# CYCLIC CHARACTERISTICS OF X-LINKED AND LINEAR CORED STRUCTURES AT ELEVATED TEMPERATURES

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## ABSTRACT

The effects of temperature on the fatigue behavior of foam core sandwich structures have been investigated. Two types of PVC cores of the same nominal density were used; one was linear HD foam and the other a slightly cross-linked H foam. In both cases the face sheet material was S2-glass/vinylester. Fatigue tests were conducted on these sandwich structures at room temperature (RT), 40° and 80°C. The tests were conducted on an MTS machine equipped with an environmental chamber. The stress ratio was set at $R=0.1$ and the frequency, $f=3$Hz. S-N diagrams were generated and revealed that fatigue life increased with decreased stress and decreased with increased temperatures. At RT, HD structures revealed much longer fatigue life compared to H structures however at elevated temperatures, a complete reversal of this trend was seen. The failure mechanisms for H beams at RT and 40°C were distinctly different from those observed at 80°C. At RT and 40°C a fatigue crack initiated in the core on the compression side and propagated parallel to the interface below the bond line. Thereafter, the crack kinked at approximately 45° to the vertical and sheared through the core reaching the tension side of the beam. The crack then propagated in the interface as a debond crack until final failure. At 80°C however, no cracks were seen. Failure was due to the collapse of the core close to the point of loading. Difference in the failure modes between H and HD foams was also observed. The characteristic shear crack in the core of the H structures at RT and 40°C was conspicuously absent in the core of the HD beams. HD cores displayed an extraordinary ability in avoiding crack initiation and this resulted in the beams sustaining considerably higher number of cycles prior to failure at RT. As temperature increased however, a reversed trend was seen and HD beams collapsed much faster than the H beams and the strength reduced almost catastrophically. Details of the experimentation, the analysis of the fatigue data, and damage mechanisms are presented.

## 1. INTRODUCTION

Foam core sandwich structures provide lightweight, high strength, and corrosion resistance to severe environmental exposures and therefore have been used extensively in aerospace, military and marine applications over the last three decades and are continually being extended into newer applications [1]. These newer applications give rise to many research issues and technological challenges. One such challenge is the determination of the effects of temperature on the fatigue performance of foam core sandwich structures. While many studies on the effects of temperature on composite laminates [2-5] and resin systems [6-7] may be found in the open literature it is evident that there is little or no quantitative research on the effects of temperature on foam core sandwich structures. In this study, sandwich structures with either cross-linked or linear closed cell PVC cores were tested. In both cases the core was considered more viscoelastic than the face sheets, and as such it was expected that they would degrade more rapidly at elevated temperatures. It is well known that a polymer can be in different regimes or states depending mainly on the surrounding temperature and partly on the molecular properties [8]. Amorphous and semi crystalline polymers do not have a distinct melting point, but a glass transition temperature, $T_g$. Polymers generally have glass temperature above room temperature. Dramatic changes in the characteristics of a number of properties of the polymer occur around this temperature. Below the glass transition

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temperature, amorphous polymer is in a glassy regime, where the elastic modulus is a direct reflection of the stiffness of the intermolecular bonds, which is the so-called Van-der-Waals bond. These bonds hold the molecules together. Since these bonds are not as strong as covalent bonds that normally exist between carbon atoms, they will deflect when a polymer is loaded. The Van-der-Waals bonds are easily influenced by temperature causing the stiffness to decrease with increase in temperature [9]. Such complex behavior under elevated temperatures will most certainly affect the performance of structural PVC foams used here as a core material. The problem is further exacerbated when both the face sheets and the PVC foam core act in concert, as is the case in a sandwich structure. The heterogeneous material response under elevated temperatures is unknown and hence there is often a tendency to 'over design' sandwich structures mainly because of uncertainties about their performance. Conservative design practices result in heavier and more costly components. The objective of this work therefore is to assess the durability of, and to establish damage mechanisms in, sandwich structures subjected fatigue in a high temperature environment with special emphasis on performance of the viscoelastic core. Knowledge gained here may perhaps be used in raising the temperature capabilities of structural sandwich composites.

