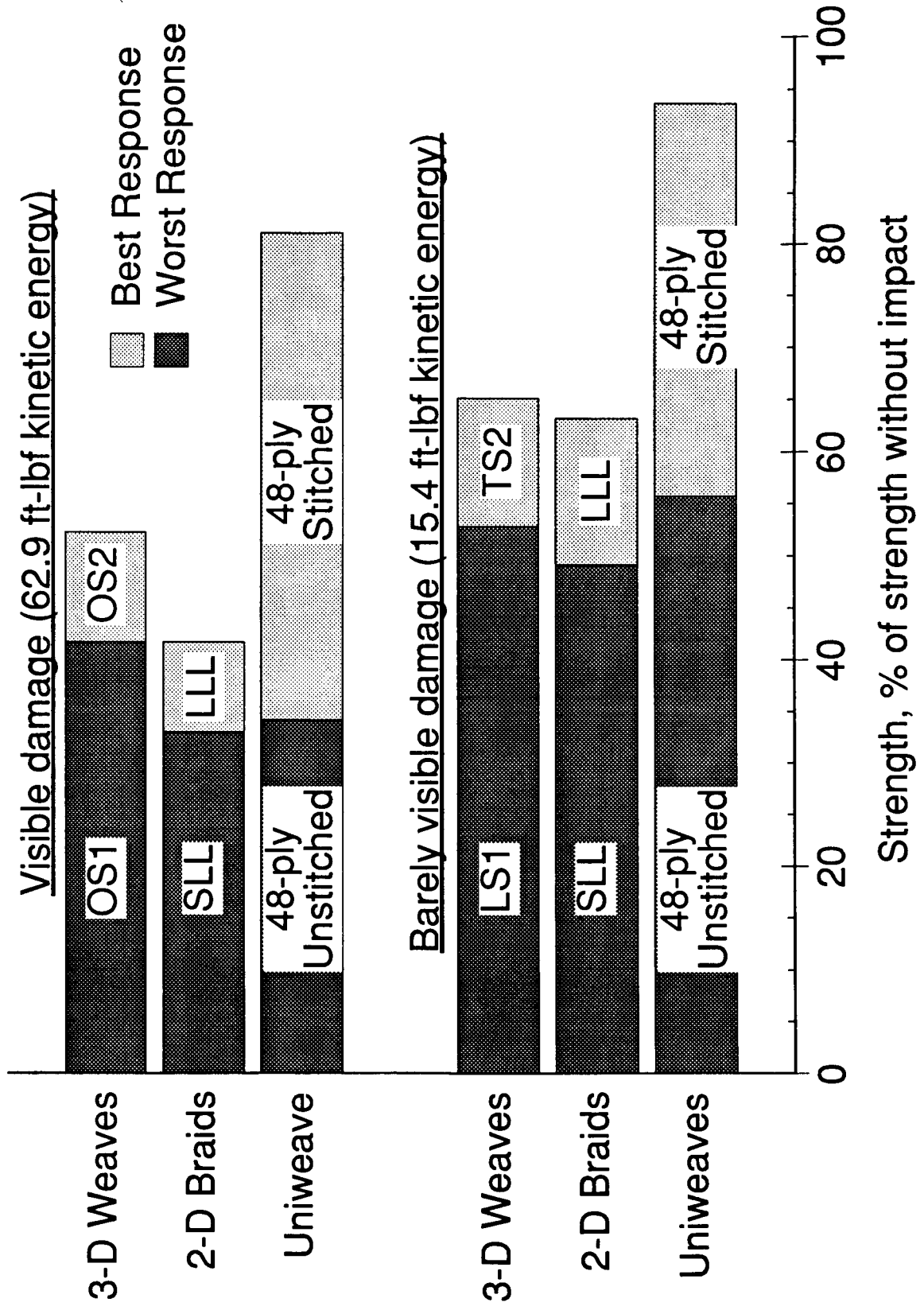
2-D Braids

- **Residual Strength** Better in Tension Than Compression.
- **LLL** retained 63% of Unnotched CAI strength with BVD.
- **LLL** retained 80% of Unnotched TAI strength with BVD.

3-D Weaves

- **Residual Strength** Better in Tension Than Compression.
- **TS2** retained 65% of Unnotched CAI strength with BVD.
- **OS2** retained 90% of Unnotched TAI strength with BVD.

DAMAGE TOLERANCE OF TEXTILES IN COMPRESSION



DAMAGE TOLERANCE OF TEXTILES IN TENSION

