Experimental and numerical evaluation of fatigue behavior of foam core sandwich structure

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Abstract

Fatigue crack growths of foam core sandwich structure loaded in three-point bending under room temperature, low temperature and hygrothermal environment have been investigated. The fatigue life and S-N curve are given, and the results of flexural fatigue test confirm the obvious effect of low temperature and hygrothermal environment on the fatigue life of foam core sandwich structure. Core shear was found to be the dominant failure mode under fatigue loading condition at all of three environments. Three-dimensional numerical simulation of the progressive collapse of foam core sandwich structure was conducted using user subroutine USDFLD in FEM software ABAQUS/Standard. The maximum stress failure criterion and Hashin failure criterion were used to judge the failure of foam core and skin, respectively. Finite element analysis explains the crack initiation and propagation under flexural load, and progressive damage method can be used to simulate the failure of foam core sandwich structure.

Keywords: Foam core sandwich, Flexural fatigue property, Crack propagation, Failure criterion

1. Introduction

Sandwich structures are widely employed in aerospace, civil and mechanical industries due to their excellent performances, such as stiffness/weight ratio, and acoustic insulation properties. Over the last decade, various improvements have been made in manufacturing of sandwich structure, and different combinations of core materials and face sheet materials have been developed. Compared with honeycomb sandwich, foam core sandwich structures have the advantage of lighter quality and better waterproof. Therefore, foam core sandwich structures are being widely replacing with honeycomb sandwich structures and other stiffened structures (Yi Ming Jen, 2009). Recently, a lot of research has been focused on the static strength and fatigue behavior of foam core sandwich structure. Basir (2006) investigated the quasi-static and flexural fatigue failure mode of sandwich structure through AE analysis. Kulkarni (2003) studied the fatigue crack growth of foam core sandwich beams loaded in flexural load. Abderrezak (2007) discussed the use of an artificial neural network (ANN) to estimate fatigue lifetime of a sandwich composite material structure subjected to cyclic three-point bending loads. However, almost the study is based on experimental method, and rare on the numerical method (Ivanez, 2010). In this paper, the fatigue behaviors of foam core sandwich structure under room temperature, cold temperature and hygrothermal environments are investigated, and the failure mode will be simulated by numerical method.

2. Experimental procedure

Cn\. Core material was foam of ROHCELL PMI71S which was homogeneous and isotropic. Both upper and lower skins were made of composite laminate T700/3234, and the symmetrical layup was [45°/-45°/0°/0°/90°/0°]s. Mechanical properties of foam core are listed in Table 1. The sandwich structure specimens studied in this paper were made by Vacuum Assisted Resin Infusion molding technology(shorted as VARI). The thickness of foam core sandwich structure was 15mm, and the core thickness was 12mm. All the specimens were 340mm in length, and 60mm in width.

The 3-point static bending tests were conducted according to GB/T1456 (2005). The experimental setup is presented in Fig.1, and the geometry of the specimen is listed in Table.2 .The diameter of the upper roller was the same as that of the lower rollers for fixture used for three-point bending. Load and support rollers had a radius of 5mm. The lower supports were placed on a rail which allowed the variation of span length, and the support span used in this test was 300mm.

Experimental tests were carried out on a material testing machine (INSTRON 8801). Static test was performed under displacement control at a constant crosshead speed of 0.5mm/min. The specimen was loaded until a load maximum was reached and load had dropped off about 30% from the maximum. The load maximum was defined as ultimate load of bending, P_{ul}.

By using the ultimate bending load acquired from the static bending tests, the maximum flexural load applied per cycle was determined at different load levels, L, as defined by

$$L = \frac{P_{\max}}{P_{ul}} \tag{1}$$

Where $P_{\max}$ is the maximum load applied per fatigue cycle. The minimum flexural load applied per cycle $P_{\min}$ was defined by stress ratio $R = \frac{P_{\min}}{P_{\max}}$ and maximum load. Fatigue testing was conducted at a stress ratio R=0.06 using a sinusoidal wave form and a frequency of 4HZ. Three-point flexural fatigue test was performed at different load levels ranging from 0.5 to 0.7.