## 2. EXPERIMENTAL

### Materials

Two types of foam core sandwich panels were manufactured using a vacuum assisted resin injection molding (VARIM), the details of which may be found in ref. [10]. The laminated face sheets employed six layers of plain weave S2-glass fibers (Owens Corning 240D). The lay-up was $[0/90]_6$. The resin used to impregnate the glass fibers was Dow Derakane 411-350 Vinylester. In the first type of sandwich panel a slightly cross-linked (H130) core was used and in the second a linear (HD130) core was used. Both were closed cell PVC cores with a nominal density of 130 $kg/m^3$. Typical properties of the base polymer [11-13] are presented in Table 1.

### Dynamic Mechanical Thermal Analysis (DMTA)

Dynamic Mechanical Thermal Analysis (DMTA) was performed on a minimum of three specimens using a TA Instruments Model 2980. The specimens were 65 mm long, 12.5 mm wide and 2.5mm thick cut with the Isomet cutter from H130 and HD 130 foam panels. The DMTA tests were performed in a three-point bend clamp, as shown in Figure 1, over a temperature range from 20-120. The load was applied sinusoidally. The storage modulus (E') and the loss factor ($\tan\delta = E''/E'$) were measured in the temperature interval 20-120°C (1Hz, 2°/min). These tests were performed mainly to establish glass transition temperatures of the foam cores. This information was required to design testing parameters for static and flexural tests.

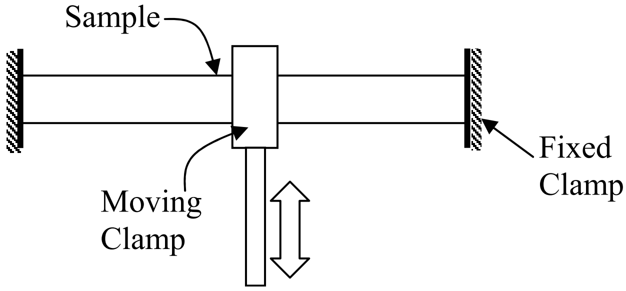



**Fig.1.** Schematic of 3-point bend clamp used for DMTA of HD and H foams

**Static Test**

Static tests were conducted at room temperature (RT), 40° and at 80°C primarily to establish loads levels for the fatigue tests at these temperatures. The tests were conducted in an environmental chamber fitted onto a servo hydraulic testing machine (MTS) with 100kN load capacity. The temperature in the environmental chamber was controlled with a model 779 MTS electronic controller. Sandwich beams of dimensions 16.5mm x 16.5mm x 200mm were cut from the manufactured panels for quasi-static and fatigue tests using a Felker saw fitted with a diamond coated steel blade. The beams were tested in three-point bend configuration with a span length of 160mm. A loading nose with a radius of 10mm was used in order to prevent localized indentations in the face sheet of the beams. For sandwich beams the stress, $F$, in the face sheets is [14,15];

$$F = \frac{P\,L}{2t_f(t_s + t_c)b} \qquad \text{Eq. (1)}$$

where $P$ is the applied load, $L$ is the span length, $t_f$ is the thickness of the face sheet, $t_s$ is the thickness of the sandwich , $t_c$ is the thickness of the core and $b$ is the width is the beam. The stress in the beam is equivalent to the facing stress.

A minimum of four replicate specimens of each sandwich type was prepared for the static tests. The specimen was placed in the environmental chamber. Heating rates were kept to 10°C/min to minimize any thermal shock effects. After reaching the target temperature the chamber temperature was kept constant for at least 1 hour before the start of testing to allow for thermal equilibrium. In order to monitor the temperature of the beams an Omega HH12 digital thermometer with two external probes was used. One probe was attached onto the side of the core and the other probe was used to measure the surrounding air inside the chamber. Ideally, insertion of the temperature probe into the core would yield accurate core temperature but may cause a high stress zone and consequently accelerate failure. Therefore the probe was glued to the side of the beam and covered with a piece of foam for insulation. At all times the air temperature inside the chamber was accurate to within 2˚C of the values displayed on the electronic controller. Once the beams reached the required temperature they were tested in displacement control at a crosshead speed of 1.27 mm/min.

