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Effects of Contour Cuts on Shear Properties of Ductile Foam Cores

by

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Abstract

Ductile foam cores have been more prominent in the marine industry due to increased energy absorption and higher strain to failure properties. As a result of the curvature and complexity of marine applications, these ductile cores are cut and scored. This study evaluates the effect of contour cuts on shear properties of common closed-cell ductile foam cores. Sandwich laminates constructed with polyvinyl chloride (PVC) and styrene acrylonitrile (SAN) foam core, which consisted of typical contour cuts, were examined in this study. The facings of the sandwich specimens were composed of E-glass reinforcement in a vinyl ester matrix. The panels were subjected to a 4-point beam test in accordance with ASTM C393 and the ASTM C273 standard shear test, to determine the shear properties.

Introduction

Ductile foam cores have become more prominent in the marine industry due to increased energy absorption and higher strain to failure properties. In areas with high slamming loads, such as hull bottoms, the shear properties of the foam core become critical. A sandwich construction can be designed to either absorb the energy with brute strength or it can be designed so that it will give with the load. In the latter scenario, the core can elongate up to 60% under the load, increasing the energy absorption capacity. This theory assumes that the core is homogenous and continuous, but in most cases the foam core is cut and scored to fit the curvature and complexity of marine vessels. In new manufacturing processes, such as infusion, these cuts are filled with a relatively brittle resin compared to the foam core. The purpose of this study was to investigate the effects of contour cuts on shear properties of ductile foam cores.

In this study, two ductile foam cores were examined, a cross-linked polyvinyl chloride (PVC) foam core and a styrene acrylonitrile (SAN) foam core. Both cores have high toughness and ductility compared to other more brittle foams. The shear properties for each foam core were evaluated with various contour cuts. These cuts were filled by a vinyl ester resin during the infusion process. The shear properties were determined with a standard shear test where the sandwich construction is loaded in shear, parallel to the plane of the facings, as well as a 4-point flexural sandwich test.

Description of Ductile Foam Cores

The ductile foam cores used in this study were a cross-linked polyvinyl chloride (PVC) foam and a styrene acrylonitrile (SAN) foam. Both foams are considered closed-celled. The PVC core material has a nominal density of 6.3lb/ft^3, while the SAN core material has a nominal density of 7.3 lb/ft^3. The shear strength, shear modulus, and shear strain; supplied by the supplier; is listed below for both ductile cores in Table 1. [1,2]

Both the PVC and SAN foam cores were cut and scored to find the effects on the shear properties. In this study, three different contour cuts were examined, along with a baseline. The baseline for both the PVC and SAN foam cores was a plain, perforated core (PP). The PP foam core has 1/8” (3.2 mm) holes through the thickness on the corners of a 4”x 4” (102 mm x 102 mm) square with one hole in the middle. Figure 1 is a representation of the PP foam core.

After a baseline was established, the first type of contour cut that was investigated was a grid-scored (GS) core (Figure 2 and 3). This type of core is cut in both the longitudinal and transverse direction. The cuts go approximately through the entire thickness, which creates small squares of foam. The squares, which measure approximately 1.18 in x 1.18 in (30 mm x 30 mm), are held on by a woven fiberglass scrim. Due to different manufacturing methods, the GS contour cuts for the PVC foam were slightly larger (0.05 in, 1.3 mm) than the SAN foam (0.02 in, 0.5 mm).

A double contoured or double cut (DC) core was also studied for both the PVC and SAN foam material. This material has both longitudinal and transverse cuts that run approximately 60% through the thickness. The cuts are offset and produce a small perforation at the intersections. The cuts are spaced approximately 1.18 in (30 mm) apart. Figure 4 is a schematic of a double contoured foam core.

Another contour cut that was examined was a triple cut (TC). TC foam core is similar to DC except on one side, the material is cut three times in one direction instead of only once (Figure 5). The spacing between each triple cut is approximately 0.3 in (7.5 mm). Since the triple cut (TC) is orthotropic, it was tested in both the longitudinal (TC-L) and transverse (TC-T) directions.

The PVC foam core was not tested with the TC contour cut because it is not available as a standard product from the supplier.

The densities of the contour cut cores were measured in order to obtain normalizing factors. The test data was normalized to the nominal density of each specific core. Table 2 lists the measured densities of each type of core that was tested.

Experimental Procedure

The experimental procedure used in this study consisted of panel fabrication, laminate shear testing using the ASTM standard C273, and a flatwise 4-point beam test according to ASTM C393.