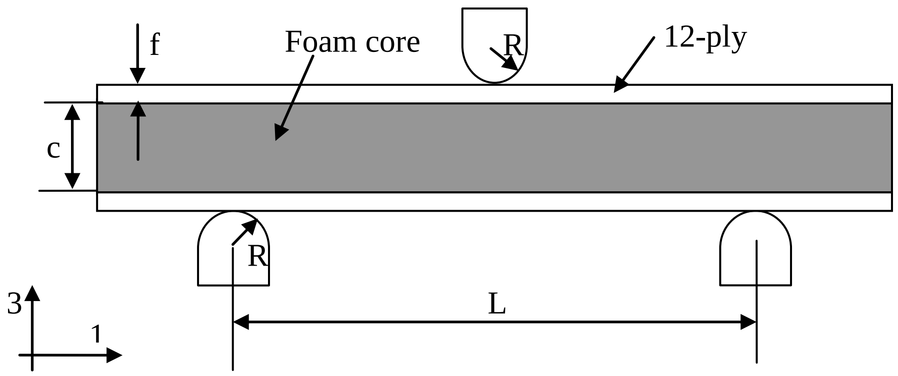


Fig.1 Three-point bending of sandwich beam with indenter and supports

Table 1 Mechanical properties of foam core material

Property	PMI71S
Nominal density (kg/m^3)	75
Modulus (MPa)	92.0
Poisson's ratio (MPa)	0.37
Tension strength (MPa)	2.3
Compressive strength (MPa)	1.5
Shear strength (MPa)	1.3

Table 2 Test configurations for 3-point bending tests

f (mm)	c(mm)	L (mm)	R (mm)
1.5	12	300	10

3. Experimental result

3.1 The effect of temperature

Flexural fatigue tests were performed at different load levels(from r=0.5 to r=0.7), but the test environment is always room temperature. Then flexural fatigue tests were performed at low temperature(-55℃) and hygrothermal environments(70℃,85%) , at load level of 55%. Five replicate specimens of sandwich structure beams were used for the flexural fatigue tests at each temperature.

The experimental results of flexural fatigue tests performed on sandwich structure beams at different test environments are presented in Table 3. The number of cycles to failure N_f was recorded just before final failure. The retention percentage is based on the fatigue life at room temperature. The coefficient of variation(short for COV) reflects the discrete degree of fatigue life. All the COVs of fatigue life at three test environments are less than 30%, and it represents that the experimental data are in creditable range. From Table 3, it can be seen that the number of cycles to failure N_f is the greatest in cold temperature, and smallest in hygrothermal environment.

From the results of flexural fatigue test, it can be seen that the cold temperature can improve the property of sandwich structure. However, hygrothermal environment greatly reduces the fatigue property. The failure mode of foam core sandwich structure under room temperature, cold temperature and hygrothermal environment is almost the same to each other, and all the specimens failed suddenly due to core shear, as seen in Fig.2. The entire crack formation and growth sequence occurred in a fraction of a second, and the final crack pattern observed under static loading appeared to be quite similar to that of fatigue loading. The crack initially occurred at the interface under the loading point, then propagated along the interface between the upper skin and foam core, but after a short distance crack propagating path deflected, and the crack propagated along the interface between the lower skin and foam core until final failed.

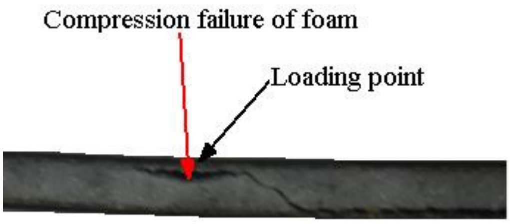


Fig.2 Failure modes of foam core sandwich beams

Table 3 Fatigue life of glass/PEI sandwich beam at different temperature

Test environment	Experimental data		
	N_f	Retention percentage	COV
Room	131708	100%	28.7%
Cold	164964	↑25.25%	22.5%
Hygrothermal	73822	↓43.04%	29.7%

3.2 S-N curve

Summarized, fatigue models can be generally classified into three categories: S-N curves; the residual stiffness/strength model; and the progressive damage model. All the three categories of fatigue models are aimed to determine final failure and the fatigue life of composite or metal material. S-N curves do not take into account damage accumulation, but they predict the number of cycles to failure under fixed loading conditions (Hashin Z, 1973 and Fawaz, 1994). Therefore, S-N curve is widely used in the prediction of the number of cycles to failure.