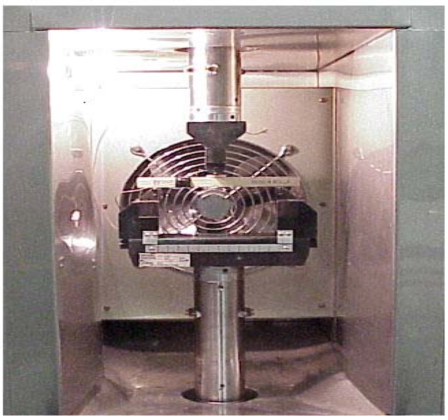


**Fig.2.** Three-point bend test conducted within an environmental test chamber

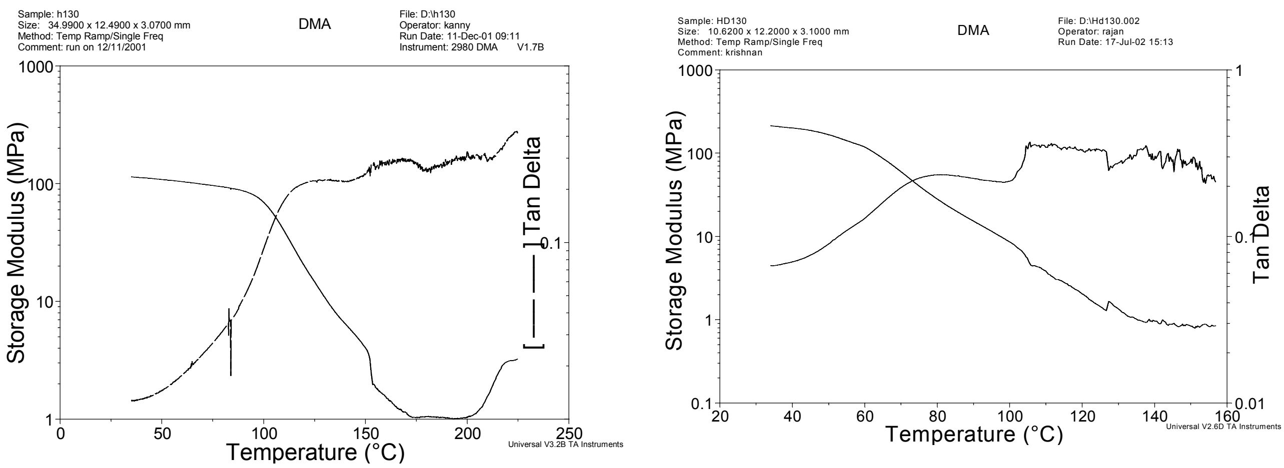
**Cyclic Flexure**

Cyclic flexural tests were performed in the environmental chamber described earlier. Four replicate HD130 and H130 sandwich beams of the same dimensions as in static tests were used. The tests were performed at room temperature**,** 40° and at 80°C. The temperature controller maintained the temperature of the specimen to within 2˚C of the target level. The tests were conducted under load control at a stress ratio, R=| $P_{min}$| /| $P_{max}$| =0.1, and a frequency of 3Hz using the MTS machine. Fatigue data were generated at stress levels of: 85%, 80% and 70% and 60% of the static ultimate flexural strength. The fatigue life of the specimens is characterized as the number of cycles to ultimate failure. The applied maximum bending stress is plotted against the number of cycles on a logarithmic x-axis scale.

**Post Fracture Examination**
Scanning electron microscopy (SEM, JSM 5800 JEOL) was used to examine the morphologies of fractured surfaces and to investigate the influence of temperature on the formation of microcracks within the specimens. Additionally, the failed beams were examined in a Unitron optical microscope model FSB coupled to a complete video image marker system VIA150.

## 3. RESULTS AND DISCUSSION

**DMTA**
The general features of the viscoelastic response of both H and HD foams are shown in Figures 3(a-b) respectively. Storage modulus, E' and damping ratio, tanδ are plotted as a function of temperature for both foams. It is clear from the plots that these foams have a glass transition temperature range but no distinct melting temperature. They appear stiff below that temperature and viscous above it. Both foams exhibit tanδ peak at the $T_g$. The glass transition temperature range for H and HD foams specimen was established and was marginally higher than the corresponding values of the base polymer given in Table1. Fatigue testing was done at RT, 40° and 80°C, these temperatures being at or below the glass transition temperature, $T_g$ of both types of materials.