Panel Fabrication

The test specimens were cut from PVC and SAN cored sandwich panels, which were fabricated using the process of vacuum infusion. This process was chosen for this study due to its repeatability, its ability to produce an ideal resin to glass ratio (60% reinforcement by weight), and its ability to fill the contour cuts with resin. Each type of core, with the various contour cuts, were infused with two knitted fiber plies, composed of 25 oz/yd^2 (850 g/m^2) 0/±45/90 E-glass reinforcement, while a vinyl ester resin was used as the matrix. After the panels were infused, they were post cured for at least 4 hours at 165°F (74°C). Once the sandwich panels returned to room temperature, the test specimens were cut to size.

ASTM C273

ASTM Method C273, "Standard Test Method for Shear Properties of Sandwich Core Materials," is a test in which the foam cored laminate is bonded to two rigid test blocks. In this study, an epoxy adhesive was used to bond the 12.5"x 3" (318 mm x 76 mm) samples to the steel test blocks. Once the samples were bonded to the blocks, they were loaded into the test fixture. The samples were tested, at room temperature, in a tensile shear at a speed of 0.06 in/min (1.5 mm/min).[4] Figure 6 shows a picture of the test set-up.

ASTM C393

The test method ASTM C393, "Standard Test Method for Flexural Properties of Sandwich Constructions" was used to perform the 4-point flexural tests on the PVC and SAN sandwich laminates with the various contour cuts. A set-up of the test can be seen in Figure 7. The specimens measured 3"x 14" (76mm x 356mm) in size and were tested in a quarter span configuration. The support span was 12" (305mm) while the loading span was set to 6" (152mm). The tests were performed at a crosshead speed of 0.10 in/min (2.54 mm/min). [5]

Test Results and Discussion

Since the measured densities differed from the published nominal densities, the data was normalized to the specific nominal density of each core type. Also, due to a significant difference in nominal density between the PVC and SAN foam cores in this study, the two were not compared against each other but rather the contour cuts were compared to the baseline of the specific foam core.

ASTM C273

The shear properties for both PVC and SAN sandwich constructions were tested in shear using ASTM method C273. The complete sandwich laminate was tested in a tensile shear. The shear strength, shear modulus, and shear strain were measured. The plain, perforated (PP) core was used as the baseline in each case. Typical shear stress versus shear strain graphs are shown below in Figures 8 and 9 for the PVC and SAN foam core laminates. The average shear properties for both materials are listed in Table 3. The properties obtained were normalized to the nominal density of each foam core; PVC was normalized to 6.3 lb/ft^3 (100 kg/m^3) and SAN was normalized to 7.3 lb/ft^3 (116.5 kg/m^3).

The baseline for the PVC foam sandwich construction, PP, has an average shear strength, shear modulus, and shear strain of 239 psi (1.64 MPa), 4771 psi (32.9 MPa), and 32.7%, respectively. It can be noted that the load continues to increase even after yield, which is around 225 psi (1.6 MPa). The grid-scored (GS) PVC foam sandwich laminate increased the modulus by 165% and has a 36% increase in shear strength compared to the PP foam core sandwich. The shear strain, however, decreases to approximately 7%. The double cut (DC) PVC laminate, on the other hand, has approximately the same shear strength as the PP material. Despite this similarity, the shear strain decreases to 12.1% which is a 63% drop. The modulus, however, increases 50% compared to the PP sandwich laminate. Overall, the GS and DC contour cuts significantly increase the shear modulus of PVC foam core, but both contour cuts significantly reduce the shear strain.

Figure 9 shows the typical shear stress versus strain curves for each of the contour cuts that were tested for the SAN sandwich constructions. The SAN PP material was used as the baseline in order to compare the three contour cuts. Unlike the PVC PP laminate, the PP material continues to elongate after the yield point without increasing the load. The average shear modulus, shear strength, and strain for the SAN PP material was 6798 psi (46.9 MPa), 233 psi (1.61 MPa), and 46.6%, respectively. All three contour cuts behaved similarly; they increased in modulus and shear strength, and decreased in shear strain, compared to the SAN PP baseline. The

TC foam core tested with the triple cuts in the transverse direction (TC-T) and the SAN GS produced similar results, increasing the modulus by approximately 33%, increasing the shear strength by 17%, and decreasing the strain by 75%. The TC-L foam core, on the other hand, affected the shear properties more dramatically; the modulus increased to 12,477 psi (86.0 MPa), the shear strength increased to 308 psi (2.12 MPa), and the shear elongation decreased to 10.1%. The SAN DC foam core laminate had the lowest shear modulus and shear strength of the contour cut SAN specimens, yet had the highest shear strain at 13.7%. The shear strain for DC was still 70% lower than the SAN baseline. All three types of contour cuts affected the shear properties but the SAN TC-L produced the largest differences in shear properties compared to the baseline.

