

DYNAMIC RESPONSE OF SANDWICH COMPOSITES

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ABSTRACT

Sandwich composites are being aggressively pursued as structural materials by various defense and commercial industries. These include navy, air force, army, automotive and sporting industries to name a few. In the context of structural load bearing members and absorbing dynamic loads, foam core sandwich composites offer unique advantages over traditional composites. The cellular construction of the foam materials not only provides lightweight capability but also a deformation mechanism that allows efficient absorption of energy. Of particular interest in this study is to investigate the behavior of the foam materials and their sandwiches under high strain rate (HSR) loading which are very much prevalent in their actual applications.

A systematic approach has been taken to study the response of PVC foam materials at strain rates ranging from quasi-static to around 2000 S^{-1} . First, room temperature response has been extracted for various density foams and determined their strain rate sensitivities and failure characteristics. Next, two microstructures in the construction of the core materials, namely linear and cross-linked foams were considered in the investigation. This study revealed that both the categories of the foam had direct dependence on temperatures well below the T_g of the base polymer. Consequently, the next phase of the investigation included HSR tests at elevated and sub-ambient temperatures. The study has revealed that at room temperature, the delamination at the sub-interface zone underneath the actual core-skin interface is the critical failure mode. This sub-interface is characterized by the separation of the dry and resin-soaked cells near the core-skin interface. Failure modes however changed as the test temperature changed to sub-ambient.

In another attempt to improve the mechanical properties of core materials, Part-A of liquid polyurethane foam has been infused with 3.0% by weight of TiO_2 nanoparticles and mixed with Part-B to fabricate nanophased foams. These foams were then used in a VARTM set up to manufacture sandwich composites. Both the sandwich and the foam materials were subjected to high strain loading and their responses were determined. A significant increase in strength was observed with the nanophased cores.

INTRODUCTION

Sandwich Composites

The concept of sandwich construction for ship structures and other marine applications is not entirely new - it has been an epoch-making project for the Swedish Navy since 1995 when it contracted the Karlskrona Shipyard for the construction of Visby class Corvette surface combatants. The era of mass scale ship building with sandwich constructions is just beginning. United States Navy and the Office of Naval Research (ONR) have also identified affordability of structures including sandwich structures as their focal points of research. Superior battlefield performance requires maneuverability, stealth capability and safety of the crews during any attack. These features are essential in Mine Counter Measure (MCM), Anti Submarine Warfare (ASW) and also in regular patrolling operations. A composite sandwich construction provides formidable

advantages over conventional metal structures such as low weight, high speed and low manufacturing costs of surface combatants. Sandwich structures when built with composite face sheets will also enhance the vessel's self defense capability by lowering the acoustic noise signature and by boosting the shock resistance. While sandwich constructions have such good attributes for navy applications, they offer almost similar amount of benefits in other areas as well, such as aerospace, automotive and sporting industries.

Structures in these applications are often subjected to high strain rates due to impact by hard objects, mine blast, projectile impact, collision, etc. Traditionally cellular or metallic foams are used as core materials in the sandwich construction to absorb energy under such impact events. Use of foam core for example, will require first hand knowledge of the effect of impact velocity and strain rate on the behavior of those materials. In order to improve

the dynamic performance of sandwich structures a through understanding of foam behavior to high strain rate loading is essential for tailoring and using these materials effectively in such applications. Very limited knowledge, however, exists on the behavior of such materials to high strain rate loading. Previous studies [1-6] have investigated the response of a sandwich specimen in compression at both low and high strain rates. Such studies show that the dynamic behavior of a sandwich is indeed a function of the properties of the core material. PVC foams are widely used as core materials in naval sandwich structures. The behavior of such foams at high strain rate loading has not yet been determined to the fullest extent. Most studies [7-9] cited in the literatures were conducted on polymeric materials including styro and polyurethane foams.

Nanophased Foams

For over half a century, polymer foams have been used to lighten, stiffen and strengthen their structure in various sectors including marine and aerospace applications. The PVC was the first foam material, which was formulated for a marine environment. This foam was created by Dr. Lindemann a German scientist in the late 1930's. Other foams based on chemical components have also been developed over the years. The polyurethane foam is popular for some of its moderate properties like good moisture resistance, high shear strength, excellent dampening, vibrational and oscillating environment tolerance. Recently researchers have investigated nano-composites containing polymer-nano-particle to improve their physical, mechanical and chemical properties. Nano-particles embedded in polymer matrix have attracted increasing interest because of the unique properties displayed by nano-particles. Due to nanometer size of these particles, their physicochemical characteristics differ significantly from those of molecular and bulk materials [10,11]. Nanoparticle-polymer nano-composites synergistically combine the properties of both the host polymer matrix and the discrete nano-particles there in. Such nano-composite materials are expected to have novel electrical and mechanical properties [12,13].