(a) (b)

**Fig.3.** E' and tanδ as a function of temperature for (a) H and (b) HD foams, DMTA 3 point bending (1 Hz, 2°/min)

**Table 1.** Typical properties of vinyl chloride homopolymer based on data from Refs [11-13]

| Property | Units | Value |
|---|---|---|
| Density | $kg/m^3$ | 1390-1430 |
| Modulus | MPa | 2960 |
| Glass transition temperature | ºC | 75-85 |
| Crystalline melting point | ºC | 120-210 |
| Thermal Conductivity | W/mK | 0.12-0.18 |

**Quasi Static**

Figures 4(a-b) shows representative load-displacement curves, at three temperatures, for HD and H sandwich beams respectively. The mechanical properties such as flexural modulus and strength decreased with increased temperature however the decrease was more substantial in the HD beams. Close inspection of the beams revealed that damage mainly occurred in the cores and was more severe in the HD beams. This suggests that linear foam cores are more temperature sensitive than cross-linked foam cores. The temperature sensitivity was indicated by the extent of the damage in the core.

HD beams tested at RT revealed a linear load–displacement (*P-δ*) response as shown in Figure 4a. After reaching approximately 70% of the ultimate load the response became non-linear and the material exhibited ductile behavior. This non-linearity continued up until the

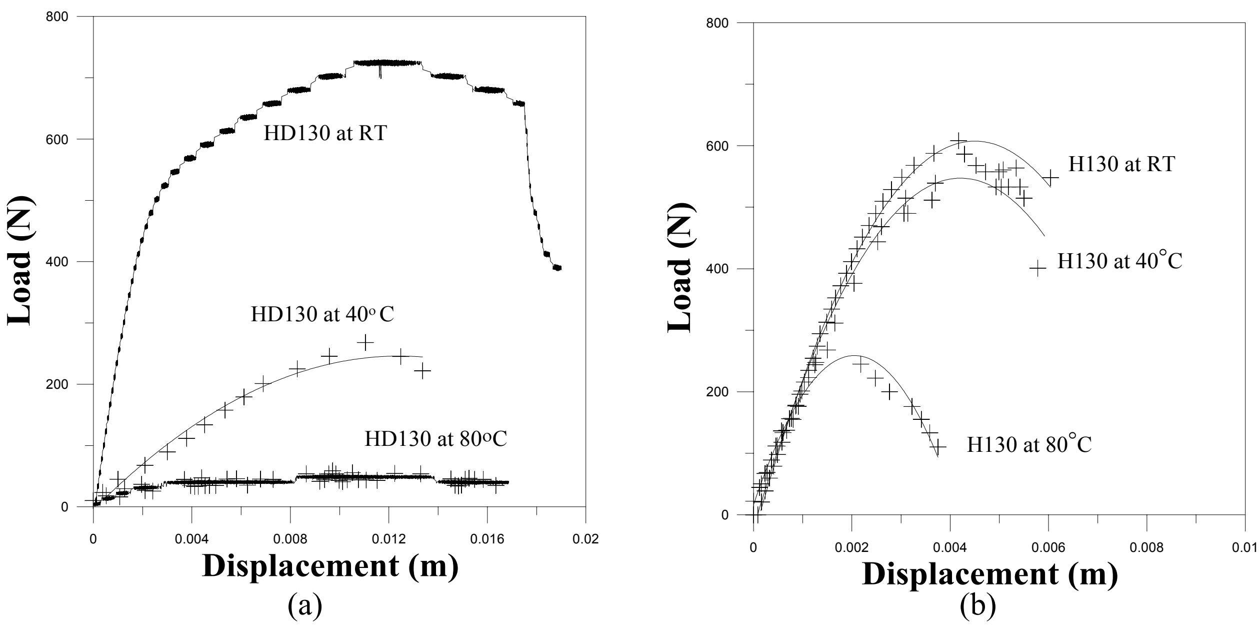



**Fig.4.** Load-displacement curves at RT, 40 and 80°C for (a) HD and (b) H sandwich structures.

maximum load was reached. Thereafter yielding occurred in the core and this corresponded with compaction of foam cells just below the tougher resin rich interface. Further compaction and crushing of the core marked the final failure event.

