Characterization of IM7/8552 Thin-ply and Hybrid Thin-ply Composites

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Composite materials have increasingly been used for aerospace applications due to improved performance and reduced weight compared to their metallic counterparts. Inclusion of thin-ply material, plies with cured thickness half or less than standard composites, have potential to improve performance and reduce structural weight. Limited characterization of thin-ply IM7/8552 material in 30 and 70 grams per square meter fiber areal weights has been carried out using a series of selected American Society for Testing and Materials (ASTM) tests. Tests included unnotched tension, unnotched compression, v-notched rail shear, open-hole tension, and open-hole compression. Unidirectional, cross-ply, quasi-isotropic and hybrid hard laminates were included in the study, and were compared to standard-ply laminates. Properties compared include fiber volume, laminate moduli, and failure strength, with failure modes also being examined. The thin-ply specimens exhibited similar or superior performance to standard ply laminates in many of the cases compared. Improvements in strength for laminates containing thin-ply material were seen for unidirectional laminates under unnotched tension, quasi-isotropic laminates under unnotched tension and compression, and hard laminates under open hole tension. Additional investigation is required to determine appropriate ply stacking rules for hybrids of thin and standard plies to avoid undesirable failure modes such as axial splitting. However, the observed performance improvements demonstrated by the conducted ASTM tests of hybrid thin-ply hard laminates could have benefits for improved structural weight in aircraft.

I. Nomenclature

E =Young's modulus
G =Shear modulus
t_{lam} =Laminate thickness
t_{ply} =Ply thickness
ν =Poisson ratio

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II. Introduction

Composite materials have increasingly been used for aerospace applications due to improved performance and reduced weight compared to their metallic counterparts. However, due to the numerous failure mechanisms that can occur in composite structures, design criteria are generally very conservative and take into account damage such as barely visible impact damage (BVID) and the presence of fastener holes and notches. Conventional composites used today are typically fabricated from plies of material having a cured ply-thickness of approximately 0.0055 in. or greater (these composites will be called "standard-ply" herein). However, recent research suggests that thinner plies, those with cured ply thicknesses at or below 0.0028 in., hold the potential for reducing structural weight and increasing performance due to their unique structural characteristics [1-5]. These characteristics include:

- Improved damage tolerance
- Resistance to microcracking (including cryogenic-effects)
- Improved aging and fatigue resistance
- Reduced minimum-gage thickness
- Thinner sections capable of sustaining large deformations without damage
- Increased scalability (e.g., thinner quasi-isotropic laminates)

However, the use of thin-ply composites in aerospace structures is an area of composites technology that has not yet been fully explored or exploited. Therefore, a joint study was undertaken by NASA Langley Research Center (LaRC) and Glenn Research Center (GRC) in support of the NASA Convergent Aeronautics Solutions (CAS) project to investigate potential benefits of utilizing thin-ply composites in aircraft structures. The purpose of this paper is to provide some initial characterization of an aeronautical-quality, thin-ply, carbon-fiber composite material, IM7/8552, and to provide some insight into how these characteristics can be incorporated into future composite structures. Where possible, results are compared to published National Center for Advanced Materials Performance (NCAMP) results [6-9].

III. Test Specimens and Tests

In the current study, two thin-ply, low-areal-weight forms of IM7/8552 prepreg material produced by the Hexcel Corporation were used, namely 70 grams per square meter (gsm) and 30 gsm (note that the areal weight refers only to the carbon fiber in the prepreg). The 70 gsm material was fabricated with IM7 from 12K tow and has a 38% resin content by weight, and the 30 gsm material was fabricated with IM7 from 6K tow and has a 36% resin content by weight. The standard-ply material used in the study was the 190 gsm variant of IM7/8552, with 35% resin content by weight. It is important to note that the thin-ply prepreg material is fabricated by the vendor on an as-needed basis in small quantities, and is therefore not a standard product but a special order. A consequence of the thin-ply prepreg not being a standard production-line product is that it can be difficult to get the same uniform quality as is found in the standard-ply material. Figure 1 shows photographs of three prepregs used in this study. The 70 gsm material appears to be of fairly comparable quality to the 190 gsm material, but the 30 gsm material has more fiber waviness and gaps. Significant spreading of the tows is required for the 30 gsm material, and this process may be the source of the observed waviness and gaps. However, once production of thin-ply material becomes more common it is anticipated the quality of the prepreg will improve.

The two thin-ply prepregs used in this study were characterized individually, and then as part of hybrid laminates consisting of both thin-ply material and standard-ply material. Thin-ply panels were fabricated in unidirectional, cross-ply and quasi-isotropic laminates. Manufacturing a panel with the 70 gsm and 30 gsm used in this study would require over 2.6 times and 6 times the number of plies being laid up compared to a comparable standard-ply panel, respectively, with the associated increase in manufacturing time. Therefore, hybrid laminates were studied as a compromise that was intended to minimize the number of thin-ply layers (manufacturing time) while attempting to take advantage of their beneficial performance characteristics. In a hybrid laminate, the intention is for the standard-ply lamina to provide the primary load carrying capability in the laminate while the thin-ply lamina carry secondary loads and serve to suppress failure modes in the laminate. Optimizing hybrid composites allowing full variation of stacking sequence, orientation, and thickness of plies was beyond the scope of this study. Therefore, the design of the hybrid composites evaluated herein used a simplified approach of using thin-ply material for all ±45-degree plies while using the standard-ply 190 gsm material for the 0- and 90-degree plies. In addition, one or more thin-ply layers were placed between all standard ply layers, so that the standard ply blocks in a laminate were separated into a set of individual single layers of standard-ply prepreg.