For convenience, the modified S-N curve was plotted with maximum applied load/ultimate load, Pmax/Pul, (which is also defined as the load level L) on the Y-axis, and the number of cycles to failure on the X-axis. The modified S-N curve data at room temperature is shown in Fig.3. Modified S-N curve shows that the number of cycles to failure of foam core sandwich structure increases with reductions in the load level, L. The fatigue life at load level of 50% is nearly one hundred million times, so the fatigue limit strength of the foam core sandwich structure is about 50% of the ultimate strength. The S-N equation as shown in Eq.(3) can be used to evaluate the fatigue life of foam core sandwich structure.

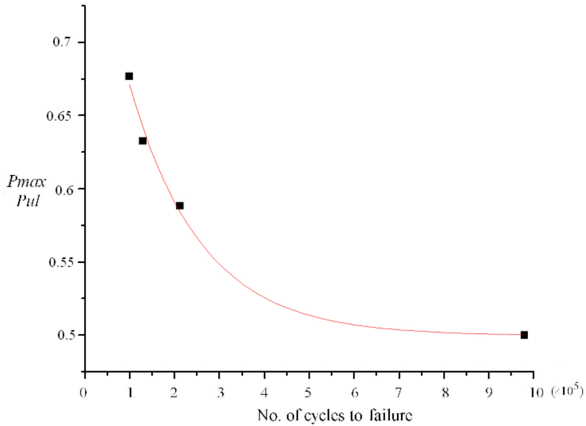


Fig.3 Modified S-N curve data for foam core sandwich structure on fatigue life

$$L = 0.21exp(\frac{-N}{179943}) + 0.50 \tag{2}$$

There are many proposed experimental results charactering the damage evolution of composite laminates by stiffness degradation, but rare on foam core sandwich structure. In this study, the shear stiffness of foam core sandwich structure was obtained through the load of displacement. The curve is demonstrated in Fig.4, showing the shear stiffness degradation under load level of 55% at room temperature. The fitting equation is shown in Eq.(3) which can be used in the evaluation of fatigue life.

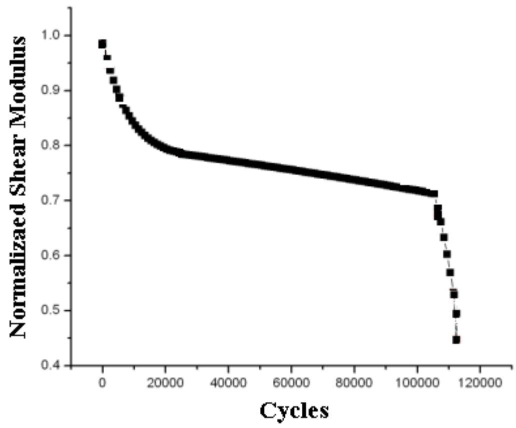


Fig.4 Shear stiffness under room temperature at load level of 55%

$$\begin{aligned}
\Delta G &= 0.218\exp(\frac{-N}{8303.9}) + 0.775 \\
\Delta G &= 1 - 0.217\exp((N - 24415)\times 3.67\times 10^{-6}) \qquad (3)\\
\Delta G &= 1 - 0.285\exp[(N - 105322)\times 8\times 10^{-5}]
\end{aligned}$$

4 Finite Element Analysis

To simulate damage initiation and propagation until the final damage occurs, progressive damage models have been developed and implemented by finite element method. The commercial package ABAQUS was used to develop the finite element(FE) model of foam core sandwich structure and carry out the progressive damage analysis through the user subroutine USDFLD. In the present analysis, the material properties of composite skin and foam core both depend on three field variables based on failure criterion. The procedure is as below: firstly perform a stress analysis, then check for failure at each integration point by using a set of failure criterion, and thirdly, if failure occurred, degrade the material properties. This procedure must be repeated at every increasing load level until the analysis is not convergence because so many integration points fail(ABAQUS V6.10).

