FATIGUE OF 3D SANDWICH-FABRIC COMPOSITES UNDER CORE SHEAR LOADING

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SUMMARY: The core shear fatigue behaviour of 3D sandwich-fabric composites has been investigated. Four types of glass fibre-epoxy sandwich panels with different core properties were used in this research. A three point bending fatigue test set-up was used. The use of one millimeters thick metal plates as extra skins on the panels generates mainly shear loading in the sandwich core. Fatigue tests were performed at different load levels, based on the static 3PB strength. During the test, the load was kept constant and the bending displacement was monitored to obtain data on the properties degradation. Based on the stiffness degradation curves, a fatigue design criterion for sandwich-fabric panels is proposed. Damage growth was monitored by means of stereo light-microscopy and X-ray radiography (upgraded to a Tomohawk Computer Tomography System) techniques. Comparison of the stiffness degradation curves showed that it is strongly influenced by the core microstructure. Damage investigation revealed the material phenomena, responsible for this degradation.

KEYWORDS: sandwich structures, fatigue, damage, textile composites, NDE technique.

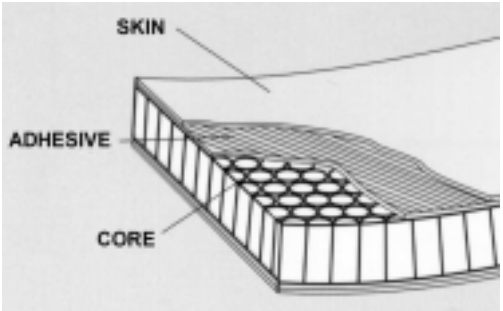
INTRODUCTION

Fatigue in Sandwich Structures

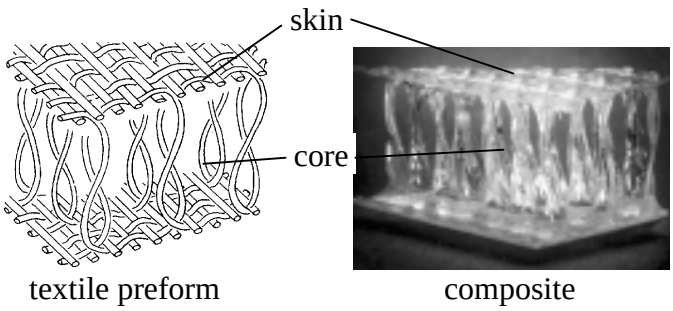
Repetitive loads often cause premature structural failure even though they are well below the static design load. This phenomenon called fatigue is a known cause for structural failure but is not often reported for sandwich structures. The light, cost-effective and durable sandwich constructions have a gained reputation for being a very good concept to avoid fatigue failure. The materials consist of thin, stiff and strong outer skins and a thick and light core, and both are normally joined by an adhesive (Fig.1a). The core, that strongly influences the sandwich properties, is designed with a high safety margin due to lack of knowledge about its fatigue properties.

The core is of particular interest for the sandwich panels since the core normally has light weight with limited stiffness and strength. The core shear properties become important as the core takes most of the shear deformation in a bending sandwich. If the core properties are not high enough, core shear failure or large shear deflections will occur during bending

(particularly at shorter loading spans). Then, for long-term use, it is significant to evaluate the sandwich materials in fatigue with emphasis on the shear behaviour of the core.



a) general sandwich structure



b) 3D woven sandwich structure

Fig. 1: Sandwich structures.

Sandwich with An Integrated Core

This research focuses on the core shear fatigue response of integrated core sandwich panels, based on woven distance-fabrics (Fig.1b). This relatively new sandwich structure has been developed at KU-Leuven to overcome the common delamination problems in sandwich materials. By means of the velvet weaving process an integral skin-core structure is produced as a preform for an innovative sandwich structure with a low production cost and a high skin-core delamination resistance.

The sandwich preform is made of glass or carbon fibres and impregnated with epoxy, phenolic, or other thermoset resins. To improve the shear resistance of the panels, the empty core can be foamed up by liquid foam injection (polyurethane, phenolic,....). Panels with a large variation in core layout can be obtained and lead to a wide range of core properties. These materials are used in many applications: hard-tops for cars, side-spoilers for trucks, radar domes, mobile homes, a small aircraft, furniture and interior wall panels for fast ferries. Applications in the structural part of transport vehicles (trains, busses,….) where fatigue loading is an important issue are currently under development.