Another goal of this study was to see if using thin-ply layers would permit higher thickness percentages of 0-degree plies than are typically used for fabricating hard (much stiffer in one direction than the other) laminates. Laminate splitting, fiber separations in the load direction, is a failure mode that must be considered for notched, hard laminates. This failure mode is normally avoided by following empirically derived composite design guidelines that have evolved for use of standard-ply composites. Among these guidelines are limits for the maximum and minimum percentages of layers in the different ply angle directions. However, there are no guidelines for laminates having a mixture of thin and standard plies, so the limits for acceptable thickness percentages are unknown. A full exploration of the expanded design space possible when considering laminate thickness as a design variable has yet to be attempted, so the present results should be considered a small sampling of possible benefits that can be obtained when varying ply thickness within a laminate. The most comparable hard laminate found in the literature [6-9] consisted of 16 standard plies, with ply thickness percentages of [0/±45/90] orientations given as [50/40/10]. The two hybrid panels in this study were fabricated with the identical stacking sequence, but due to the differences in the thin-ply (±45-degree) thicknesses, the 0-degree standard-ply percentages were 60% and 72% of the laminate thickness for the 70 gsm and 30 gsm material, respectively. The 60% value is at the limit of typically recommended percentage of 0-degree plies [10], and the 72% value significantly exceeds the limit. Additional information for the panels evaluated in this study is shown in Table 1. Specimens were cut from two sets of panels, one set using 30 gsm material and one set using 70 gsm material, that were identified as panels "A" through "F".

Panels were fabricated at GRC using hand lay-up according to the ply sequences listed in Table 1. Trapped air was a concern throughout the lay-up process, in particular with the 30 gsm material. To mitigate air entrapment, a handheld roller was used to push out air after each ply was laid down for both the 70 gsm and the 30 gsm plies. Additionally, vacuum debulks were applied for three hours mid-way through the lay-up and also just prior to autoclave cure. The bagging configuration for each panel is illustrated in Figure 2. Panels were cured according to the suppliers recommended cure cycle. After cure, each panel was characterized by C-scan to evaluate the quality and identify any defects. The C-scans identified regions of the panel to avoid in extracting the specimens to be tested. Additionally, micrographs were made to examine void content and ply quality. Figure 3 shows micrographs for representative quasi-isotropic laminates for the 30 gsm and 70 gsm materials. From the micrographs, the ply quality is good in terms of ply thickness and uniformity. However, it is clear that the void content, seen as solid black regions in the micrograph, is higher in the 30 gsm panel, which is a consequence of the poorer quality of the prepreg shown in Figure 1. Measured void contents were as large as 0.45% for 30 gsm laminates and 0.12% for 70 gsm laminates.

Panels were cut into test specimens to conduct a series of American Society for Testing and Materials (ASTM) standardized tests. Table 2 lists the test specimens and ASTM tests, such as unnotched tension (UNT) [11], unnotched compression (UNC) [12], v-notched rail shear (VNRS) [13], open-hole tension (OHT) [14], and open-hole compression (OHC) [15]. The specimen types were identified using the panel from which they were cut, the type of ASTM test for which that specimen was used, and where applicable, the loading direction relative to the 0° fiber direction (e.g., -0° is loading aligned with the 0° fiber). The number of test specimens for each specimen type are provided in the table, and each specimen was marked with the specimen type and a dash number representing the replicate of that specimen type. The tests defined in Table 2 were conducted at the Wichita State University National Institute for Aviation Research (NIAR). All results presented herein are averages, with the published results taken from Ref. [8]. All testing was conducted at ambient room temperature, designated as room temperature dry (RTD) in the references.

IV. Test Results and Discussion

Test results from the thin-ply ASTM tests are presented and discussed in this section. First, unnotched tension specimen information and results are presented. Second, unnotched compression results. Next, open-hole tension results are presented, followed by open-hole compression. The final results presented are for the v-notch rail shear tests.

A. Unnotched Tension

Table 3 presents the unnotched tension specimen information and results. As shown, the average ply thicknesses for the 30 gsm and 70 gsm materials in this study are 0.0012 and 0.0028 inch thick, respectively. Figure 4 presents the normalized tension moduli, which are normalized using the comparable NCAMP results. The tension Young's moduli for the unidirectional thin-ply specimens (the "A" panel specimens) show excellent agreement with each other, within less than 0.5% difference in the fiber direction and less than 5% difference in the transverse direction. However, the thin-ply materials differ from the standard-ply by greater amounts, with the fiber direction modulus being approximately 7.7% less than the standard-ply modulus, and the transverse direction modulus being approximately 9-

14% higher than standard-ply modulus. Some of the difference between thin-ply and standard-ply moduli may be due to the thin-ply resin content being slightly higher than the NCAMP standard-ply resin content of 35% by weight, and the somewhat lower quality of the thin-ply prepreg material as mentioned previously and exhibited in Figure 1. No obvious reason is immediately apparent for the increase in transverse modulus observed for the thin-ply material compared to the standard ply material.

The normalized unnotched tension failure strengths for unidirectional layups (the "A" panel specimens) and quasi-isotropic layups (the "C" panel specimens) are compared in Figure 5. For unidirectional layups, the fiber direction strengths are the same or slightly higher than the reference standard-ply material, and the transverse strengths are 8% and 24% higher for the 30 gsm and 70 gsm material, respectively. Though not shown in the figures, but as seen in Table 3, the results for the specimens with quasi-isotropic layups show that the thin-ply laminates exhibited slightly lower equivalent laminate Young's modulus than the standard-ply laminates. This result is similar to what was found for the unidirectional specimens, however, as shown in Figure 5, the thin-ply quasi-isotropic laminate unnotched tension strength that is over 28% higher than the standard-ply. Though unnotched properties are not typically design drivers for aircraft, this increase in unnotched strength would yield a weight savings of approximately 23% for the thin-ply material compared to the standard-ply if the tensile strength were a driving requirement. The unnotched tension strengths for the hybrid laminates (the "E" panel specimens) are higher than the comparable standard-ply laminate as seen in Table 3. However, as mentioned previously and seen in the table, these hard laminates have different thickness percentages of the ply angles (especially the percent 0-degree plies) and are therefore not directly comparable. Two simplified methods of comparing the strengths of laminates having different ply thickness percentages are to compare the ratio of their strengths to either the stiffness ratio or the thickness percent of 0-degree plies. The thin-ply hybrid panels have moduli that are approximately 30% and 14% higher than the standard-ply reference laminate for the 30 gsm and 70 gsm laminates, respectively. Also, the thin-ply hybrid panels have percent 0-degree ply thickness values that are approximately 44% and 20% higher than the standard-ply reference laminate for the 30 gsm and 70 gsm laminates, respectively. The respective 30 gsm and 70 gsm hybrid laminate strengths are approximately 48% and 14% higher than the reference standard-ply laminate. The 30 gsm hybrid laminate strength appears to follow the percent of 0-degree ply thickness ratio, while the 70 gsm hybrid laminate strength appears to follow the stiffness ratio. However, due to the crude nature of these normalizations, normalized strength for hybrid laminates are omitted from the figures as such a comparison may be misleading.