To our knowledge none have attempted to improve the properties of polyurethane foam using nano-particles as additives. In this investigation, polyurethane foam has been studied by infusing nanoparticles to observe their morphological, and mechanical characteristics under dynamic loading. TiO₂ nanoparticles have been dispersed into the liquid polyurethane foam by using ultra sound cavitation process. Modification of matrix material with nanoparticles is an efficient technique to improve the properties of composite materials for specific applications. It requires only a small percentage of nanoparticles (1.5 to 3%w) to be dispersed into the virgin materials to achieve maximum benefit [14].

EXPERIMENT

Materials & Fabrication

PVC Cores

Four closed-cell PVC foam cores were used as the

core material for the sandwich specimen. Three of the four cores are cross-linked foams of various densities, 75,130, and 260 kg/m³. The fourth core used in this study also had a density of 130 kg/m³ but a lighter degree of cross-linking, which will be referred to as linear. The foams were manufactured by DIAB and are labeled R75, H130, R260, and HD130 respectively. The foams were delivered in the form of 12.7 mm thick panels. Mechanical properties of the foams as determined by DIAB using standard test methods are listed in Table 1.

Table 1 Properties of PVC foam as specified by DIAB

Property	Unit	Grade			
		R75	H130	HD130	R260
Grade		R75	H130	HD130	R260
Density	kg/m ³	75	130	130	260
Compressive strength	MPa	1.1	2.5	2.1	6.6
Compressive modulus	MPa	38	175	140	283
Tensile strength	MPa	2.0	4.2	3.2	6.7
Shear strength	MPa	0.9	2.0	1.6	4.2
Shear modulus	MPa	29	52	32	105

Polyurethane Cores

A different type of foam materials made from polyurethane was introduced in this investigation with an aim to study the effect of nanoparticle infusion into the core materials. The particular reason to choose polyurethane was that it was available commercially in liquid state which facilitates mixing with nanoparticles. The manufacturing of sandwich composites was carried out in three steps; first was the dispersion of nanoparticles into liquid polyurethane, the second, casting of the foam (core materials) and the final, fabrication of sandwich panels. In addition, a number of sandwich panels were also made with neat polyurethane foam without having any nanoparticle infusion.

Dispersion of Nanoparticles into Liquid Polyurethane

The liquid foam used in this investigation is Polyisocyanurate. It has two parts, part A (Diphenylmethane Diisocyanate) and part B (Fluorocarbon blown Polyol). Part-A was selected for infusion of nanoparticles since it is less reactive than part-B. TiO₂ nanoparticles were first carefully measured along with Part-A to have a 3% loading by weight. The mixing was carried out in a Sonic Vibra Cell ultrasonic liquid processor (Ti-horn, 20 kHz, 100W/cm²) as shown in Fig. 1 for about 10 minutes at room temperature. At this time it seemed the nanoparticles were uniformly dispersed in Part-A. In order to avoid temperature rise during sonication, cooling was employed by submerging the mixing beaker in a mixture of ice and water. After infusion of nanoparticles, the modified Part-A was mixed with Part-B at a ratio of 49:51 using a mechanical stirrer at about 1500 RPM. The mixture was then cast in a steel rectangular mold. The mold was heated to about 65⁰C prior to pouring the mixture. After about 4-5 hours the cast foam was demolded and subsequently trimmed. In parallel, the neat polyurethane foam was also fabricated

for comparison. Both categories of sandwiches were then subjected to high strain rate loading and their performances were compared.



Figure 1: Ultrasound Mixing

Fabrication of Sandwich Panels

Sandwich panels were fabricated using PVC, nanophased polyurethane and neat polyurethane foams as core materials. Vacuum assisted resin transfer molding (VARTM) process was used for manufacturing the sandwich panels. VARTM allowed simultaneous infusion of top and bottom face sheets as shown in Fig. 2. Three layers of dry plain weave S2-glass fiber preforms were placed on a flat aluminum plate to form the bottom face sheet. The core was then placed above the bottom face sheet and then three layers of the same glass fabric were put on top to define the top face sheet. After stacking, the assembly was vacuum bagged, and infusion lines were installed. Before infusion, the system was debulked for several hours. Vinyl ester (Dow Derakane 411-350) resin manufactured by Dow Corning was used in the fabrication process. After completing infusion, the system was kept under vacuum until the panel was completely cured. The thickness of each face sheet was approximately 3.8mm, while the core thickness was 12.7mm.