Modification of skin thickness to induce core shear failure

The bending fatigue behaviour and damage propagation of 3D woven sandwich panels have been studied [1]. The thin skin panels, however, failed by skin buckling instead of core shear failure. In this research, the specimen geometry was therefore modified to obtain core shear failure, in both static and fatigue testing. This can be achieved by increasing the skin thickness and stiffness.

It has to be realized that the constituents in a sandwich, the skins and the core, are subjected to different kinds of loading during bending. The skins exhibit almost entirely normal tension/compression with limited shear while the core exhibits pure shear accompanied with normal tension/compression. By using thicker and stiffer skins, the core component will predominantly exhibit shear loading which leads to pure core shear failure [2].

MATERIAL AND PROPERTIES

Material

Four types of fibre glass-epoxy panels, 2 unfoamed and 2 polyurethane (PUR) foamed panels, have been selected and produced at KU Leuven (Table 1). As the core has different structures in weft and warp direction (Fig. 1b), only the warp direction was investigated as this is the weakest direction [3]. The panel skins are identical.

Table 1: Materials.

Panel	Nominal pile length (mm)	Skin Thickness (mm)	Core Thickness (mm)	Foam	Foam density (kg/m^3)
GE/20/UF	20	0.35	18	NO	-
GE/10/UF	10	0.35	8.3	NO	-
GE/20/F	20	0.35	18	PUR	88
GE/10/F	10	0.35	9.1	PUR	76

Basic Core Mechanical Properties

The mechanical properties of the panel cores obtained from flatwise compression tests (according to ASTM-standard C365) and three point bending tests with 2 different span lengths (according to ASTM-standard C393) are shown in Fig. 2. These properties are strongly dependent on the microstructure of the core: pile fibre density, pile fibre length, pile angles, pile fibre degree of stretching, resin content and foam support [3].

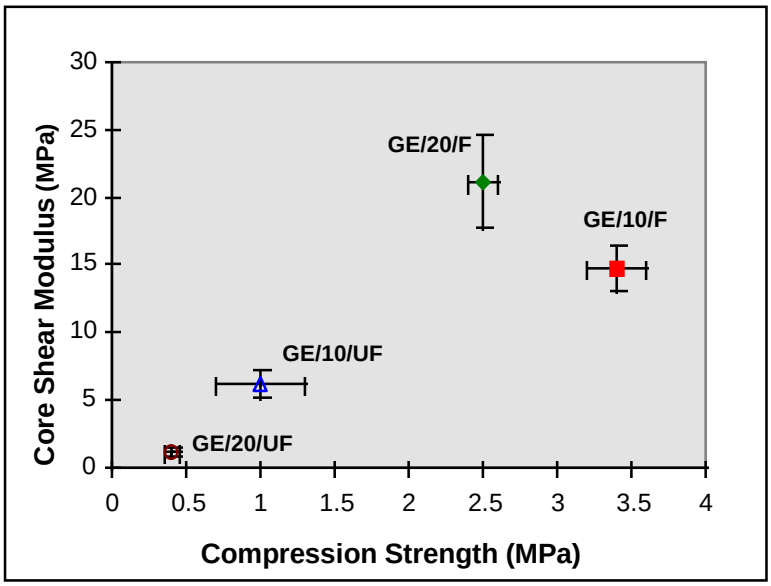


Fig. 2: Core shear modulus and compression strength of the panels.

EXPERIMENTAL PROCEDURE

In this research sandwich panels with thicker skins, in which the core exhibits mainly shear loading, were used. Metal plates, 1 mm thick, were attached as extra skins on both sides of the panels. These plates were glued by means of an Araldite two components epoxy glue. Hardening of the glue was done at 80°C for 1 hour.

Static Three Point Bending Test

3PB tests on a 250 mm span length and 50 mm wide specimens were performed on these panels until failure to obtain 3PB static ultimate load. It was proved earlier [2] that this test can be used as an alternative to the block shear test method to determine the core shear strength of these sandwich-fabric panels.