B. Unnotched Compression

Table 4 presents the unnotched compression specimen information and results. Figure 4 presents the normalized compression moduli, which are normalized using the comparable NCAMP results. The compression Young's moduli for the unidirectional thin-ply specimens (the "A" panel specimens) show excellent agreement with each other, within 1% in both the fiber and transverse directions. The thin-ply material moduli are within 2.2% of standard-ply material in the fiber direction and within 1% in the transverse direction. The cross-ply results (panel "B") provided in the table were used to calculate the fiber direction compression strength for the uniaxial specimens (panel "A") in the table per the backout factor method presented in Ref. [8]. Figure 6 presents the normalized failure strengths for unnotched compression. Failure strengths for the unidirectional thin-ply material (the "A" panel specimens) are within 3.5% for the fiber direction and within 8% for the transverse direction. Typically, the strength values are less than the standard-ply material, but this small reduction possibly results from the somewhat lower quality of the thin-ply material. Though not shown in the figure, but as seen in Table 4, specimens with quasi-isotropic lay-ups for thin-ply laminates (the "C" panel specimens) exhibited slightly lower laminate Young's modulus than the comparable standard-ply laminates. As seen in Figure 6, the quasi-isotropic thin-ply laminate unnotched compression strengths are approximately 28% and 30% higher than the standard-ply for the 30 gsm and 70 gsm material, respectively. Again, while unnotched properties are not typically design drivers for aircraft, this increase in unnotched strength would yield a weight savings of approximately 26% for the thin-ply material compared to the standard-ply if the compression strength were a driving requirement. The unnotched compression strengths for the hybrid laminates (the "E" panel specimens) are slightly higher than the comparable standard-ply laminate as seen in Table 4. Using the previously described two simplified methods of comparing these hybrid laminates, it is seen that the thin-ply hybrid panels have moduli that are approximately 33% and 17% higher than the standard-ply reference laminate for the 30 gsm and 70 gsm laminates, respectively. The percent increase in percent 0-degree ply thickness are the same as presented for unnotched tension. The respective 30 gsm and 70 gsm hybrid laminate strengths are approximately 17% and 11% higher than the reference standard-ply laminate. For compression, the thin-ply hybrid laminates would appear to not follow either ratio, and may even be poorer than the standard ply. Again, graphical comparisons for the hybrid laminates are omitted in the figures as such a comparison may be misleading.

C. Open-hole Tension

Table 5 presents open-hole tension specimen information and results. Figure 7 presents the normalized failure strengths for the open hole quasi-isotropic specimens (the “D” panel specimens), as well as the in-plane shear strength for the cross-ply specimens (the “B” panel specimens) that will be discussed in Section IV.E. For the open-hole tension quasi-isotropic layups, the equivalent moduli and open hole tension failure strengths for the thin-ply are nearly identical to the standard-ply, within 0.6%. Only the percent 0-degree plies approach can be applied to the open hole tension hybrid specimen results shown in the table because no moduli were measured during the testing. The ratio of strength to the reference NCAMP laminate in the table are over 130% and 50% for the 30 gsm and 70 gsm hybrid laminates, respectively. These strength percentages are significantly higher than the relative thickness percentages of percent 0-degree plies, but it is not clear that this comparison is the most appropriate. However, it does appear that the hybrid laminates have an improvement in notched tensile strength compared to the standard-ply hard laminates. This improvement in failure strength is significantly beyond what a simple extrapolation of the increase in 0-degree ply thickness percentages provides. In the case of the 70 gsm hard hybrid laminate, the result is a higher acceptable maximum 0-degree ply thickness percentage without laminate splitting. The 30 gsm hard laminate exhibited splitting at slightly below 40% of the maximum load, and thus the increase in strength shown in Table 5 for this case is misleading. Figure 8 compares typical hybrid hard laminates at approximately 73% of their maximum average load, where axial strain contours are overlaid on the digital image correlation (DIC) image next to the reference image. The splitting of the laminate for the 30 gsm hybrid is seen visually, but is clearly apparent in the DIC contours. Because of this splitting, additional investigation into the appropriate design guidelines for using thin-ply materials to suppress this splitting failure mode (e.g., the maximum thickness percentage of 0-degree plies that should be allowed in a hybrid laminate) are needed. Again, graphical comparisons for the hybrid laminates are omitted in the figures as such a comparison may be misleading. However, these preliminary open hole tension results suggest that weight savings for these hard laminates could be potentially large, and may manifest themselves in improved structural weight in regions that are sized by discrete source damage containing a notch.

D. Open-hole Compression

Open-hole compression specimen information and results are presented in Table 6. For the quasi-isotropic specimens (the “D” panel specimens), the equivalent moduli and failure strengths for the thin-ply are nearly identical to the standard-ply, with the exception of the 30 gsm hybrid which has a failure strength about 8% higher, as seen in Figure 7. For the hybrid laminate specimens, moduli were measured and the increase in modulus is 33% and 8% for the 30 gsm and 70 gsm hybrid laminates, respectively, when compared to the standard-ply reference. The respective 30 gsm and 70 gsm hybrid laminate strengths are approximately 12% and 14% higher than the reference standard-ply laminate. The strength increase for the 30 gsm hybrid laminate is less than either of the simplified comparison methods. This reduced increase in strength may be due to the lower quality of the 30 gsm prepreg. On the other hand, the 70 gsm laminate increase in strength is between the values predicted from the two simplified comparison methods. It appears that the hybrid laminates may have marginal improvement in the failure strength compared to the standard-ply hard laminate. Again, graphical comparisons for the hybrid laminates are omitted in the figures as such a comparison may be misleading. However, the proportional improvement in failure strength is less than the increase in 0-degree ply thickness percentages.

E. V-notched Rail Shear

V-notched rail shear specimen information and results are presented in Table 7. The shear moduli for the 30 gsm and 70 gsm specimens (the “B” panel specimens) are 0.707 and 0.718 Msi, respectively, and are approximately 4% and 6% higher than the standard-ply reference as seen in Figure 4. Maximum strengths for the 30 gsm and 70 gsm specimens are 28.29 and 27.62 ksi, respectively, however, no equivalent maximum strength was reported in Ref. [8]. Therefore, strengths at 5% strain are also reported in the table since strengths at 5% strain were reported in Ref. [8]. However, in the reference, this value was determined using ASTM D3518 rather than ASTM D7078 used herein. As seen in Figure 7, the shear strengths of the thin-ply cross-ply laminates are approximately 36% and 31% higher for the thin-ply laminates than the standard-ply laminate.