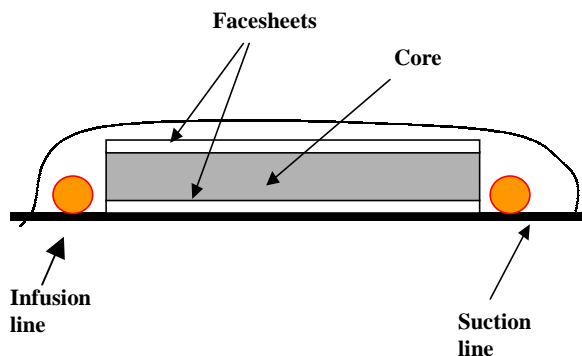


Figure 2: Schematic of VARTM process used for fabricating sandwich composites

Test Methods

PVC cores and sandwiches were subjected to quasi-static and HSR compressive loading in the thickness direction. Quasi-static compression tests were performed using an MTS servo-hydraulic testing machine. Compressive loads at strain rates of 300s^{-1} and above were conducted using a split Hopkinson pressure bar (SHPB) apparatus. A regular SHPB setup consists of three maraging steel bars: a striker, incident, and a transmission bar. Special challenges are presented when using a regular SHPB for sandwich composites or soft cores, such as, foams. When testing these types of material a very weak transmitted pulse is obtained due to the high impedance mismatch between the bar material and soft foam specimen, therefore accurate measures of strain signal are not possible. Lately, other researchers [15-19] have incorporated new techniques to study the response of low stiffness materials at high rates of compressive loading. These techniques include the use of low stiffness bars made from nylon and polycarbonate. In this study, a modified SHPB technique which consisted of an all polycarbonate system was used to evaluate the high strain rate response (Figure 3).



Figure 3: Modified SHPB apparatus and elevated temperature setup

HSR tests were performed at room and elevated temperatures. Specimens tested at elevated temperatures were first placed in a furnace and heated to the desired temperature. A temperature probe and thermocouples were used to monitor the temperature of the furnace and foam specimen (Figure 3). After heating the samples to desired temperature, they were immediately placed in the SHPB setup for testing. During this time frame, it was found that the samples lost 2-3 degrees in temperature before testing was completed. Therefore, specimens were heated correspondingly 3-4 degrees higher than the desired temperature to account for any loss of

temperature during the transportation of the specimen from the furnace to the SHPB apparatus for testing. Temperatures recorded in this study indicate the temperature of sample during the time of testing. Samples were tested at various strain rates, which were acquired by varying the beech pressure. Strain gages were mounted on both the incident and transmission bars. The voltage vs. time graph was obtained as output from the strain gages, and then converted to strain signals. The strain vs. time and stress vs. time are determined from the incident and transmission bar, respectively. The stress strain curves were then produced from the strain and stress time history by eliminating the time axis.

In order to achieve sub-ambient temperatures, specimens were first submerged in liquid nitrogen and sealed for 30 minutes as shown in Fig. 4. Afterwards, each specimen was removed from the liquid nitrogen (-196°C) and immediately placed in the SHPB for testing. Sandwich and foam specimens were subjected to compressive loading in the thickness direction for all tests.



Figure 4: Liquid Nitrogen Setup for Sub-ambient Tests

RESULTS AND DISCUSSION

A) Response of PVC Core Materials

The quasi-static compression behavior of the cross-linked PVC cores is shown in Figure 5. Three distinct phases can be identified from the stress-strain curves. Each core density portrayed an initial elastic region up to initial failure, followed by a stress plateau, then a region of densification. A similar compressive behavior was found by Gibson and Ashby [20] in a study on polyurethane foams. Each of the three phases correlates to a specific failure mechanism that the foam undergoes during compression. For closed-cell foams, the linear region is controlled by the stretching of the cell faces. The stress plateau is associated with the collapse of cells. When the cells have completely collapsed, the cell walls touch and further strain the solid itself, giving the final region of rapidly increasing stress.