ASTM C393

PVC and SAN foam core sandwich laminates with various contour cuts were also tested using the ASTM C393 4-point flatwise beam method. The peak load, deflection at peak load, and deflection at 750 lbf (3300 N) were evaluated. The deflection at 750 lbf (3300 N) was chosen as a common load point below the yield for all specimens. This common point can compare the relative stiffness of each specimen. Due to various failure modes of the different contour cut samples, the core shear stress was not evaluated in this study. Table 4 lists the average results from the 4-point beam test. Typical normalized load versus deflection graphs are shown below in Figures 10 and 11. The PVC contour cut laminates were normalized to 6.3 lb/ft^3 (100 kg/m^3) and the SAN contour cut laminates were normalized to 7.3 lb/ft^3 (116.5 kg/m^3), respectively.

The normalized average peak load and deflection at peak load for the PVC PP material were 1421 lbf (6320 N) and 0.44 in (11.11 mm), respectively. The typical failure mode for the PP samples was a localized skin compression failure. Since the core did not shear, this was considered a premature failure. Both the PVC GS and DC samples had an average peak load that was higher than the PP material. PVC GS had a peak load of 1788 lbf (7954 N), while DC had a peak load of 1548 lbf (6887 N). The GS contour cut laminate failed at 0.33 in (8.33 mm) deflection and the DC failed at 0.47 in (11.86 mm) deflection. It can be concluded that the PVC GS sandwich construction had the highest stiffness, followed by the PVC DC laminate, which can be noted on Figure 10. At 750 lbf (3300 N), the GS material, which has the least amount of deflection at 0.117 in (2.96 mm) and the DC material had a deflection at 750 lbf (3300 N) of 0.124 in (3.16 mm).

From Figure 11, it can be noted that all of the SAN contour cuts laminates have a higher peak load and relative stiffness compared to the SAN baseline, PP. Similar to the PVC PP, the SAN PP material had a premature failure due to the skin breaking under the loading fixture. The TC-L and TC-T a showed similar stiffness, at 750 lbf (3300 N) the deflection was 0.09 in (2.29 mm). However, the TC-L had a higher peak load, 1841 lbf (8070 N), than the TC-T sandwich construction. The SAN GS and DC showed a similar behavior, a similar stiffness and peak load. The peak load of GS and DC was approximately 50% more than the SAN PP. The deflection at 750 lbf (3300 N) for GS and DC was 0.1 in (2.6 mm), compared to the 0.14 in (3.57 mm) of the baseline.

The results from the ASTM C393 4-point beam test correlate to the results from the ASTM C273 shear test. When comparing the PVC contour cuts in both tests, the GS contour cut changed the shear properties more dramatically than PVC DC contour cut. The SAN test results also correlate. The TC, tested with the triple cuts in the longitudinal direction, affected the shear properties more significantly than the other contour cuts, followed by TC-T, GS, and then DC.

Conclusions

Designing marine vessels with ductile foam cores that are cut and scored need special consideration. The contour cuts have a significant affect on the shear properties, which can be concluded from this study. For all of the SAN and PVC contour cuts, the strength and modulus or stiffness increased as the shear strain decreased. The sandwich construction became less ductile compared to the baseline (PP), and as a result, the toughness decreased. This leads to lower energy absorption and lower elongation before failure.

This increase in modulus and load, and a decrease in shear strain is due to the effect of the resin-filled contour cuts. The resin, which is less ductile than the foam core, creates stiff or brittle sections throughout the thickness of the foam. From the results of this study, it proved that the more resin throughout the foam, the more the shear properties will be affected. For example, the PVC GS laminate, which had cuts throughout the thickness, unlike the DC, had more resin throughout the thickness of the foam core, which resulted in a greater change in shear properties. Also, the columns of resin in the GS material connected the skins together. This in turn, created a shear web within the foam, which exaggerated the results. The TC material had the most number of contour cuts of the SAN foam core types and therefore, had the most amount of total resin in the core. The TC laminates affected the shear properties more drastically than DC and GS.