Test data at 40˚C revealed a significant reduction in the mechanical properties. The maximum load to failure and stiffness was found to reduce by approximately 60% and 75% respectively. The reduction in stiffness resulted in increased deflection of the beam at correspondingly lower loads. At 80°C further degradation of the core was observed and was accompanied by a dramatic loss in stiffness, which is indicated by the non-linear load-displacement (P-δ) response. After taking up a small initial load (less than 10% of the load at RT) plastic yielding occurred the core. The beam remained plastically strained after the removal of the load and is shown in Figure 5.


**Fig.5.** Plastically strained H130 beam after quasi-static test at 80˚C

H130 like the HD130 beams demonstrated linear load response at room temperature; however they carried marginally lower loads and exhibited brittle failure. The principal mode of failure was core shear. In some instances stress whitening or crazing was evident on the face sheets. At 40°C, the stiffness of the beams decreased marginally and a somewhat similar load response was observed, hence the linear portion of the graph superposed the RT curve. This suggests that H130 beams with cross-linked foam cores are relatively less dependent on temperature, at least in this temperature range. Failure at 40°C was similar to that at RT and was characterized by core shear. At 80°C however, plastic yielding occurred in the core and the beams failed by collapse and compaction of foam cells at relatively low loads. Accordingly, failure in HD and H constructions, which occurred mainly in the core, may be summarized as follows; For H130 beams brittle fracture occurred beyond the elastic range at room temperature and at 40°C and plastic yielding at 80°C. For HD structures however, brittle failure occurred after the elastic-plastic range at RT and plastic yielding at the elevated temperatures. Although the properties of both cross-linked and linear foams are dependant on the temperature, the differences in the failure mechanisms suggest that cross-linked cores give PVC mechanical stability at elevated temperatures. At elevated temperatures the foam cores degraded leading to a reduction in the stiffness of the beams. For polymers below their glass temperatures, $T_g$, the modulus more or less varies linearly with temperature. A convenient approximation is given by Gibson and Ashby [13];

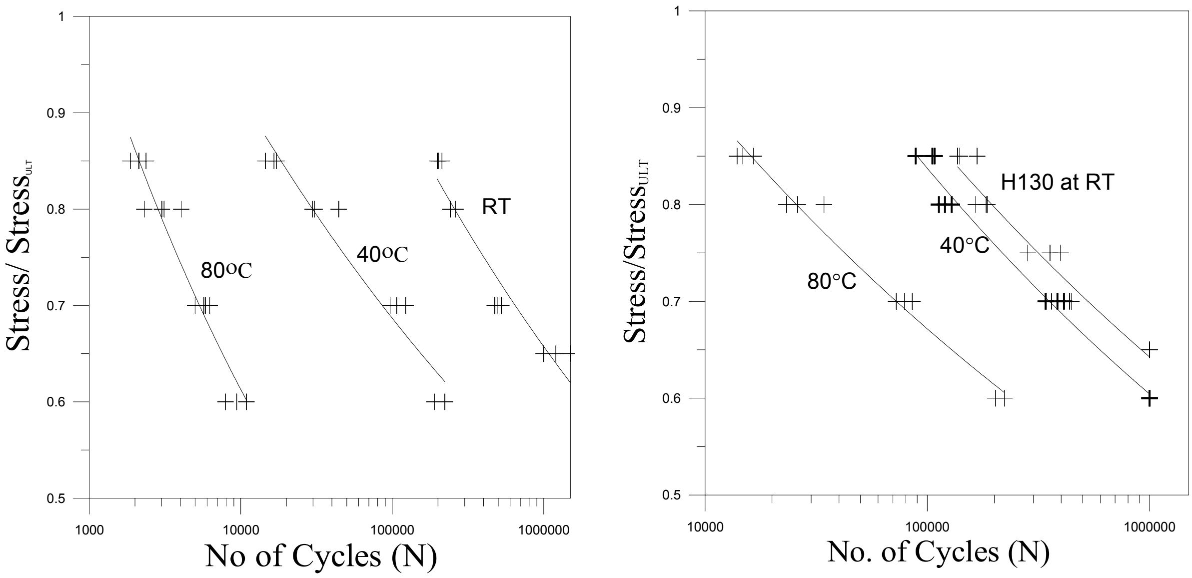
$$E_s = E_s^0 (1 - \alpha_m \, T / T_g) \qquad \text{Eq. (2)}$$

Here $E_s^0$ is the modulus at 0°Kand $\alpha_m$ is a constant.