V. Conclusions

Limited characterization of thin-ply IM7/8552 material for use in aircraft structures has been carried out using a series of selected ASTM tests. Tests included UNT, UNC, VNRS, OHT, and OHC. Unidirectional, cross-ply, quasi-isotropic and hybrid hard laminates were included in the study, and were compared to NCAMP results for standard-ply laminates. For compared results, including moduli and failure strengths, the thin-ply specimens exhibited similar or superior performance, with the exception of the fiber-direction tension Young's modulus that was less than 8% lower. This lower modulus may be the result of higher resin content and less consistent prepreg quality due to the thin-ply material not yet being a production material. Improvements in strength for laminates containing thin-ply material were seen for unidirectional laminates under unnotched tension, quasi-isotropic laminates under unnotched tension and compression, and hard laminates under open hole tension. While the 70 gsm hard laminate appears to have suppressed the splitting failure mode under open hole tension, additional investigation is required to determine appropriate design guidelines for hard hybrid laminates subjected to open hole tension loading to prevent splitting of the laminate. Additionally, the observed open hole tension performance improvements possible with hybrid thin-ply hard laminates may have benefits for improved structural weight in aircraft, such as in areas sized by discrete source damage requirements.

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Table 1. Fabricated panel information.

Panel ID	Type	Lay-up*	Size (in.)**
A-30gsm	Unidirectional	$[0]_{64}$	18 x 11
A-70gsm		$[0]_{32}$	18 x 11
B-30gsm	Cross-ply	$[0/90]_{16s}$	11 x 9
B-70gsm		$[0/90]_{8s}$	11 x 9
C-30gsm	Quasi-isotropic	$[45/0/-45/90]_{8s}$	12.25 x 10.25
C-70gsm		$[45/0/-45/90]_{4s}$	12.25 x 10.25
D-30gsm		$[45/0/-45/90]_{8s}$	13 x 18.5
D-70gsm		$[45/0/-45/90]_{4s}$	13 x 18.5
E-30gsm-hybrid	Hybrid	$[45t/0/-45t/0/45t/0/-45t/90/45t/0/-45t/0/45t/0/-45t]_{s}$	12.25 x 10.25
E-70gsm-hybrid		$[45t/0/-45t/0/45t/0/-45t/90/45t/0/-45t/0/45t/0/-45t]_{s}$	12.25 x 10.25
F-30gsm-hybrid		$[45t/0/-45t/0/45t/0/-45t/90/45t/0/-45t/0/45t/0/-45t]_{s}$	13 x 18.5
F-70gsm-hybrid		$[45t/0/-45t/0/45t/0/-45t/90/45t/0/-45t/0/45t/0/-45t]_{s}$	13 x 18.5

* "t" in hybrid panel lay-up designates the thin-ply lamina.

**First dimension in the panel size is aligned with the 0-degree direction.

Table 2. Test specimen types and testing summary.

30 gsm Specimen Type ID	70 gsm Specimen Type ID	Test Standard	Replicates
A-30gsm-UNT-0°	A-70gsm-UNT-0°	ASTM D3039	5
A-30gsm-UNT-90°	A-70gsm-UNT-90°	ASTM D3039	5
A-30gsm-UNC-0°	A-70gsm-UNC-0°	ASTM D6641	6
A-30gsm-UNC-90°	A-70gsm-UNC-90°	ASTM D6641	6
B-30gsm-UNC-0°	B-70gsm-UNC-0°	ASTM D6641	6
B-30gsm-VNRS	B-70gsm-VNRS	ASTM D7078	6
C-30gsm-UNT-0°	C-70gsm-UNT-0°	ASTM D3039	5
C-30gsm-UNC-0°	C-70gsm-UNC-0°	ASTM D6641	6
D-30gsm-OHT-0°	D-70gsm-OHT-0°	ASTM D5766	5
D-30gsm-OHC-0°	D-70gsm-OHC-0°	ASTM D6484	5
E-30gsm-hybrid-UNT-0°	E-70gsm-hybrid-UNT-0°	ASTM D3039	5
E-30gsm-hybrid-UNC-0°	E-70gsm-hybrid-UNC-0°	ASTM D6641	6
F-30gsm-hybrid-OHT-0°	F-70gsm-hybrid-OHT-0°	ASTM D5766	5
F-30gsm-hybrid-OHC-0°	F-70gsm-hybrid-OHC-0°	ASTM D6484	5

Table 3. Unnotched tension results. (Blank cells indicate no data available.)

Lay-up Type	Specimen Type	# Plies*	t_{lam} (in.)	t_{ply} (in.)	E** (Msi)	ν	Failure Strength (ksi)	Failure Strain (με)
Uni-directional	A-30gsm-UNT-0°	64	0.078	0.0012	21.29	0.349	386.1	16436
	A-70gsm-UNT-0°	32	0.092	0.0029	21.22	0.347	362.0	15499
	NCAMP-0°	6	0.043	0.0072	22.99	0.316	362.7	
	A-30gsm-UNT-90°	64	0.077	0.0012	1.49	0.0263	10.22	7185
	A-70gsm-UNT-90°	32	0.09	0.0028	1.42	0.0227	11.58	8654
	NCAMP-90°	11	0.079	0.0072	1.3		9.29	
Quasi-isotropic	C-30gsm-UNT-0°	64	0.079	0.0012	8.22	0.306	137.9	16522
	C-70gsm-UNT-0°	32	0.089	0.0028	8.12	0.310	135.2	16202
	NCAMP-0°	16	0.115	0.0072	8.39		104.7	
Hybrid	E-30gsm-hybrid-UNT-0°	[72/16/12]	0.121	0.1203	17.13	0.263	259.3	14140
	E-70gsm-hybrid-UNT-0°	[60/30/10]	0.146	0.146	14.98	0.396	201.5	12768
	NCAMP-0°	[50/40/10]	0.144		13.15		175.6	

*For hybrid type, ply percentages given by [0/±45/90] are shown

**E calculated using strains in the range 1000-3000 με

Table 4. Unnotched compression results. (Blank cells indicate no data available.)