In high slamming areas, such as hull bottoms, the shear properties are critical. In theory, the ductile foam core will elongate and absorb the load. In reality, the shear properties are compromised due to cutting and scoring the foam in order to fit the contours and complexities of the marine vessel. The reduction in shear elongation, as a result of the contour cuts must be taken into consideration in the design phase. Designing with the homogeneous core material shear properties will result in an error; the toughness of the sandwich panel will be overestimated. The contour cuts in both the PVC and SAN ductile cores greatly affect the shear properties.

References

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2. SP Systems. "Core-Cell A-Foam Product Data Sheet." http://www.spsystems.com/solutions/soltions_pdfs/pdfs_productdatasheets/cores/Corecell_A_Foam.pdf , Dec. 20, 2005.

3. "Core-Cell Core Constructions." http://www.ctmat.de/corecell.htm, Jan. 17, 2006.

4. ASTM Standard C 273-00. "Standard Test Method for Shear Properties of Sandwich Core Materials."

5. ASTM Standard C 393-00. "Standard Test Method for Flexural Properties of Sandwich Constructions."

Table 1: Published Shear Properties

		PVC	SAN
Density	lb/ft^3 kg/m^3	6.3 100	7.3 116.5
Ultimate Shear Strength	psi MPa	232 1.6	176 1.2
Shear Modulus	psi MPa	5800 40	4930 34
Shear Strain	%	35	64

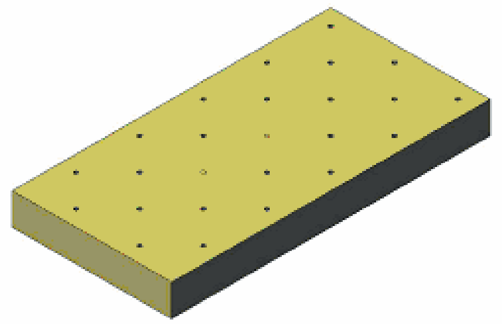

Figure 1: PP Foam Core

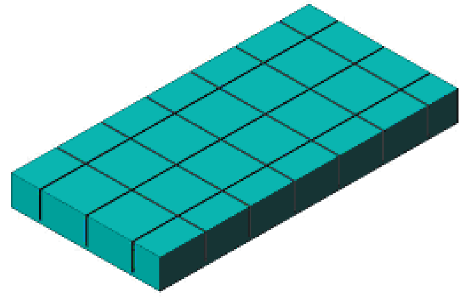

Figure 2: GS Foam Core (Topside)

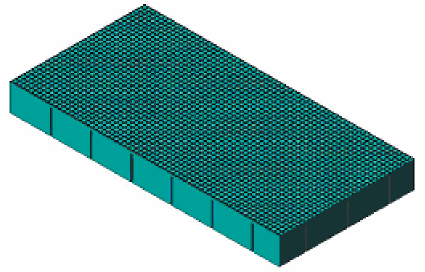

Figure 3: GS Foam Core (Scrim side)

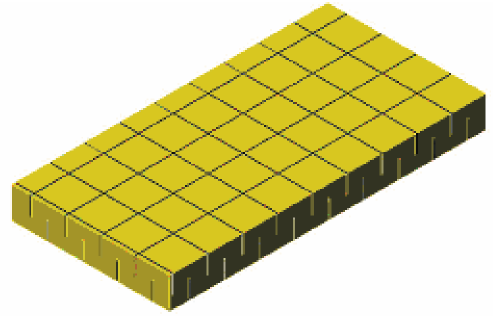

Figure 4: DC Foam Core

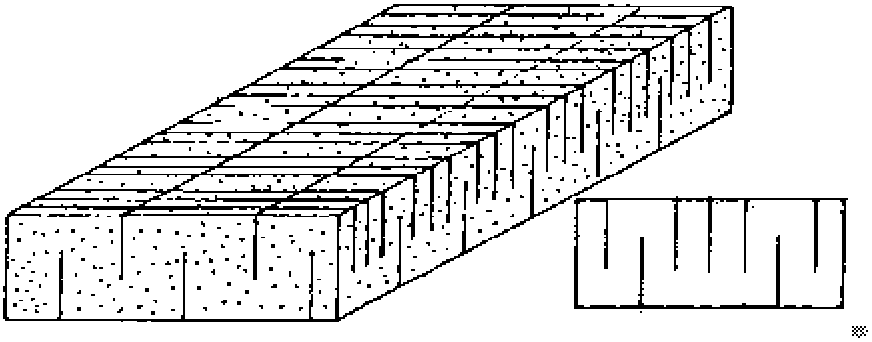

Figure 5: TC Foam Core [3]