Fatigue Test

For the fatigue test either steel or aluminium were used as extra skins. The latter will be used for damage investigation of foamed panels. Fatigue tests, with R ($\sigma_{min.}/\sigma_{max.}$) = 0.1, were performed on a Schenck fatigue machine with the same set up as used for the static 3PB test. A frequency of 3-4 Hz and different load levels, based on the 3PB static strength, were chosen The machine will stop automatically if the displacement exceeds 20 mm, due to stiffness degradation and cyclic creep. With the help of the Computer Aided Fatigue Testing program, the displacement was monitored at constant load to obtain the stiffness degradation. Stress concentrations at the load introduction point were reduced using a 15 mm width curved steel plate at the loading point.

Damage Investigation

Damage development during cyclic loading was monitored at different levels of stiffness degradation using non destructive evaluation (NDE) techniques. When inspecting the damage, the test was interrupted and after that, the test using the same specimen was continued. In order to inspect the damage inside the unfoamed panels only light-stereomicroscopy was used. For the foamed panels, penetrant enhanced microfocus X-ray radiography technique was also used to visualise the damage. Further, to examine the damage in the piles of foamed panels, the PUR foam was dissolved by means of a chemical dissolution [1].

The specimens inspected using the X-ray radiography technique have aluminium extra skins. Thus, with the power source of 50 kV and 0.2 mA, it is possible to penetrate the aluminium skins and this is still low enough maintain the contrast between the liquid penetrant (which has filled up the damage areas) and the core piles. The submersion penetration technique was performed using Zinc Iodine (ZI) or Di-iodo-methane (DIM) as liquid penetrant. For continuous monitoring, using DIM as penetrant resulted in more reliable results. After inspection and before continuing the test, this penetrant can be removed easily in a vacuum oven, hence the attack of the corrosive penetrant into the material can be eliminated.

In the X-ray radiography chamber, the specimen was put on a motor-controlled holder that can move the specimen in all directions 360° rotation around the vertical axis, raising and lowering. With the help of the Computer Aided Tomography system, two dimensional images of the specimen can be captured at every degree of rotation and reconstructed to be a stereolook image by which the exact position and size of the damage can be determined.

RESULTS AND DISCUSSIONS

The Core Shear Strength

The results from 3PB test can be seen in table 2. Since the specimens fail in core shear, the core shear strength of the panels can be obtained from 3PB ultimate load.

Table 2: Core shear strength of the panels.

Panel with thick skins	Ultimate Load P_u (N)	Core Shear Strength τ_{cr} (MPa)
GE/20/UF	422.0 ± 26.0	0.21 ± 0.01
GE/10/UF	697.0 ± 5.0	0.70 ± 0.01
GE/20/F	1921.0 ± 40.0	0.97 ± 0.02
GE/10/F	1023.0 ± 69.0	0.99 ± 0.07

The Fatigue Response

The fatigue response of the panels containing a sandwich fabric core is depicted in figure 3. It shows the typical load-displacement response of a sample at various cycles throughout a fatigue test. Not as the classical steel fatigue behaviour, it demonstrates the existence of property degradation due to accumulation of damage in the structure. It also has to be noted that the test panels did not fail, but tests were stopped because the displacement limit of 20 mm was exceeded.