Lay-up Type	Specimen Type	# Plies*	t_{lam} (in.)	t_{ply} (in.)	E** (Msi)	ν	Failure Strength (ksi)	Failure Strain (με)
Uni-directional	A-30gsm-UNC-0°§	64	0.078	0.0012	19.70	0.368	244.1	7840
	A-70gsm-UNC-0°§	32	0.091	0.0028	19.50	0.367	240.2	7765
	NCAMP-0°§	14	0.101	0.0072	20.04	0.356	248.9	
	A-30gsm-UNC-90°	64	0.078	0.0012	1.39	0.027	38.22	
	A-70gsm-UNC-90°	32	0.091	0.0028	1.40	0.028	41.84	
	NCAMP-90°	14	0.101		1.41	0.024	41.44	
Cross-ply	B-30gsm-UNC-0°	64	0.078	0.0012	11.00	0.048	130.5	14916
	B-70gsm-UNC-0°	32	0.091	0.0028	10.64	0.048	128.6	13020
Quasi-isotropic	C-30gsm-UNC-0°	64	0.079	0.0012	7.76	0.329	118.1	20125
	C-70gsm-UNC-0°	32	0.085	0.0026	7.79	0.306	114.1	20007
	NCAMP°	16	0.115	0.0072	7.86	0.334	87.05	
Hybrid	E-30gsm-hybrid-UNC-0°	[72/16/12]	0.121	0.12	15.86	0.273	141.7	9622
	E-70gsm-hybrid-UNC-0°	[60/30/10]	0.146	0.146	13.95	0.397	134.2	10569
	NCAMP-0°	[50/40/10]	0.144		11.9		120.8	

*For hybrid type, ply percentages given for [0/±45/90]

**E calculated using strains in the range 1000-3000 με

§Failure strength calculated using cross-ply data and backout factor method presented in Ref.8

Table 5. Open hole tension results. (Blank cells indicate no data available.)

Lay-up Type	Specimen Type	# Plies*	t_{lam} (in.)	t_{ply} (in.)	E** (Msi)	ν	Failure Strength (ksi)	Failure Strain (με)
Quasi-isotropic	D-30gsm-OHT-0	64	0.0792	0.0012	8.44	0.349	58.67	
	D-70gsm-OHT-0	32	0.0912	0.0028	8.43	0.0263	58.82	
	NCAMP-0 (Ref. 8)	16	0.115	0.0072	8.39	0.347	59.00	
Hybrid	F-30gsm-hybrid-OHT-0	[72/16/12]	0.1225			0.0227	202.65	
	F-70gsm-hybrid-OHT-0	[60/30/10]	0.1490			0.316	131.03	
	NCAMP-0 (Ref. 8)	[50/40/10]	0.1440		13.15		86.59	

*For hybrid type, ply percentages given for [0/±45/90]

**E calculated using strains in the range 1000-3000 με

Table 6. Open hole compression results. (Blank cells indicate no data available.)

Lay-up Type	Specimen Type	# Plies*	t_{lam} (in.)	t_{ply} (in.)	E** (Msi)	ν	Failure Strength (ksi)	Failure Strain (με)
Quasi-isotropic	D-30gsm-OHC-0°	64	0.080	0.0012	8.40		52.85	
	D-70gsm-OHC-0°	32	0.092	0.0029	7.76		48.55	
	NCAMP-0 (Ref. 8)	24	0.173	0.0072			49.08	
Hybrid	F-30gsm-hybrid-OHC-0°	[72/16/12]	0.123	N/A	17.44		71.12	
	F-70gsm-hybrid-OHC-0°	[60/30/10]	0.149	N/A	14.23		71.94	
	NCAMP-0 (Ref. 8)	[50/40/10]	0.144	0.0072			63.24	

*For hybrid type, ply percentages given for [0/±45/90]

**E calculated using strains in the range 1000-3000 με

Table 7. V-notch rail sheer results. (Blank cells indicate no data available.)

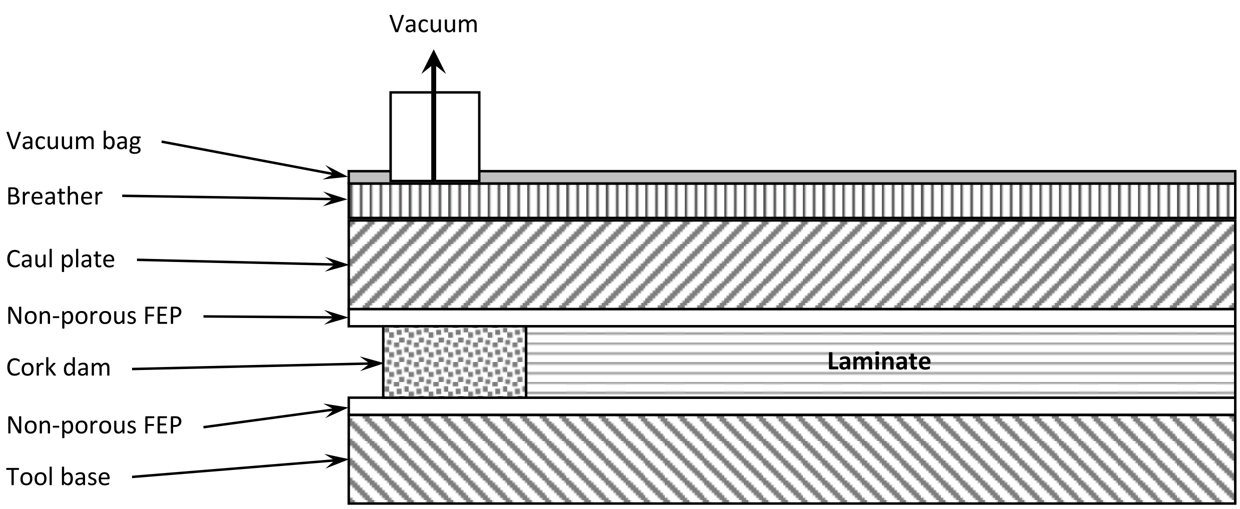
Lay-up Type	Specimen Type	# Plies	t_{lam} (in.)	t_{ply} (in.)	G* (Msi)	ν	Failure Strength @5% Strain (ksi)	Failure Strength (ksi)
Cross-ply	B-30gsm-VNRS	64	0.077	0.0012	0.707		14.46	28.29
	B-70gsm-VNRS	32	0.089	0.0028	0.718		15.18	27.62
	NCAMP (Ref.8)**	12	0.086	.0072	0.680		13.22	