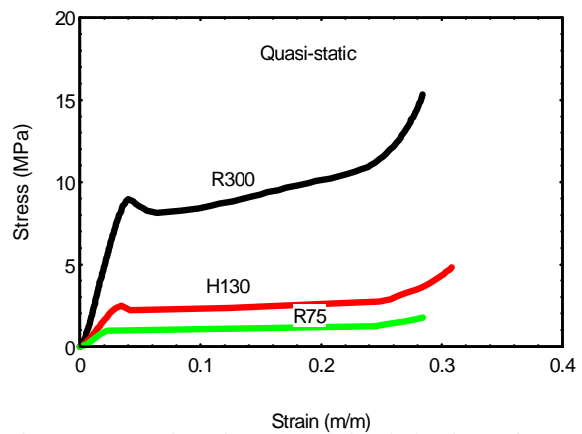


Figure 5. Quasi-static compressive behaviors of PVC foam cores at room temperature

The compressive response of the foams is related to its relative density, which is a ratio of the foam density to the density of the solid from which it is made. As the relative density increases the cell size decreases, which means more of the solid is contributing to the foam mechanical properties rather than the gas (usually air) within the cells. For this reason, as the density of the PVC foams increase, an increase of compressive strength is observed. A 73% increase in strength was observed when comparing R75 and H130, whereas, a 130% increase was achieved when comparing R75 and R300. A similar behavior was found by Brezny and Green [21] in a study regarding the effect of cell size on the mechanical behavior of cellular carbon foams. They observed that the strut strength of the carbon foams was not constant but rather increased with smaller cell sizes which caused the compressive strength to increase inversely with cell size. Also as density of the PVC foam increased, the rapid densification occurs at a smaller strain which leads to a shortening of the stress plateau. Increase in stiffness is also observed with increasing density.

The stress-strain curves for H130 foams at higher rates of strain are illustrated in Fig. 6. In general, a slight increase of strength was observed at higher rates of strain. This increase was moderate with this particular density (H130), however, it was more prominent with lower density (R 75), and almost insignificant with higher density (R300) foams. The stiffness of the foams was not much affected by the increasing strain rate, especially at the higher densities. The higher core density also achieved the highest failure stress for the entire range of densities. If the area under the stress-strain curves is considered to be a measure of the energy absorbed by the foam, then energy absorption increased proportionally with strain rate for all three cases (R75, H130 and R300). As shown in Fig. 6, a large amount of the energy absorption occurs through the collapse of the cells which is represented by the stress plateau; relatively very small amount of energy is absorbed in the linear regime. An increase in strain and an elongation of the plateau was also observed with increasing strain rate for each foam density. The elongation of the stress plateau indicates an increase of collapsed cells with strain rate, which can be seen in Fig. 7. Cell collapse and densification bands were

more pronounced in the lower density foams (R75 & H130). As the density increases to 300, a slight change in failure mode was observed. R300 specimen achieved a lesser degree of densification along with some shearing near the center of the specimen. The extent of damage increased as the strain rate increased.

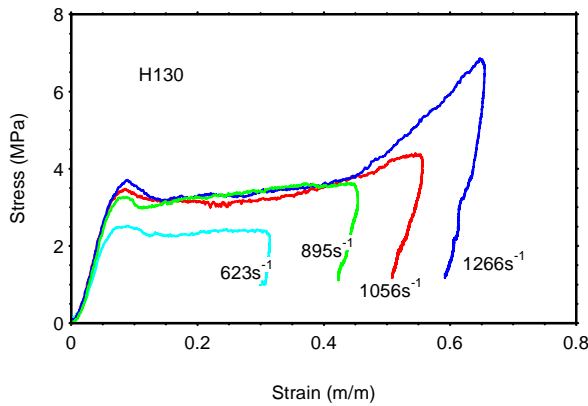


Figure 6. H130 stress-strain curve at various strain rates



Virgin 335s⁻¹ 731s⁻¹ 1093s⁻¹
(a)



Virgin 623s⁻¹ 895s⁻¹ 1056s⁻¹ 1266s⁻¹
(b)



Virgin 466s⁻¹ 755s⁻¹ 990s⁻¹ 1127s⁻¹
(c)

Figure 7. HSR compression of foam cores at various rates (a-c) R75, H130, and R300

Effects of Temperature

The effect of temperature on the high strain rate response of H130 foam is illustrated in Fig. 8. All the specimens within a specific category were tested at similar strain rates. Stress-strain curves are very similar to what has been seen earlier. Tests were also conducted at quasi-static loading, and it was observed that similar to quasi-static loading, as temperatures increased a decrease in strength occurred. Also foam stiffnesses reduced slightly as the temperature increased. The response of R75 and R300 was almost identical to that of H130,

except that at higher density the temperature effects both on strength and stiffness became more pronounced. This is reflected in the temperature sensitivity curves shown in Fig. 9. It is clearly seen that as the relative density increases, the sensitivity to temperature also increases. In case of higher density foam (R300, relative density, 0.208) degradation rate also seems to increase as one approaches to the T_g (85-95°C) of the solid polymer.