Table 2: Measured Density from Specific Contour Cut Foam Core

Measured Density	lb/ft^3 (kg/m^3)
PVC PP	6.4 (103)
PVC GS	5.5 (88)
PVC DC	5.9 (94)
SAN PP	6.8 (109)
SAN GS	7.6 (122)
SAN DC	7.5 (120)
SAN TC-L	7.8 (124)
SAN TC-T	7.8 (124)

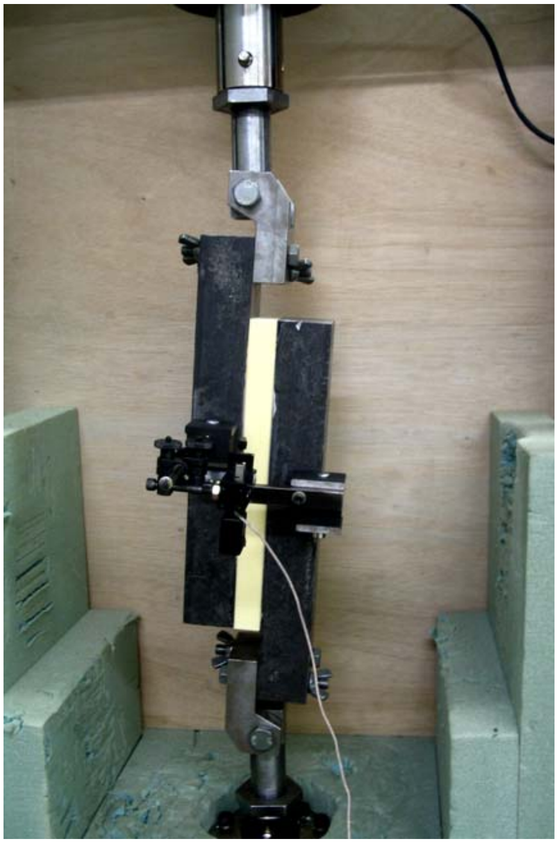

Figure 6: ASTM C273 Test Set-Up

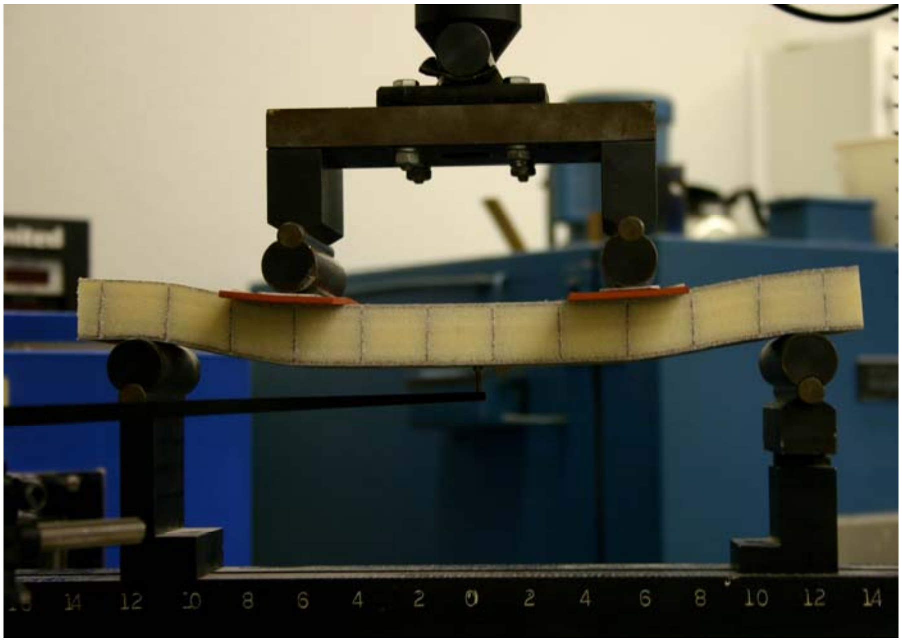

Figure 7: ASTM C393 Test Set-Up

Table 3: Normalized Average Shear Properties from ASTM C273

ASTM C273	Shear Strength psi (MPa)	Shear Modulus psi (MPa)	Shear Strain (%)
PVC PP	239 (1.64)	4771 (32.9)	32.7
PVC GS	325 (2.24)	12642 (87.2)	6.9
PVC DC	232 (1.60)	7203 (49.7)	12.1
SAN PP	233 (1.61)	6798 (46.9)	46.6
SAN GS	275 (1.90)	9258 (63.8)	11.7
SAN DC	250 (1.72)	8379 (57.8)	13.7
SAN TC-L	308 (2.12)	12477 (86.0)	10.1
SAN TC-T	272 (1.87)	8849 (61.0)	11.6

