Materials Physics and Mechanics. 2022;48(2): 217-231
Research article
http://dx.doi.org/10.18149/MPM.4822022_7
Received: June 24, 2021
Accepted: April 13, 2022

EXPERIMENTAL INVESTIGATION OF THE MECHANICAL BEHAVIOR OF HONEYCOMB SANDWICH COMPOSITE UNDER THREE-POINT BENDING FATIGUE

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Abstract. The present experimental work deals with the mechanical fatigue behavior under 3-point bending stress of composite aluminum panels with an aramid honeycomb core. The testing conditions (applied load and frequency), under cyclic loading, the analysis of rigidity loss, and the damage modes are the tools for this experimental investigation. The specimens consist of aluminum sheets, one millimeter thick each for the skins, and a honeycomb aramid structure, eight millimeters high for the core. As a first approach, the static 3-point bending tests made it possible to determine the deflection variation as a function of the force applied, which will be exploited to carry out fatigue tests on an EPSIFLEX machine type. They are made for three loading levels of imposed deformation with a load ratio of 0.2 and a frequency of 5 Hz. The results obtained allowed the determination of the stiffness loss curves and the Wöhler curves in order to optimize the loading conditions and the service life of the sandwich composite material. The tests were carried out for 3 cyclic loading; they show that the optimal load ensuring better service resistance of the experimented sandwich panels is 0.7 of the material elastic limit (720 N). Static and cyclic flexion fractography showed the different modes of skin damage (indentation) and honeycomb core (delaminating and shearing) leading to the specimens' ruin.

Keywords: 3-point bending, composite material, stress amplitude, fatigue threshold, damage

***Acknowledgements**. No external funding was received for this study.*

Citation: Mzad H. Experimental investigation of the mechanical behavior of honeycomb sandwich composite under three-point bending fatigue. *Materials Physics and Mechanics.* 2022;48(2): 217-231. DOI: 10.18149/MPM.4822022_7.

1. Introduction

Composite materials are materials with specific mechanical properties, namely low density, high strength, high rigidity, and excellent durability. There are two main categories of composite materials used in the industry: laminate composites and sandwich composites. In a simple way, sandwich structures are composed of two thin skins and a light-thick core between them. Their lightness and good bending properties have increased their use, particularly in the aeronautical industry and civil infrastructure.

Kiyak et al. [1] have experimented, under three-point bending and compression tests, with various cell structures of sandwich composites having a carbon fiber core. The results show that cell shape and cell density change are parameters that affect bending and compression peak loads in the same proportion. A numerical validation of the results was performed using the commercial code ANSYS.

Many structural parameters affect the mechanical behavior of these complex systems: the nature of material constituents, the stacking sequences, and the relative thicknesses of the different layers [2, 3].

Du et al. [4] have fabricated, in the laboratory, light-weight sandwich panels containing biofiber-based paper-reinforced polymer (PRP) composites as the skin materials. Their investigation focused on the fabrication process, testing, effects of the honeycomb core cell size and core height on flexural properties, and load-deflection behavior of the sandwich panels.

The tailor-folding method was proposed in order to fabricate a composite sandwich panel with a carbon fiber reinforced polymer (CFRP) hexagon honeycomb core [5]. This method has the potential to automatically fabricate the composite sandwich panel, with the advantage that the continuous fibers reduce the stress concentration and reinforce the constraints between the adjacent cell walls.

Belingardi et al. [6] performed experiments on both undamaged and partially debonded face specimens of sandwich honeycomb beams. The study allows monitoring the specimen's bending stiffness variation during fatigue cycling and determining residual properties after fatigue cycling. In the study presented by Al-Fasih et al. [7], the impact damage under four-point loading of cracked honeycomb composite beams was investigated. The elaborated model helps to prevent any anticipated failure of composite structures containing skin defects.

The effects of environmental factors, as well as loading frequency and block loading, on the fatigue life of honeycomb core composite sandwich structures were considered in several analytical models and experimental works [8-10]. Three-point failure modes in aramid-aluminium composite sandwich beams under dynamic fatigue loading were assessed within a defined range of excitation frequencies and loading levels.

Jen et al. [11] studied the impact of the face sheet thickness on the fatigue strength of aluminum composite panel specimens under four-point bending fatigue tests. A number of local parameters are utilized; they have been shown to correlate adequately with the fatigue life data of the studied specimens with various honeycomb core densities.

The experimental labor proposed by Shi et al. [12] deals with the conception of stronger sandwich structures using carbon-fiber face-sheets and an aluminum-honeycomb core. The approach used combines the concepts of resin-fillet reinforcement and short-Kevlar-fiber interfacial toughening.

Mamchits et al. [13] proposed an alternative composite version of a hatch cover design using an innovative method of manufacturing. Numerical methods were used to select the most rational materials and design parameters. The study was concluded by the assessment of the economic expediency of the production of composite hatch covers.