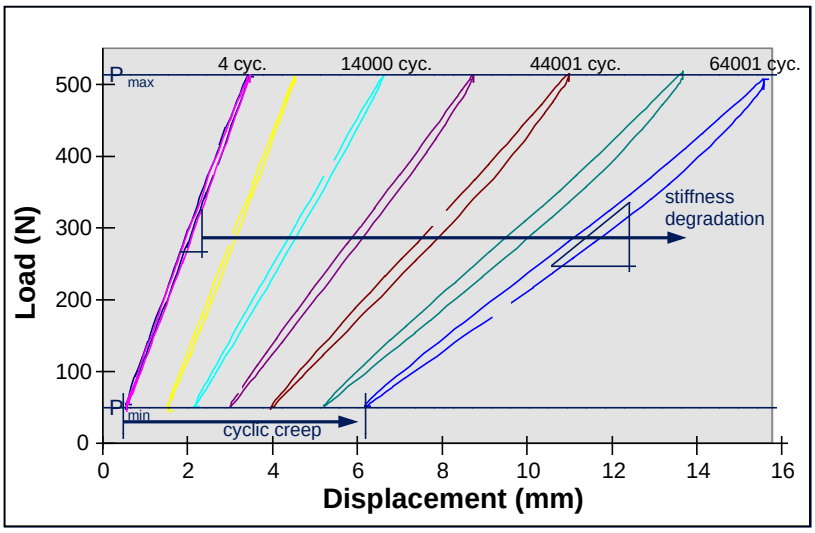


Fig. 3: The fatigue response of the panels.

From figure 3, it can be seen that the following phenomena occur as the number of cycles increases:

a. The hysterisis slope decreases : this is equivalent to the stiffness degradation. In this paper, the apparent stiffness (load/displacement) was determined by taking the slope of the line between the maximum load and corresponding displacement and the minimum load and corresponding displacement.
b. The displacement at minimum load increases as the number of cycles increases. This phenomenon is known as cyclic creep.
c. The hysterisis area increases as the number of cycles increases. This shows probably an indication of damage development due to a crack closure phenomenon [4].

Core Shear Modulus Degradation

The use of thick and stiff extra skins combined with the use of a short span length resulted in a large portion of shear deflection (≥ 95%) of the total deflection. Moreover, damage in the

skins did not occur during cyclic loading. Hence the bending deflection can be neglected and then the core shear modulus degradation can be obtained directly from degradation of the apparent stiffness.

Figure 4 and figure 5 show the typical curves of core shear modulus degradation of all panels at different load levels during cyclic loading. Generally, it can be seen that starting with a plateau, all the curves dropped with a certain slope. This shape already reveals the existence of the core degradation. It is also obvious that the onset of the degradation for a panel is determined by the level of the applied load during fatigue loading: the higher the loading applied, the earlier the slope started to decrease.

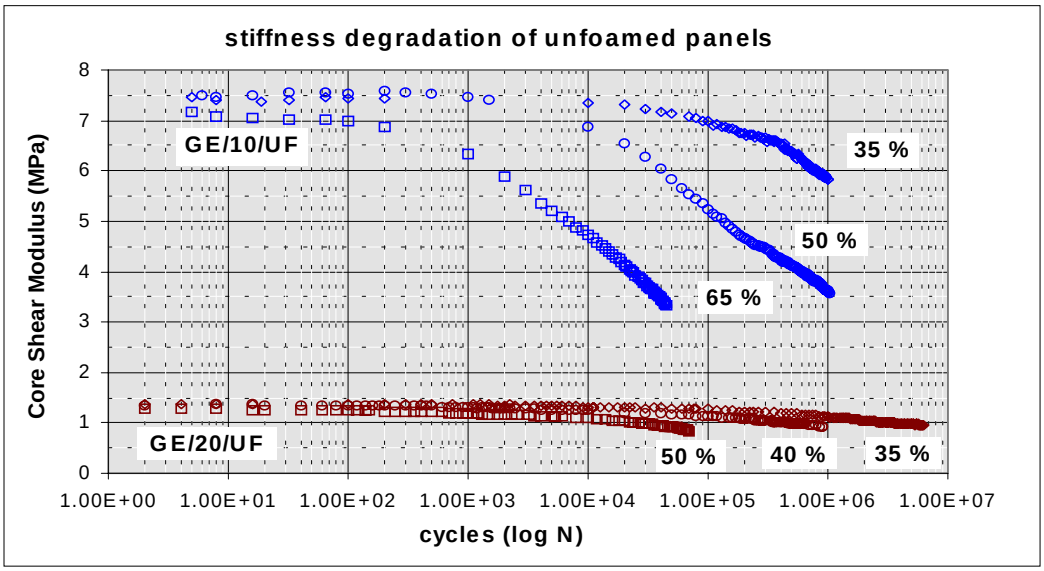


Fig. 4: Stiffness degradation of the unfoamed panels at different levels of static strength.