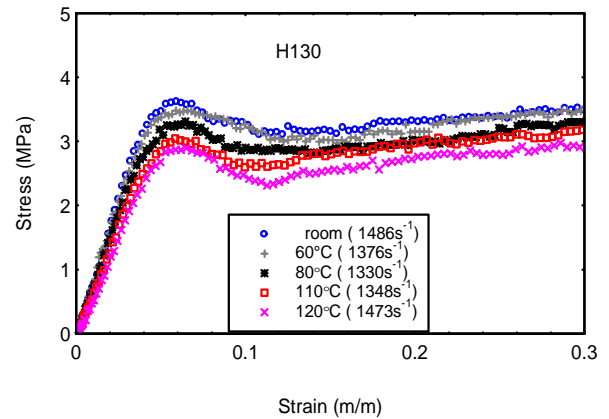


Figure 8. HSR response of H130 core at various temperatures

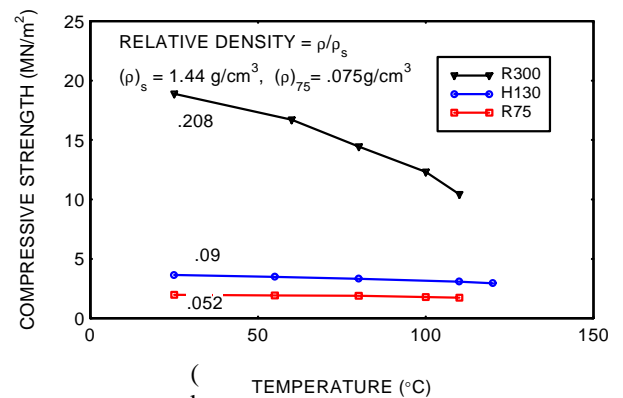


Figure 9. Temperature sensitivity of cores at HSR loading

Although a similar trend was obtained at quasi-static and HSR loading, differences can be seen in the strength of the foams. For instance, when comparing the strength degradation of the R75 specimen within a particular strain regime, Table 2, the strength decreased with increased temperature for both quasi-static and HSR, but the strength degradation was more pronounced in the quasi-static regime than at higher rates of loading. This behavior was observed in all densities. Table 3 shows the peak stress of R75 for a variety of temperatures at both quasi-static and a rate of 1400s⁻¹. When comparing the effect of strain rate at a specific temperature, the strength of the foams increased as one moves from quasi-static to higher rates. For example, the peak stress of the R75 specimen increased 48% at room temperature, and as temperature increases, this percentage increases to 129%. This phenomenon may be due to a combination of the presence of the gases within the closed cells at elevated temperatures, and the short time response during HSR

loading. The compressibility of a gas in a closed-cell depend on temperature, therefore as temperature increases the pressure within the cell increases, hence giving an additional restoring force to the foam. Although the overall strength of the foam is decreasing, the gases within the cell are contributing some strength during the short duration of the loads at HSR.

Temperature (° C)	Quasi-static Strength Degradation	HSR ~ (1400s ⁻¹) Strength Degradation
55-60	3.8%	0%
80	12.3%	3.6%
110	42.3%	12.2%

Table 2. Strength degradation at quasi-static and high rates of strain (R75)

Temperature (°C)	Quasi-static Peak Stress (MPa)	HSR (1400s ⁻¹) Peak Stress (MPa)	Strength Increase (%)
RT	1.30	1.93	48
55-60	1.25	1.93	54
80	1.14	1.86	63
110	0.75	1.72	129

Table 3. Temperature effects at quasi-static and high rates of strain (R75)

Effect of Microstructures

Several specimens H and HD category foams were subjected to quasi-static as well as high strain rate loading. As shown in Figure 10, three phases of failure, which are typical of foams can be identified. The quasi-static compressive strength of HD was approximately 30% lower than the H grade of the same density. The H and HD achieved a compressive strength of 2.75 MPa and 2.11 MPa which was well comparable to the compressive strength supplied by the manufacturer, and reported by Danielsson [22,23].