**Flexural Fatigue**

The results of fatigue tests at three different temperatures, the macroscopic behavior trends in stiffness, and the post mortem microscopic evaluation of damage mechanisms in HD and H sandwich beams are given. Fatigue tests are analyzed in the S-N diagrams shown in Figures 6(a-b). For both types of beams the number of cycles to failure at RT was considerably higher than at the elevated temperatures and the fatigue life increased with decreased stress and decreased with increased temperature.

The number of cycles to failure, $N_f$ for HD beams was significantly higher than that for H beams at RT, however at elevated temperatures the reverse was true. Figure 6a reveals that the fatigue life of HD beams decreases substantially at elevated temperatures, particularly at 80°C. At this temperature the beams failed after $10^4$ fatigue cycles while they sustained $10^6$ cycles when tested at RT, both these tests being done at a stress level of 60%. This equates to a 99 % reduction in fatigue life. H130 beams on the other hand were not as temperature sensitive. Figure 6b shows that the fatigue data trends at 40°C and at RT are fairly similar, however at 80°C premature failure occurs. This was due to substantial degradation in the core.



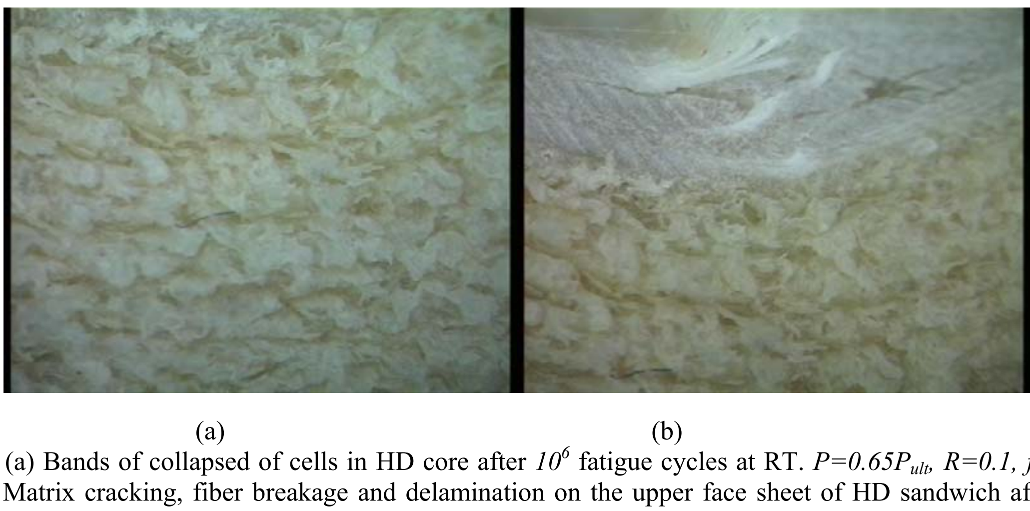

(a) (b)

**Fig.6.** S-N curves at RT, 40 and 80°C for (a) HD sandwich beams and (b) H sandwich beams

## 4. FAILURE ANALYSIS

### *HD130 at room temperature*

HD beams subjected to cyclic loading at RT demonstrated a remarkable resistance to crack initiation and no damage was visible for at least 80% of the fatigue life. Soon thereafter a narrow band of collapsed cells of the order of one cell size (0.3-0.4mm) appeared in the core just below the interface on the compression side of the beam. The band of collapsed cells increased in length to approximately 40mm before a second tier of collapsed cells appeared immediately below the first. These bands of collapsed cells progressed toward the tension side of the beam, leading to a loss in stiffness and subsequent increase in the deflection of the central part the beam. Failure of the face sheets ensued. Matrix cracking and fiber breakage was the principal mode of failure in the face sheets. Figure 7a shows bands of collapsed cells through the thickness of sandwich structure and Figure 7b shows failure of the upper face sheet.