*G calculated using strains in the range 2000-6000 με

**NCAMP value using $[45/-45]_{3s}$ specimens and ASTM D3518

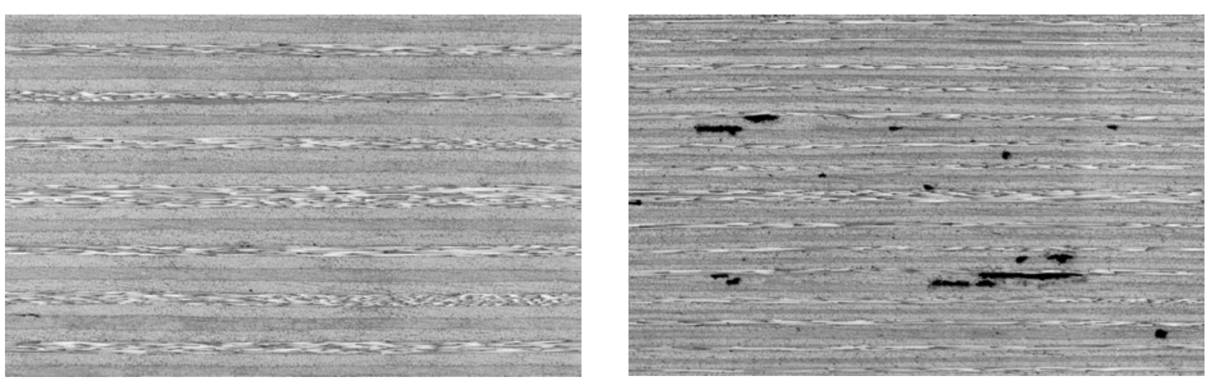
a) 190-gsm b) 70-gsm c) 30-gsm

Figure 1. Prepreg IM7/8552 material in 190 gsm, 70 gsm and 30 gsm areal weights.



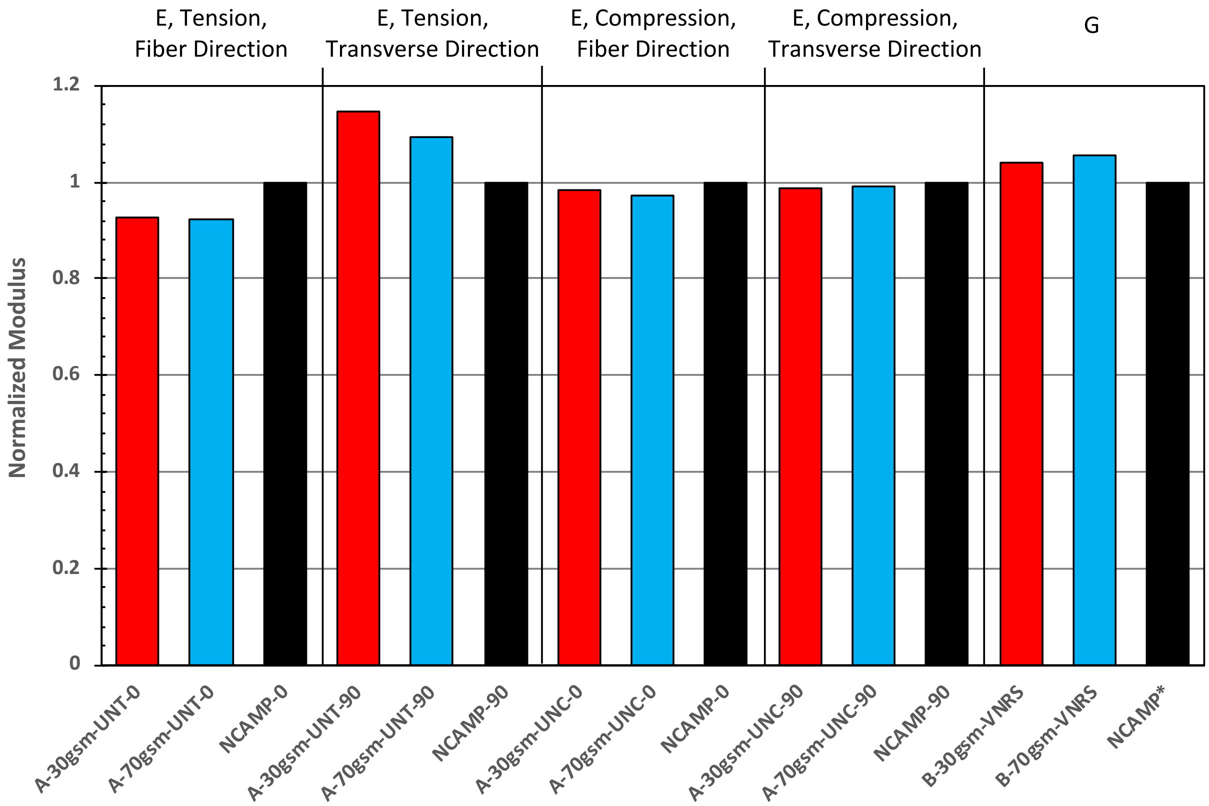
(FEP = Fluorinated Ethylene Propylene)

Figure 2. Bagging configuration.



a) 70-gsm material (32 plies) b) 30-gsm material (64 plies)

Figure 3. Representative micrographs for quasi-isotropic thin-ply laminates.



*NCAMP value using [45/-45]$_{3s}$ specimens and ASTM D3518

Figure 4. Comparison of normalized moduli, normalized on NCAMP[8] values.