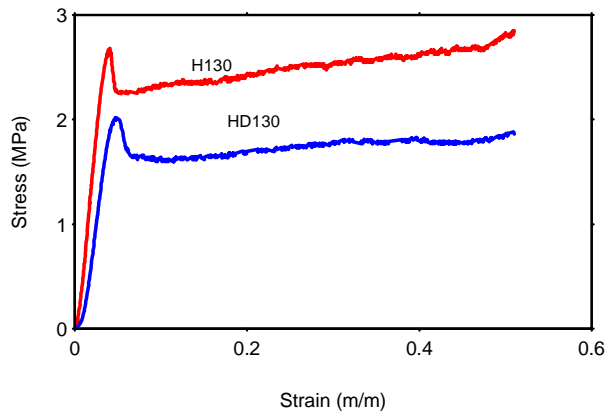


Figure 10. Quasi-static compressions of H130 and HD130 Foams

The high strain rate response of the H and HD grades were first evaluated at room temperature. Strain rates ranged from 700 to 1580s⁻¹. Similar to quasi-static loading, the three phases of failure were still present, but a reversal of the foam performance was observed as shown in Fig. 11. It is noticed that throughout the entire range of strain rate, HD grade is superior to that of H grade. Figure 11 also indicates that the compressive strength of the HD is approximately 20% higher than that of H grade. The HD also has a slightly higher stiffness than the H. This change in the foam performance from quasi-static to high strain rate regime was surprising. According to Gibson and Ashby [20], the relative density, cell size, and cell shape all affect the mechanical properties of cellular foam. Since the foams considered in this study have the same relative density, the properties must be governed by its microstructure. When comparing the cell shape and cell size [24], the shape of the H130 cell is seen to be somewhat hexagonal, whereas the HD130 cell shape appears to be slightly irregular and elongated. The cells of HD also appear to be smaller and cell walls thicker. Since HD grade has smaller cells and thicker walls its strut (edges where cell walls meet) strength may be higher according to Brenzy and Green [25]. Brenzy and Green explored the effect of cell size on the mechanical behavior of cellular materials, such as cellular ceramic. They found that the strut strength directly affects the mechanical behavior of cellular solids by doing simple crushing test. The crushing strength varied inversely with cell size and it is consistent with increasing strut strength with decreasing cell size.

Now if we compare the quasi-static and dynamic compression of a cell, the rate of loading is slower at quasi-static regimes, which means the cell does not instantly fail, but simply collapses after it reaches its maximum strength. At dynamic or impact loads the compressive input force only lasts for a short period of time, therefore the cells are more likely to be crushed rather than just simply collapsed. During this crushing phenomenon, we believe relatively stronger struts of HD foams offer more resistance to HSR loading than those of regular H foams. This is however, not the case during quasi-static loading. This also suggests that the strut strength has a significant role on the dynamic properties and less effect on the quasi-static properties.

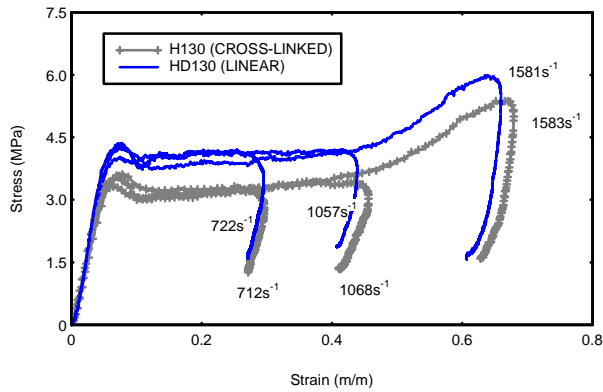


Figure 11. Stress-strain curves of H130 and HD130 foams at various strain rates and at room temperature

The effect of temperature on the high strain rate response ($1057s^{-1}$) of the two PVC foams is illustrated in Fig. 12. The reduction in strength was more pronounced in the HD grade. This higher sensitivity of HD to elevated temperatures may be due to the foam being more viscoelastic because of its lighter degree of cross-linking. However, from room temperature to about $60^{\circ}C$, the HD grade portrayed better compressive properties. As temperatures increased above $60^{\circ}C$ the foam properties reversed. This may be due to the fact that H grade being more cross-linked, the ability of the polymer to flow at higher temperatures was more difficult than a linear polymer (HD). The molecules of a polymer with a linear structure also possesses the ability to slide by each other upon heating [26] which may have contributed to strength degradation.

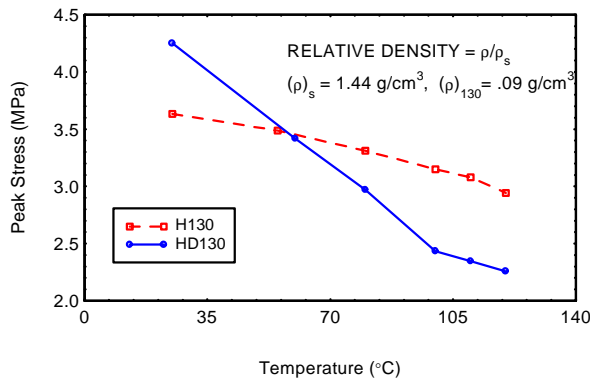


Figure 12: Temperature sensitivity of H and HD foam at $1057s^{-1}$

B) Sandwich Response With PVC Cores

Response of sandwich composites made from various core materials as mentioned earlier were also evaluated at quasi-static and HSR loading. Since the loading was in the thickness direction, the core mainly controlled the performance of the sandwich constructions. In all cases, the sandwich response was very similar to that of its core