(a) (b)

**Fig.7.** (a) Bands of collapsed of cells in HD core after $10^6$ fatigue cycles at RT. $P=0.65P_{ult}$, $R=0.1$, $f=3Hz$ ,7(b) Matrix cracking, fiber breakage and delamination on the upper face sheet of HD sandwich after $10^6$ cycles at RT. $R=0.1$. $f=3Hz$.

***HD130 at Elevated Temperatures***
At 40°C a fair amount of degradation occurred in the core and collapsed cells were clearly visible close to the upper and lower face sheets. These collapsed cells led to a reduction in height of the beams and hence a volume change. Correspondingly, deflection in the central part of the beam increased leading to failure. No cracks were evident in the core of these beams at this temperature. At 80°C a similar damage mechanism was seen initially, however this time a substantially larger volume change occurred. The volume change was due in part to a reduction in height of the core. The core also concaved as shown in Figure 8 and once again no cracks were evident in the core. Failure at the elevated temperatures always initiated as collapse in the core. Additionally, the matrix resin decomposed at 80°C and there was a strong odor of resin. HD foams do not lead the heat away easily and hence the resin in the interface area decomposed and this resulted in face/core delamination at the edges as shown in Figure 9a. Delamination also occurred at the point of loading as shown in Figure 9b. At this time the load carried by the matrix decreased and was shed to the fibers. This led to an increase in the strain in the essentially elastic fibers. As the stresses in the fibers increased they began to break randomly leading to the final failure event.

**Fig.8.** Degradation of HD core after $5x10^3$ cycles at 80 deg.C. The core concaved and the height of the beam reduced.

(a) (b)

**Fig.9.** (a-b) HD sandwich beams after $10^6$ cycles at 80°C (a) face /core delamination (b) delamination of face sheets at point of loading.

**H130 Beams**
When H130 beams were tested at RT, no visible changes were observed for most of its fatigue life. Shortly before failure however, numerous small shear cracks formed in the core. They coalesced into a larger dominant crack on the compression side of the beam. The crack propagated horizontally parallel to the interface and just below the bond line in the core. Thereafter, the crack kinked at approximately 45° to the vertical and propagated to the tension

side. Upon reaching the tension side the crack proceeded to propagate as a debond crack to the edge of the beam as shown in Figure 10.

**Fig.10.** Crack propagation in the core of H130 specimen tested at RT

Beams tested at 40°C displayed a similar damaged mechanism except for a minor amount of compaction in the core prior to the final failure event. At 80°C however, failure was by gradual compaction of the core. Sandwich structures tested herein have closed cell PVC cores. These cores have a very low thermal conductivity. Typically conductivity values range from 0.12-0.18 W/mK see Table1.These low thermal conductivity values mean that these cores are good insulators, but a consequence of that is that the material has limited ability to lead away heat. As seen in this study even a small increase in temperature causes a drastic reduction in fatigue life especially with linear HD cores.

## 5. CONCLUSIONS

Quasi static and fatigue tests performed on HD and H sandwich constructions at various temperatures reveal that:

1. Mechanical properties such as the moduli and strength of the beams decreased with increased temperature however, the decrease was more substantial in the HD beams.
2. Failure in both HD and H constructions occurs in the PVC core. For H130 beams, at room temperature and 40°C, brittle fracture occurs beyond the elastic range and plastic yielding at 80°C. For HD structures however, at RT, brittle failure occurs after the elastic-plastic range and plastic yielding at elevated temperatures.
3. The behavior of PVC foams is influenced by the presence of cross-links. HD cores have no cross-links and hence degraded faster than H130 foams at elevated temperatures.
4. The fatigue life of both types of beams increased with decreased stress and decreased with increased temperatures. At RT the fatigue life of HD beams was significantly longer than H beams; however at elevated temperatures the reverse was true.
5. Failure of H beams at RT and at 40°C was by a fatigue crack in the core. At 80°C however, gradual collapse of the foam core was evident.
6. HD cores displayed an extraordinary ability in avoiding crack initiation and this resulted in the beams sustaining considerably higher number of cycles prior to failure at RT. At elevated temperatures however, HD beams collapsed much faster than the H beams and the strength reduced almost catastrophically. The principal failure mode was the collapse of the core.

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