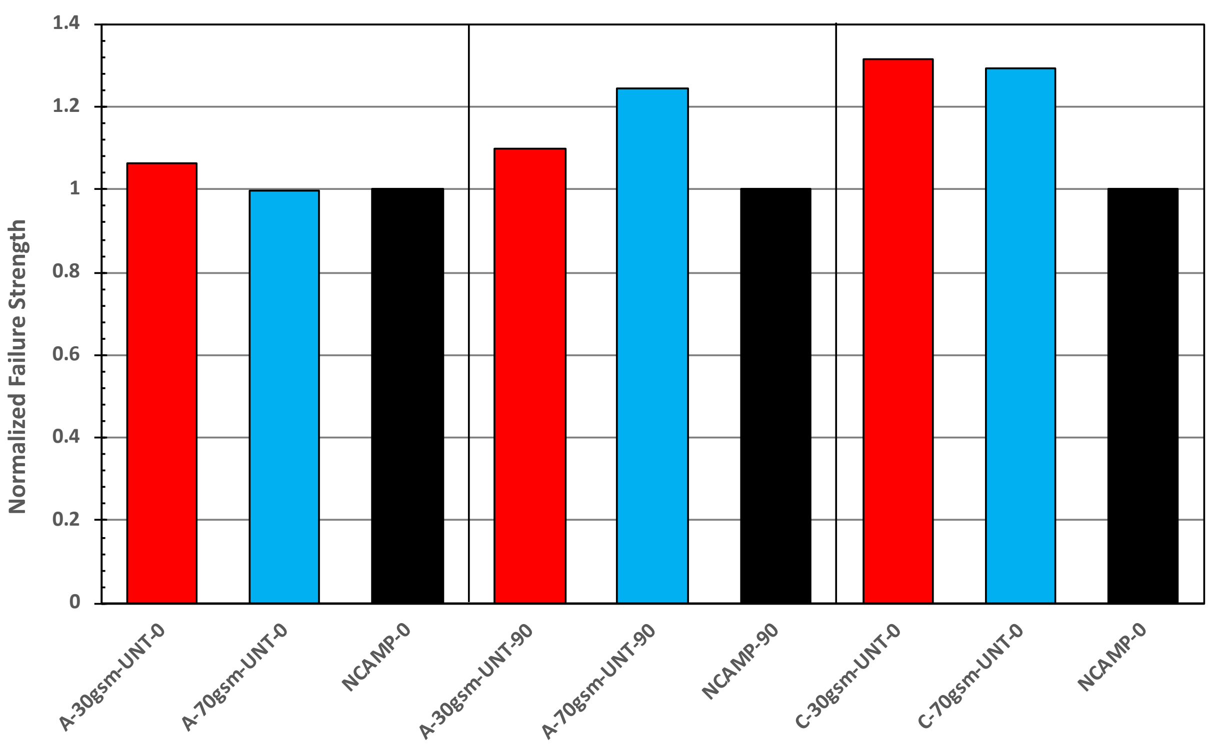


Figure 5. Comparison of normalized unnotched tension strengths, normalized on NCAMP[8] values.