except that stiffness and strength were slightly higher because of the presence of the composite face sheets. In order to assess the integrity of sandwich structures at sub-ambient temperature, tests were also conducted under HSR loading by soaking specimens with liquid nitrogen. Response of two categories of sandwiches made from H and HD foams is shown in Fig. 13. Figure 13 compares the sub-ambient response of the two sandwich specimens with the same core density but different degrees of cross-linking at similar strain rates. The HD, which is the linear core, out performed the H grade by about 33%. In a previous study [27] where the HSR response of the two sandwich specimen was evaluated at room temperature, the HD sandwich outperformed the H category by only 15%. Therefore as temperature drops below room temperature, the difference between the two sandwich responses seems to increase.

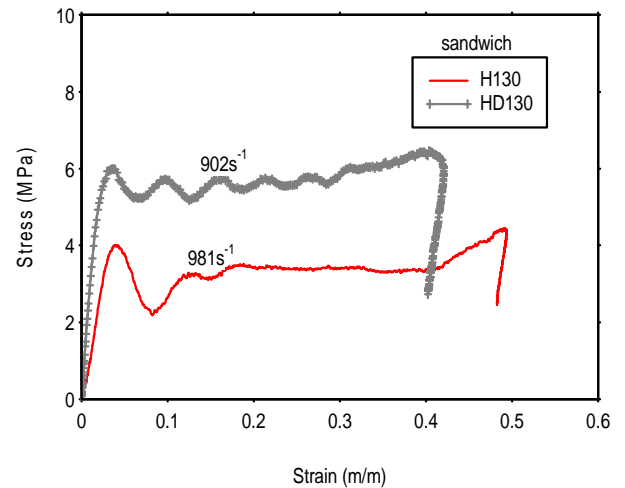
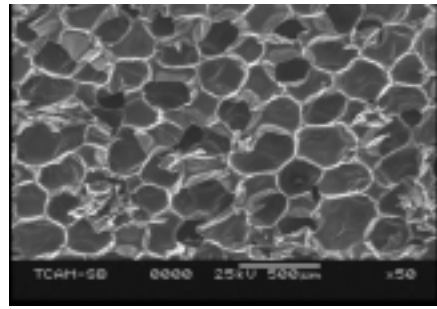


Figure 13: HSR response of H130 and HD130 sandwich composites at sub-ambient temperature.

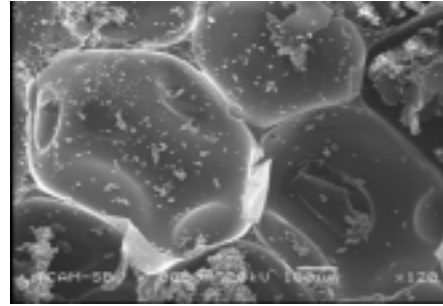
With nanophased Polyurethane Cores

Sandwich composites with nanophased cores were also tested under HSR loading. Prior to sandwich fabrication the nanophased core materials were however tested, under quasi-static compression and flexure, and the results are included in the reference [28,29]. Since significant enhancement in properties was noticed with nanoparticle infusion during quasi-static loading, it was decided to test these materials also under HSR loading. Response of sandwich composites with nanophased core is shown in Fig. 14. The core in this case was polyurethane foam infused with 3%wt loading of TiO_2 nanoparticles. Core thickness and face sheet constructions were identical to those of PVC core sandwich specimens. Density of the polyurethane cores was $88 kg/m^3$ which was close to that of R75 PVC cores. A quick comparison with Figs. 11 and 13 reveals that the performances of polycore sandwiches are very similar to that of PVC core sandwiches. The benefits of nanoparticle infusion are obvious in Fig. 14. Peak stress of the nanophased sandwich is almost 37% higher than their neat counterparts. We also observe a significant