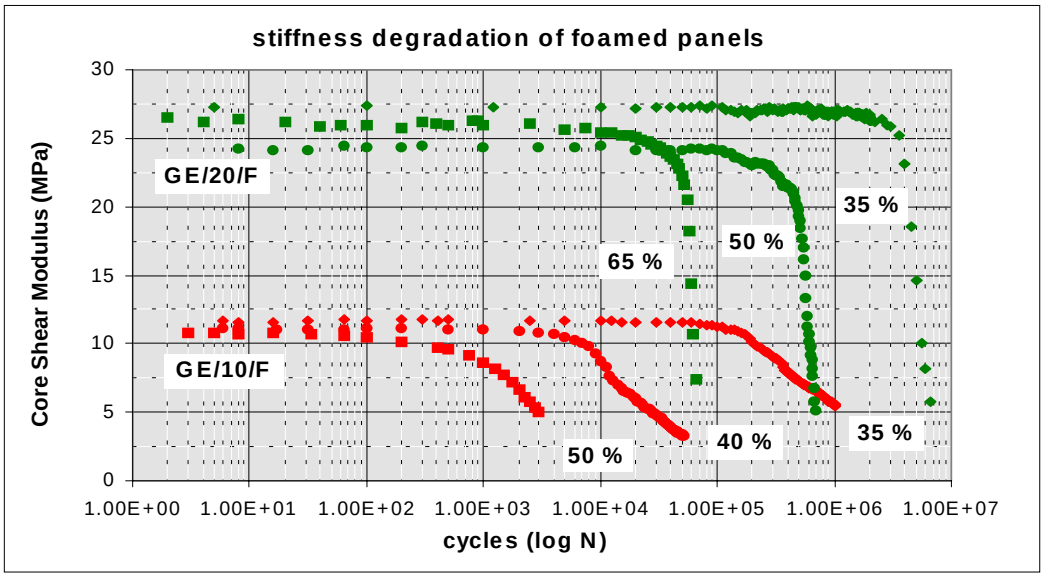


Fig. 5: Stiffness degradation of the foamed panels at different levels of static strength.

Comparison of the shape of stiffness degradation curves for the different panels (Fig. 4 and 5) shows that it is strongly influenced by the core microstructure but not influenced by the applied static strength level. The curves for the different panels show a different slope (Table 3) and starting point (Fig. 7). Unfoamed panels (Fig. 4) show a gradual stiffness degradation,

while the foam panels (Fig. 5) have no significant degradation for some time, followed by a dramatic stiffness drop. This behaviour is related to the damage mode obtained in each panel type (*see further*).

Fatigue Design Criterion for Core Stiffness Degradation of Panels

To compare the relative core shear stiffness degradation behaviour, the curves of figure 4 and 5 are normalised to the initial core shear stiffness of the panels which is obtained from the beginning of the cycle. As an example, the degradation curves at 35% of the static failure load are presented in figure 6. It is shown more clearly that the shape of the curve is dependent on the core microstructure. The difference in the shape of the curve can be represented in the degradation slope and the point at the onset of degradation. As can be seen in figure 6, this point was taken at the crossing point of the degradation slope and the line of initial stiffness.