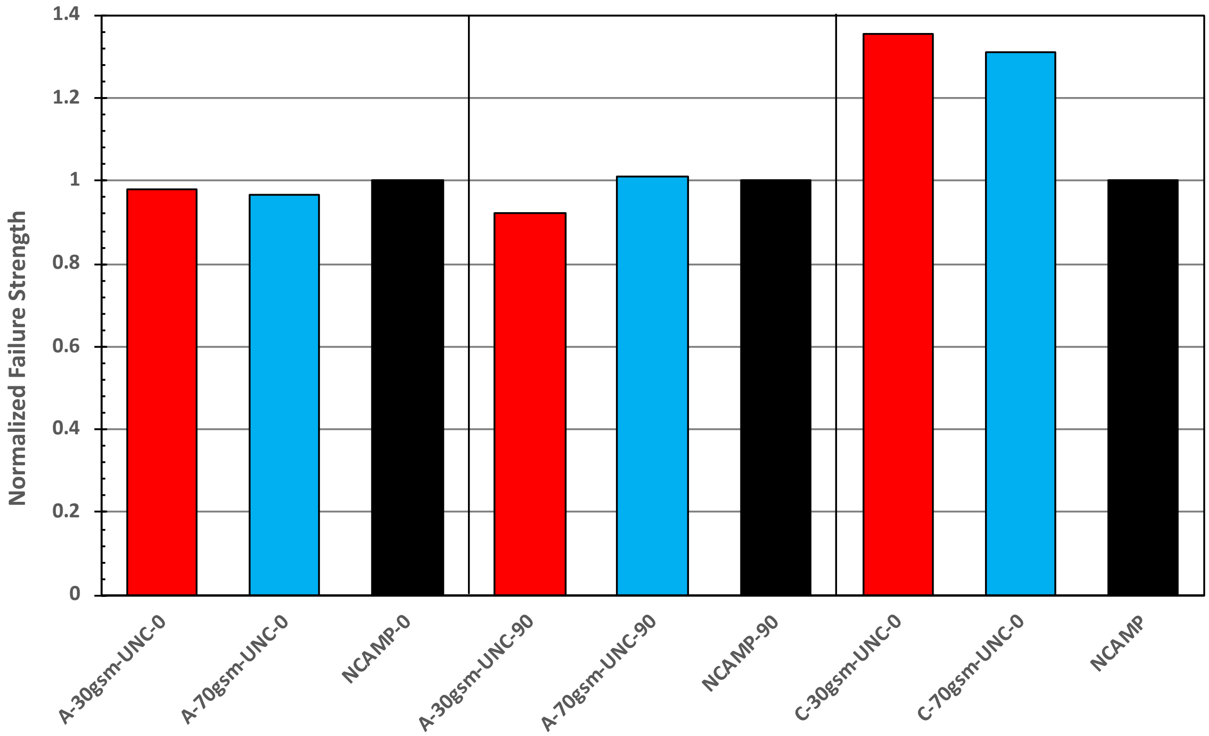
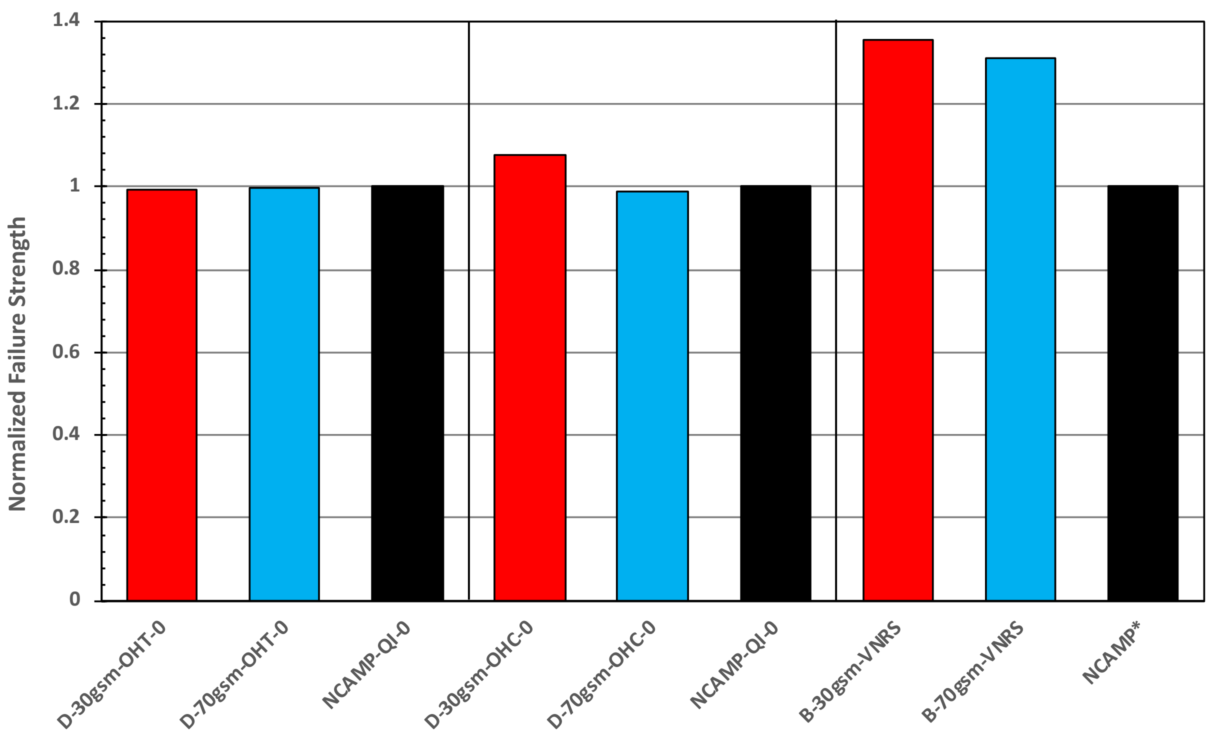
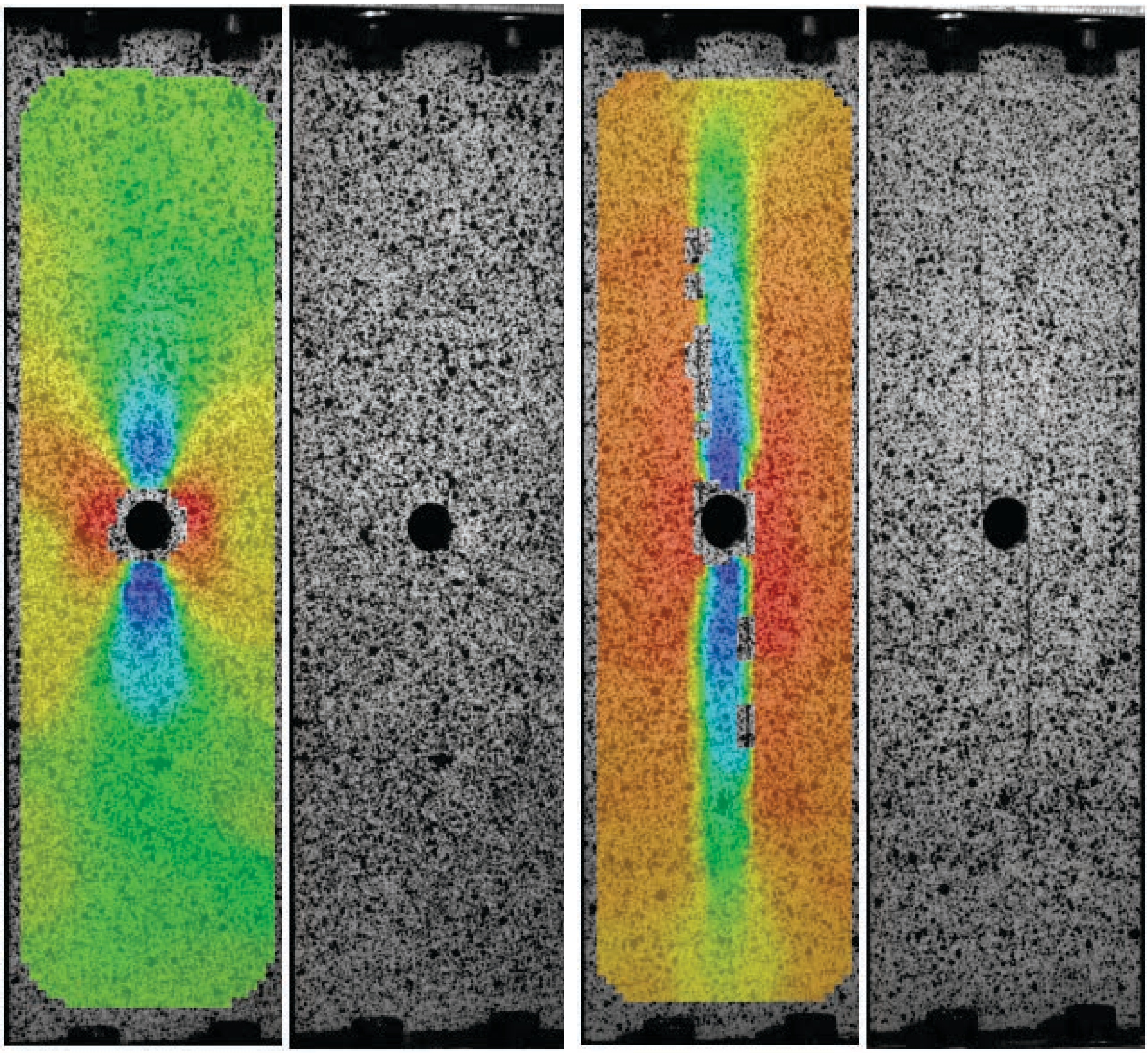


Figure 6. Comparison of normalized unnotched compression strengths, normalized on NCAMP[8] values.



*NCAMP value using $[45/-45]_{3s}$ specimens and ASTM D3518

Figure 7. Comparison of normalized open hole failure strengths and 5% strain shear strengths, normalized on NCAMP[8] values.



a) 70-gsm material b) 30-gsm material

Figure 8. Hard laminate comparison of typical OHT hybrid specimens showing no splitting in 70 gsm laminate and splitting of 30 gsm laminate at approximately 73% of maximum average load.