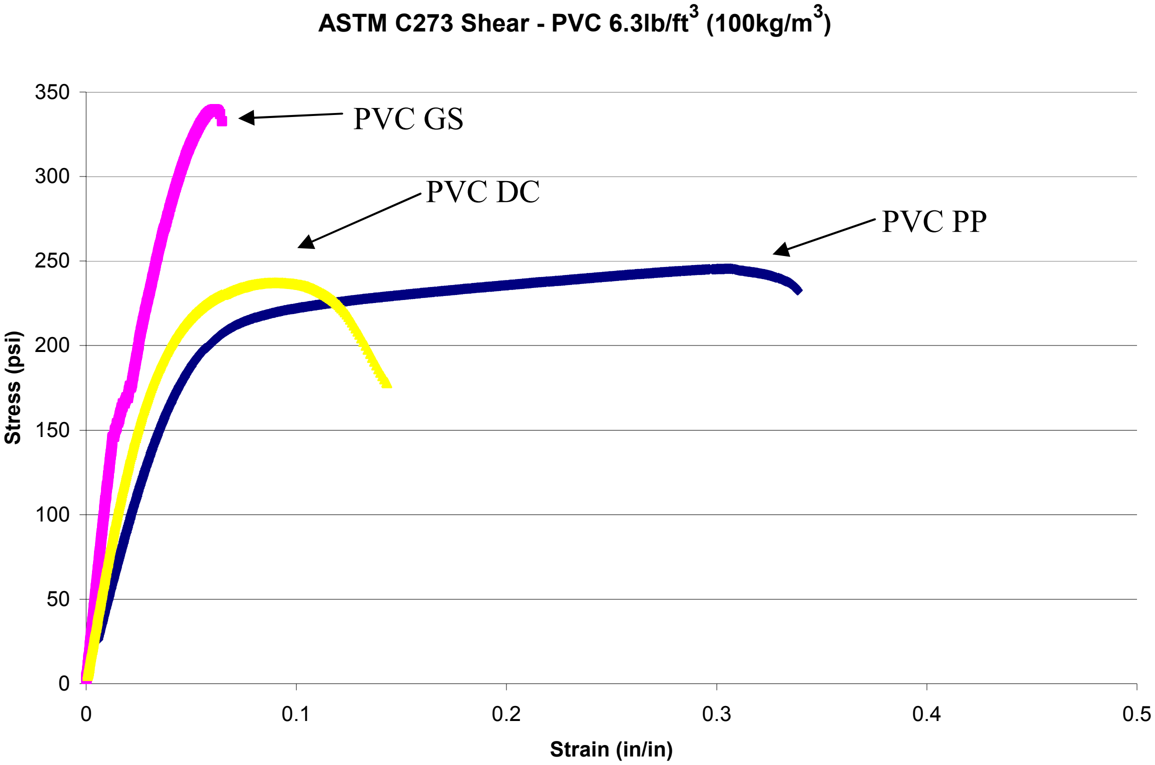

Figure 8: Typical Normalized Stress/Strain Curves for 6.3lb/ft^3 PVC

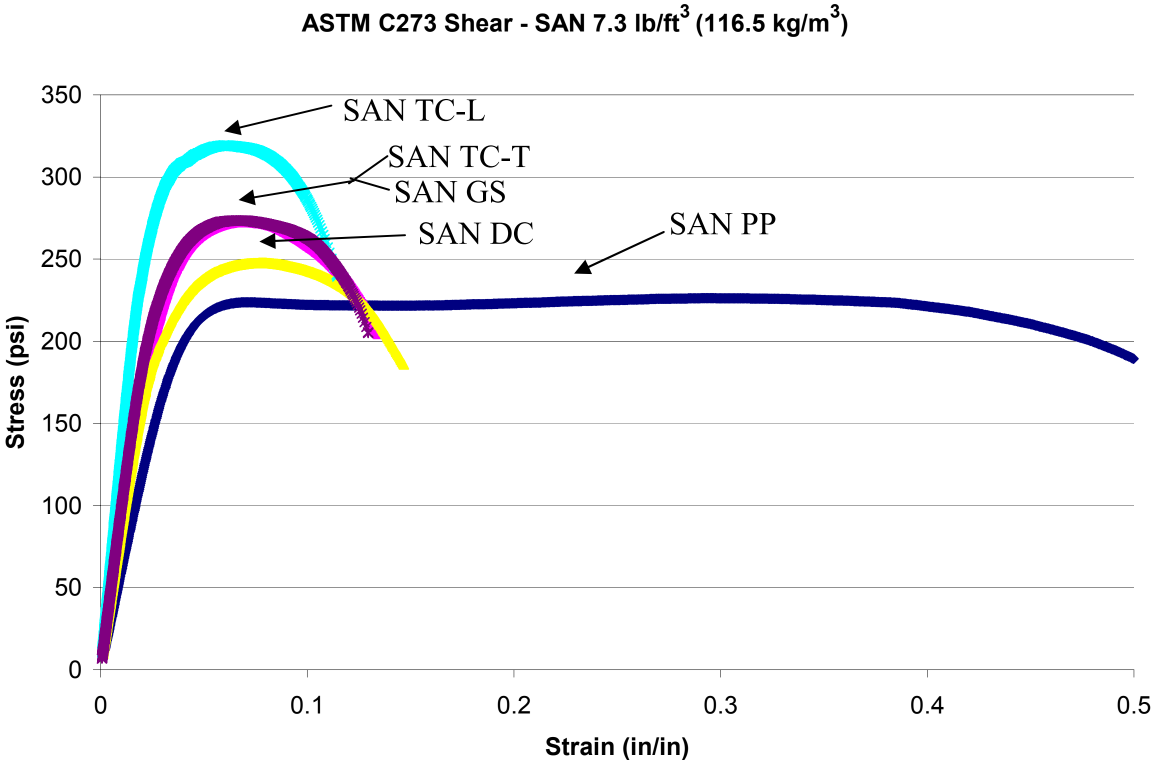

Figure 9: Typical Normalized Stress/Strain Curves for 7.3lb/ft^3 SAN

Table 4: Normalized ASTM C393 4-Point Beam Results

ASTM C393 4- Point Beam	Peak Load lbf (N)	Elongation @ Peak in (mm)	Elongation @ 750 lbf in (mm)	Failure Mode
PVC PP	1421 (6319)	0.44 (11.11)	0.131 (3.35)	Local Comp.
PVC GS	1788 (7954)	0.33 (8.33)	0.117 (2.96)	Shear
PVC DC	1548 (6887)	0.47 (11.86)	0.124 (3.16)	Shear
SAN PP	1112 (4945)	0.33 (8.48)	0.140 (3.57)	Local Comp.
SAN GS	1684 (7489)	0.39 (9.79)	0.100 (2.54)	Shear
SAN DC	1632 (7277)	0.42 (10.64)	0.106 (2.70)	Shear
SAN TC-L	1841 (8070)	0.35 (8.98)	0.090 (2.28)	Shear
SAN TC-T	1706 (7591)	0.36 (9.18)	0.091 (2.30)	Shear