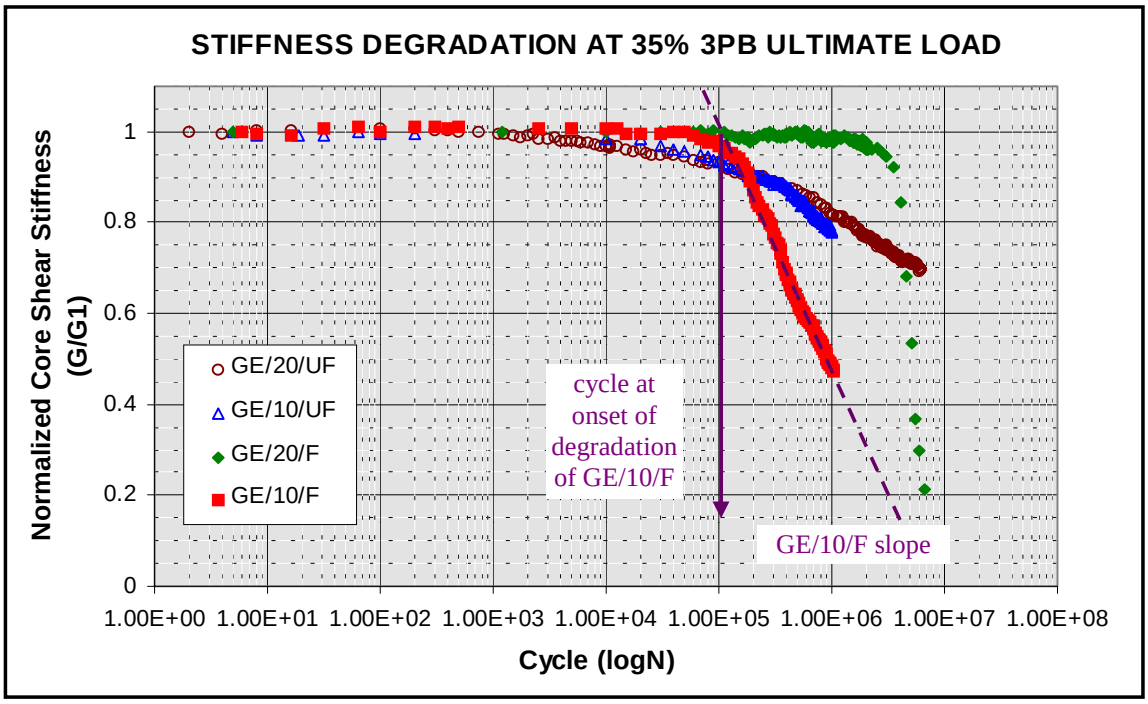


Fig. 6: Normalized stiffness degradation during cyclic loading of four different panels.

Table 3 shows the values of degradation slope of all panels. In figure 7, the cycles at the onset of degradation of the panels at different levels of core shear stress is plotted. The core shear stress in Y- axis of figure 7 is normalized to the static core shear strength of the panels, thus the onset of degradation of each panel at the relative core shear stresses can be obtained. It has to be noted that the curves in figure 7 is not the same as the Wöhler curves since the onset of degradation is not the fatigue limit of the panels. These two parameters: cycles at onset of degradation at certain core shear stress (Fig. 7) and stiffness degradation slope (Table 3) can be used to design a panel for fatigue loading.

For example, the static design requirements for floor panel are: 50 % of the maximum displacement is permitted at maximum 35% of the static strength. Assuming that most of the deflection is carried by the core, and the cyclic creep is very small, the fatigue lifetime of the panel can be obtained as follows:

i. From figure 7 the cycles at onset of degradation at 0.35 normalized core shear stress can be obtained.
ii. Combined with the stiffness degradation slopes from table 3 and percentage of allowable degradation (50%), the fatigue lifetime of the panel can be predicted using a formula below.

$$\text{Fatigue lifetime of panel} = \text{cycles at onset of degradation} + \frac{\text{percentage of allowable degradation}}{\text{stiffness degradation slope}}$$

This resulting fatigue limit is valid for sandwich-fabric panels where most of the load is transferred into the core. In reality, since the load is also distributed into the skins this fatigue limit is an underestimation.

Table 3: Stiffness degradation slopes of the panels.

Panel	GE/20/UF	GE/10/UF	GE/20/F	GE/10/F
Slope (1/logN)	-0.08 ± 0.020	-0.10 ± 0.012	-1.93 ± 0.450	-0.28 ± 0.033