4.1 Finite Element Model

Two dimensional (2D) four-node quadrangle elements(S4R) were used for face sheets and three dimensional (3D) eight-node brick elements (C3D8R) were used for foam core. The foam core was modeled as homogenous and isotropic, and the cell structure was not considered. The skin and foam core were joined together through 'tie' interaction in ABAQUS, and the FE model is shown in Fig.4.

The lower rollers, upper roller and foam core sandwich structure were modeled, respectively. In order to prevent the contact surfaces from penetrating into each other, contact pairs were defined between the surfaces that contact with each other. The surfaces of lower and upper roller were modeled as master surfaces, while the ones of specimen were modeled as deformable surfaces.

The displacement load along through-thickness direction of foam core sandwich structure was loaded on the indenter. The lower rollers were restrained in all the translational and rotational degrees, while the upper indenter was restrained in all the six degrees except the load direction.

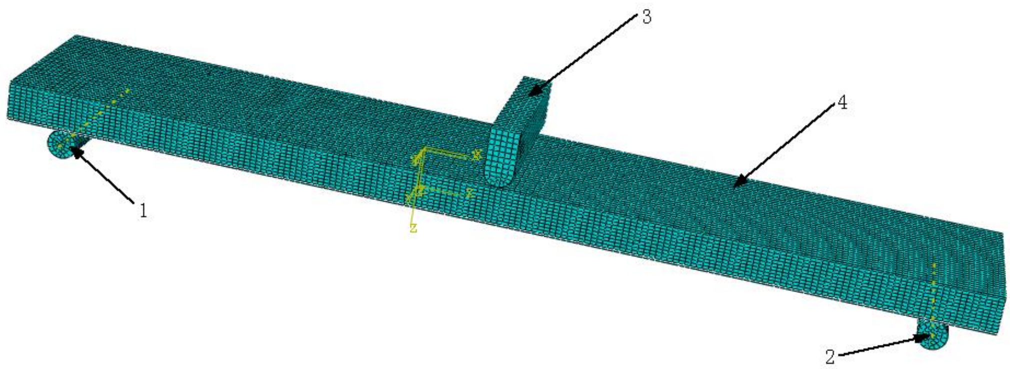


Fig.4 FE model of three-point bending

4.2 Failure criterion

In this study, research was focused on the failure of foam core and skins. Hashin failure criterion is used to assess the severity of the stress state and decide which regions of the laminates skins will fail (Hashin Z, 1980 and Marie-laure Dano, 2000). The maximum stress failure criterion is used to judge the foam core element failure. According to the maximum stress failure criterion, failure occurs when one stress component along the principal material axes exceeds the corresponding strength in that direction.

$$\begin{cases} \sigma_t > [\sigma_t] \\ \sigma_c > [\sigma_c] \\ S > [S] \end{cases}$$

where $[\sigma_t]$, $[\sigma_c]$ and $[S]$ are the tensile strength, compression strength and shear strength, respectively. All the strength values are listed in Table 1.

5 Results and Discussion

From the experiment, the failure mode is directly viewing, but the reason that causes the failure mode was still unknown. In this section, the bearing strength, failure mode and propagation of failure are investigated numerically, and the reason will be revealed. The three-point bending load of foam core sandwich structure at room temperature was simulated by the method in section 4, and the result will be compared with the experiment data.

Table 4 The static strength and fatigue life of foam core sandwich structure

	Experimental data	Simulations	Error
Strength /N	1600	1701	6.31%
Fatigue life /time	106829	82152	23.10%

Table 4 gives the experimental and numerical results. The bending load predicted is 1.701KN, and the experimental result is 1.6KN. The difference between simulation and experiment is 6.31%. It is approved that the numerical method can be used to evaluate the failure load of foam core sandwich structure under three-point bending load.

The simulation result shows that the stress S13 and S33of foam core is bigger than other components, and the stress S13 plays a main role in the process of damage progression. Therefore, the stress S13 is used to evaluate the fatigue life of foam core sandwich structure. The distribution of stress S13 is given in Fig.5. The maximum S13 is 0.7517MPa, and the stress ratio is 57.82%. Based on the S-N curve in Eq.(2), the fatigue life was calculated, and the result is listed in Tab.4. From the Tab.4, the difference of predicted result and experimental data is less than 23.1%, which is in the tolerance design. So the stress S13 is the appropriate parameter to evaluate the fatigue life of foam core.