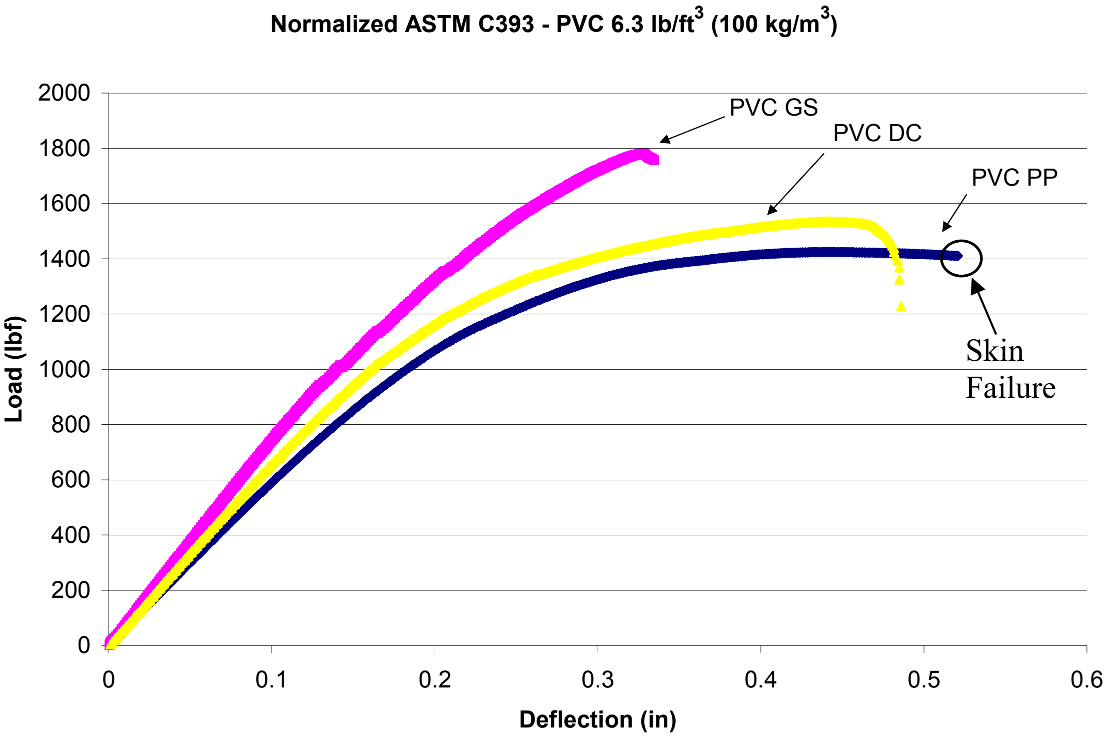

Figure 10 : Typical Normalized Load versus Deflection Curves for 6.3lb/ft^3 PVC

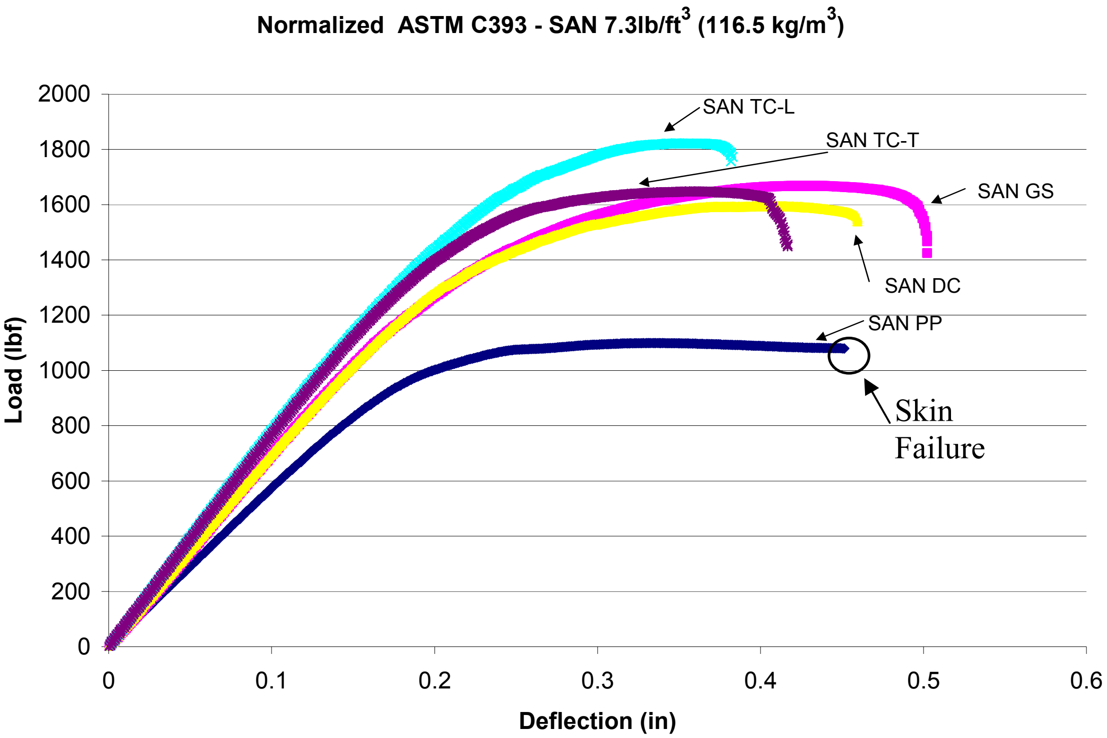

Figure 11: Normalized Load versus Deflection Curves for 7.3lb/ft^3 SAN

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