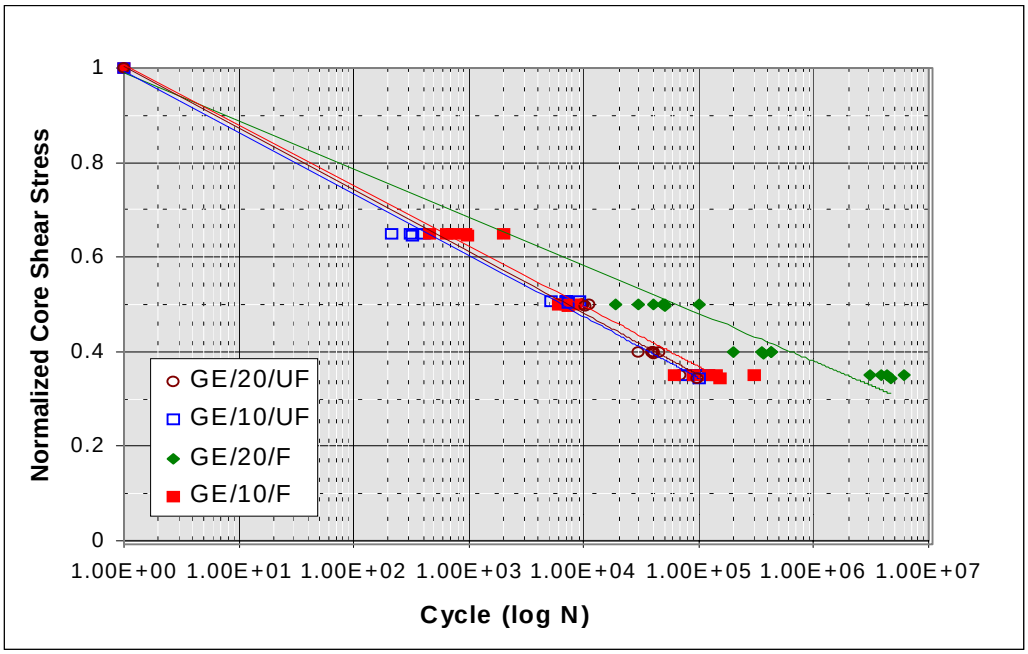
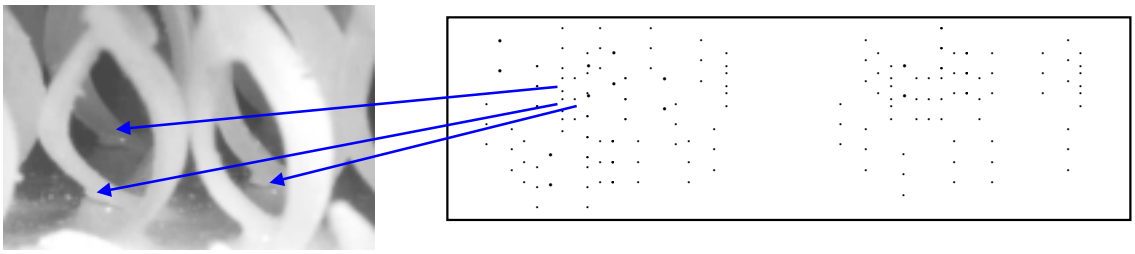


Fig. 7: Normalized Core Shear Stress versus Cycles at the Onset of Degradation of the panels.

Damage Analysis

Stereo microscopy and X-ray radiography investigations of the panels, that were subjected to cyclic loading, revealed two major types of damage for unfoamed and foamed panels: cohesive failure at the pile feet and shear cracking of the foam.

For unfoamed panels, cohesive failure at the pile feet initiates and occurs all over the panel (Fig. 8). The mechanism of how this damage started and propagated is explained in reference [1]. As this damage is the major damage that occurs in all unfoamed panels, it is responsible for the stiffness degradation of all unfoamed panels. This also can be the reason why the degradation slopes for both 10 mm and 20 mm unfoamed panels are about the same (-0.08 and -0.1 1/logN), as the same damage mechanism takes place on the panels.