Fig.6 shows that damage progressive of foam core structure. The main failure mode of foam core sandwich structure is compressive failure and shear failure. When the load is 1432.6N，compressive damage firstly occurred at the middle of foam core under the upper skin, and then extend to the bottom and span size of the foam. And shear damage occurred at the load of 1701N, later than compressive damage, as the compressive stress is bigger than shear stress. Shear damage extend mainly along the interface of foam core and the lower surface.

From damage progression analysis, it can be seen that the foam core sandwich structure firstly fail in compression at the middle of foam core, then the damage extend along the interface of upper skin and foam core. In the second stage, the failure mode is the combination of compression and shear, but the compression damage predominate the failure mode. In the next stage, the shear failure becomes the main failure mode, the damage changes direction, and extends along the interface between the lower skin and foam core. The progression procedure obtained numerical analysis is coincided with experimental result. Therefore, progressive damage method can be used to simulate the failure of foam core sandwich structure.

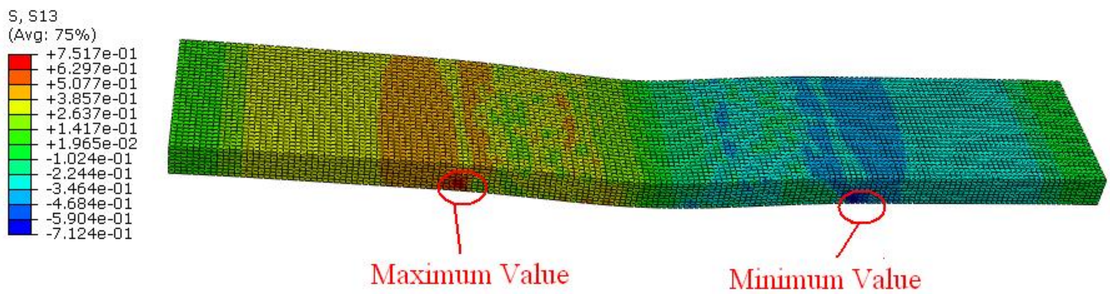
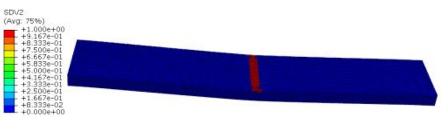
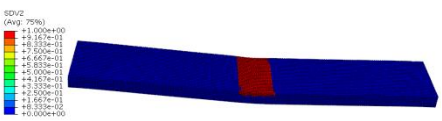
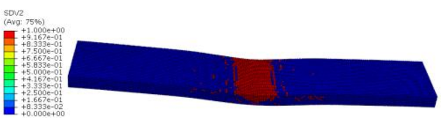
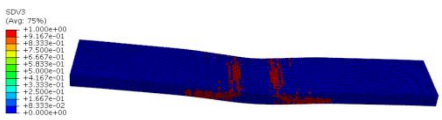


Fig.5 Stress (S13) contour of foam core

Fig.6 Damage progression of foam core

Load /N	Compressive damage	Shear damage
1432.6		--
1701		
1229		

6. Conclusions

The static and fatigue properties of foam core sandwich structure loaded in flexural load under room temperature, low temperature and hygrothermal environment were investigated by experimental method. Besides, the maximum stress failure criterion and Hashin failure criterion were used to judge the foam core and skin, and damage initiation and propagation of sandwich structure were simulated by finite element method. On the basis of the above work, some useful conclusion can be drawn.

(1) The flexural fatigue tests under different environments shows that the number of cycles to failure N_f is the greatest in cold temperature, and smallest in hygrothermal environment.

(2) The main failure mode of foam core sandwich structure is compressive failure and shear failure. Compression failure results in the damage initiation, but shear failure is the reason for damage progressive.

(3) The progression procedure obtained by numerical analysis is coincided with experimental result. Therefore, progressive damage method can be used to simulate the failure of foam core sandwich structure.

Acknowledgements

This study is supported by Fundamental Research Fund (JC201237, JC20120231) at Northwestern Polytechnical University and National Science Foundation(No:51205315).

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