increase in the stiffness of the nanophased sandwiches as it is evident in the initial slopes of the stress-strain curves. Such gain in modulus with nanoparticle infusion has been typical with the doping of nanoclays or nanoparticles with polymeric matrices [30-32]. The gain in modulus is quite understandable since a highly stiff material such as TiO_2 is being mixed with a relatively softer material like polyurethane. A rule of mixture calculation based on volume fraction and individual stiffness would certainly reflect the trend. However, the enhancement in strength by about 37% was somewhat surprising since that was not the case with nanoclays studied earlier in the previous references. To further investigate the polyurethane foam and its nano-composites, SEM analyses were carried out. The micrographs for two categories of foams are shown in Fig. 15. As-prepared neat polyurethane foam is shown in Fig. 15(a). Cell edges and cell walls are distinctly visible with almost uniform cell structures throughout. Cell sizes as seen in the micrograph are approximately $250\mu\text{m}$. Once it is doped with 3% TiO_2 as shown in Fig. 15(b), the dimension of the cell structures increases to about $500\mu\text{m}$. With this enhancement in cell dimension, the cell structure still seems to be intact and uniform. Dispersion of nanoparticles in the cell edges and walls can be clearly seen in Fig. 15(b). It is also observed that the nanoparticles are dispersed uniformly throughout the cell structure of the polyurethane foam. We believe that the infusion of nanoparticles into the cell structures brings about the improvement in strength. Since the solid polymer becomes stiffer due to nano-infusion, it would offer more resistance to deformation, and at the same time the nanoparticles embedded in the cell structures would deflect initial cracks along their interfaces delaying the formation of the dominant crack to cause the eventual failure.



(a)



(b)

Figure 15: Scanning electron micrographs of a) neat polyurethane foam, and b) polyurethane foam with 3% TiO_2

SUMMARY

The following are the summary from the above investigation:

1. With the increase in strain rate there is a moderate increase in the compressive strength of foam core materials.
2. At quasi-static and high strain rate regimes, increasing the temperature resulted in a degradation of strength and stiffness in all categories of foams. This degradation however, increased with the density of the core materials.
3. During HSR and elevated temperature tests some degree of recovery of volumes of the strained samples were noticed. However, this recovery in volume did not signify any increase in the residual strength of the cores.
4. Microstructures of the core materials were seen to have distinct impact on their performances. Cross-linked (H) and linear (HD) foams tested under quasi-static and HSR loading demonstrated that their performances is in fact reversed when strain regime is changed. For example, at higher rates of strain HD outperformed H but the reverse was true at quasi-static loading.
5. With increasing temperature the degradation in

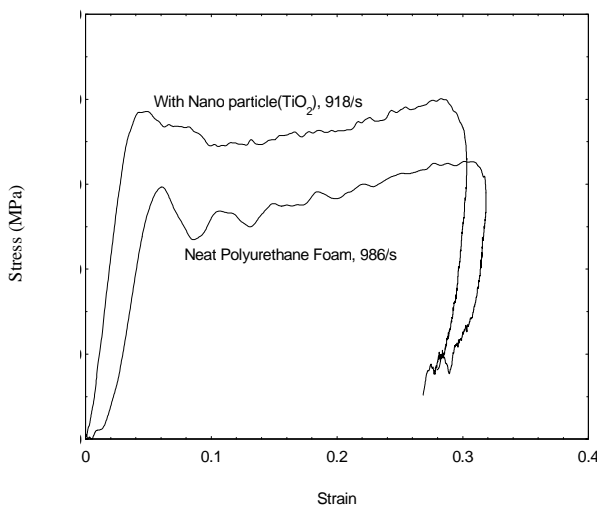


Figure 14: HSR Response of Nanophased (Polyurethane) Sandwich Composites

strength of HD category foam was much more severe than that of H category. Degree of cross-linking in the base polymer was responsible for such behavior.

6. A moderate increase (with respect to room temperature) in HSR compressive strength of sandwich composites was observed at sub-ambient temperature. This increase in strength was higher for sandwiches with HD cores.
7. Although the increase in strength at sub-ambient temperature was moderate, the failure modes were significantly different than those seen at room temperature. At sub-ambient temperature the failure was characterized by complete pulverization and expulsion of the core materials accompanied by the separation of face sheets. On the other hand at room temperature, the failure was dominated by delamination, core crushing together with partial core shear.
8. With regard to nanophased foam, an ultrasonic cavitation process has been introduced to infuse liquid polyurethane foam with TiO₂ nanoparticles. The dispersion of the nanoparticles has been found to be uniform throughout the cell structures.
9. The nanophased foams have been successfully utilized as core materials to manufacture sandwich composites through a low cost VARTM process.
10. It has been observed that with 3%wt loading, the gain in HSR compressive strength over the neat system is around 37%.
11. This gain is attributed to the enhanced cross-linking in the polymer due to the presence of nanoparticles which we believe are acting as catalysts. The catalytic effect causes significant changes in the cell structure and the cell size almost doubles due to particle infusion. It is also observed that embedded nanoparticles resist the deformation of cell structures and resist crack growth allowing sustenance of higher load.

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