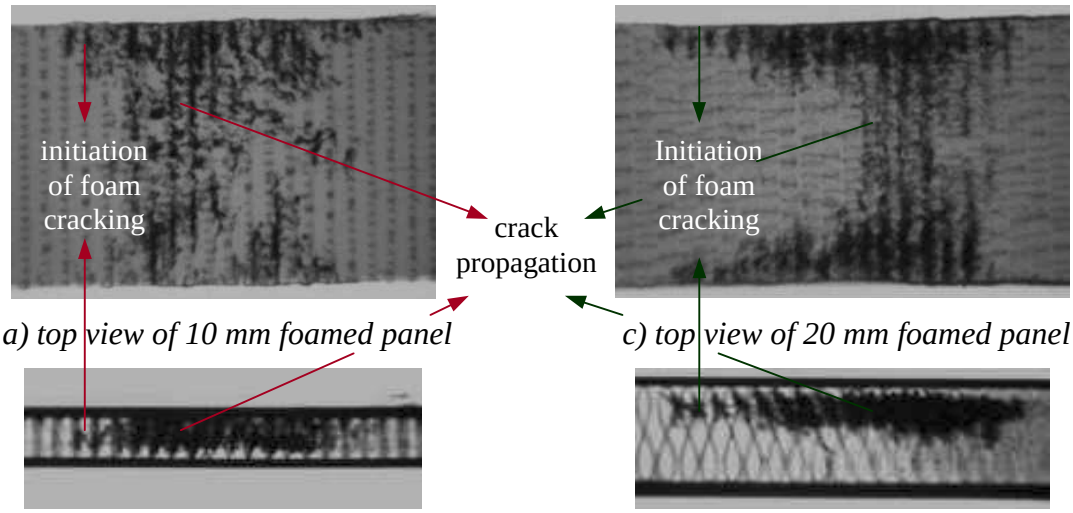


a) cohesive failure at the piles feet

b) cohesive failure all over the unfoamed panels (each dot represents a cracked pile foot)

Fig. 8: Damage in the core of the unfoamed panels.

For foamed panels, limited cohesive failure at the pile feet was found before significant degradation occurs. The significant drop of the stiffness, however, was initiated by shear cracking of the foam at the edges of the panels that propagated through the entire core over half of the span length (Fig. 9). Thus the shear foam cracking is responsible for the stiffness degradation on foamed panels. From figure 9b and 9d, it can be seen that the foam cracking in the 10 mm and 20 mm foamed panels initiates from a different location. For 10 mm foamed panels, it is reasonable that the damage initiated from the middle of the core since the core shear stress maximum occurs in that area. For the 20 mm unfoamed panel, the initial damage location occurs at the connection between two piles. It is possible that at that location, due to the shape of the piles, the high strain results in premature foam failure.



a) top view of 10 mm foamed panel

c) top view of 20 mm foamed panel

b) side view of 10 mm foamed panel

d) side view of 20 mm foamed panel

Fig. 9: Types of damage in the core of the foamed panels.

Although the same damage was obtained in the 10 and 20 mm foamed panels, comparison of the stiffness degradation slopes shows that the 20 mm foamed panels degrade much faster than the 10 mm foamed panels. This phenomenon is related to the importance of the contribution of the rather brittle PUR foam in the core properties. Looking at the contribution of the foam in the 20 mm panels, the core shear modulus increases with a factor 20. As a result if the foam reinforcement starts to crack, a dramatic stiffness drop occurs. For the 10 mm panels, the foam contribution increases the core shear modulus by a factor 2 and results in faster stiffness degradation than the unfoamed panels but not to the same extent as the 20 mm foamed panel. Thus, since the contribution of the foam as reinforcement in the 20 mm panels is much higher than in the 10 mm panels, when the foam failure occurs in the core, it will

have a more important effect in stiffness degradation on the 20 mm panels than on the 10 mm foamed panels. As a conclusion, the effect of using foam in the 3D sandwich-fabric construction as reinforcement against cyclic loading is not as significant as its effect in static reinforcement.

CONCLUSIONS

- The core shear fatigue behaviour of 3D woven sandwich-fabric panels has been investigated. Damage accumulation during cyclic loading was revealed in three phenomena: stiffness degradation, cyclic creep and the increase of hysterisis area.
- The stiffness degradation curves for the different panels are strongly influenced by the core microstructure.
- Two types of damage were found for unfoamed and foamed panels: cohesive failure at the pile feet and shear cracking of the foam are responsible for the core stiffness degradation.
- The effect of using foam in the 3D sandwich-fabric construction as reinforcement against cyclic loading is not as significant as its effect in static reinforcement.
- A fatigue design criterion for sandwich-fabric panels has been proposed. Two parameters, the number of cycles at the onset of degradation for a specific core shear stress and the stiffness degradation slope, can be used to determine the fatigue life time of 3D-woven sandwich panels.

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