Han et al. [14] evaluate experimentally the effects of out-of-plane compression and transverse shear of honeycomb-corrugated hybrid sheets under three-point bending. By ensuring good interfacial bonding in the hybrid-cored sandwich, the strength and energy absorption are both greatly improved, which allows the use of these structures for ultralight load-bearing and energy-absorbing applications.

Many studies have been conducted to investigate the effects of potential flaws in composite structures, such as fiber laying direction defect and fiber straightness defect, on the effective mechanical properties [15, 16]. The findings revealed that accounting for imperfections in the composite microstructure, such as fiber laying direction deviation and fiber curvature, was of limited importance. However, the configurations L and W of honeycomb cells affect the sandwich lifetime.

Sankaranarayanan et al. [17] explored the impact of zirconium carbide (ZrC) and magnesium on the mechanical and tribological properties of aluminium matrix composites. Their study revealed that the hybrid aluminium composite can be considered a unique material with high strength, low weight, and wear resistance. Moreover, within the framework of the molecular dynamics method, Rozhkov et al. [18] conducted a simulation on the mechanical behavior of a graphene nano-inclusion in a matrix of zirconium dioxide stabilized by yttrium oxide. According to the constructed model, defect-free graphene manifests itself as an excellent reinforcing element of the composite.

Hussain et al. [19] performed a computational method on the fatigue behavior of honeycomb sandwiches using the commercial package ANSYS. The model based on actual experiments allows the prediction of flexural strength and fatigue life of aluminum honeycomb sandwich structures under three-point bending conditions.

A three-point static bending study was carried out on two types of laminated composite materials to assess the influence of the test speed and the effect of the stacking sequence on their mechanical behavior [20]. The laminates, reinforced with E fibers and an epoxy resin matrix, were manufactured by a successive lamination process of sixteen identical reinforced layers and then subjected to vacuum polymerization. The experiments revealed that the ply orientation has an influence on the flexural modulus and the fatigue resistance, which decreases when the plies at 0° and 90° are alternated.

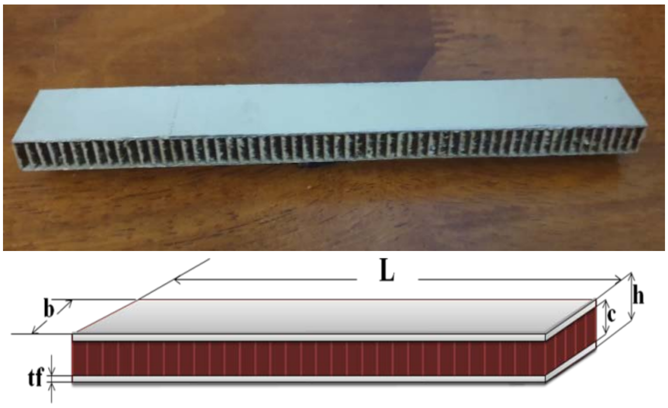
The aim of this work is to determine the mechanical fatigue behavior of sandwich composite (aluminum/aramid) panels with a honeycomb core, in 3-point bending, under varied loads. In particular, the rigidity loss evolution in function of load in order to identify the optimal conditions for using this type of sandwich panel, allowing a better lifetime. Static and cyclic tests were performed on four specimens for the loading levels of 90%, 80%, and 70%. The experimental results obtained on the structure's behavior and damage will be presented and analyzed.

2. Test conditions

Geometrical specifications. Sandwich composites have been designed with the intention of providing greater flexural rigidity while maintaining minimal mass. The materials used are selected according to the rigidity and the desired tensile or compressive strength: metal, composite laminate made of glass or carbon fibers. For applications requiring higher stiffness, honeycomb-structured cores are used.

The considered specimens (Fig. 1a) are cut according to the L-direction of sandwich panel cells (Fig. 2), with aluminum skins and a honeycomb-shaped aramid core. Their dimensions (Fig. 1b) have been defined according to the specifications of ANSI A208-2. The width (*b*) of the specimen is set at 25 mm to meet the standard requirements. The skin (*tf*) is 1 mm thick, while the core and the structure are, respectively, c = 8 mm and h = 10 mm. The total length (L) of the test piece is 210 mm.

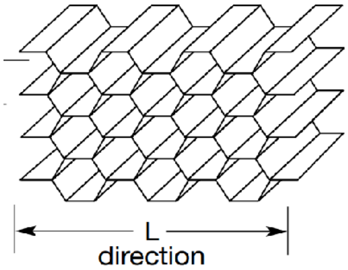
Material properties. Sole design influences the mechanical properties of sandwich composites. Honeycomb cores have a hexagonal structure that curves moderately, but the cells deform depending on the orientation, and the mechanical properties are modified. The core and skin properties of the studied sandwich panel are given in Table 1. The core is made up of aramid cells with a 148 kg/m^3 density in the shape of regular hexagons with an inscribed circle of 6.4 mm in diameter (Fig. 2).



(a)

(b)

Fig. 1. (a) Sandwich specimen **(b)** Dimensions according to ANSI A208-2



Parameter
$\theta = 30°$
D = 6.4 mm
a = 3.695
b = 3.695
t' = 400 µm
t = 175 µm

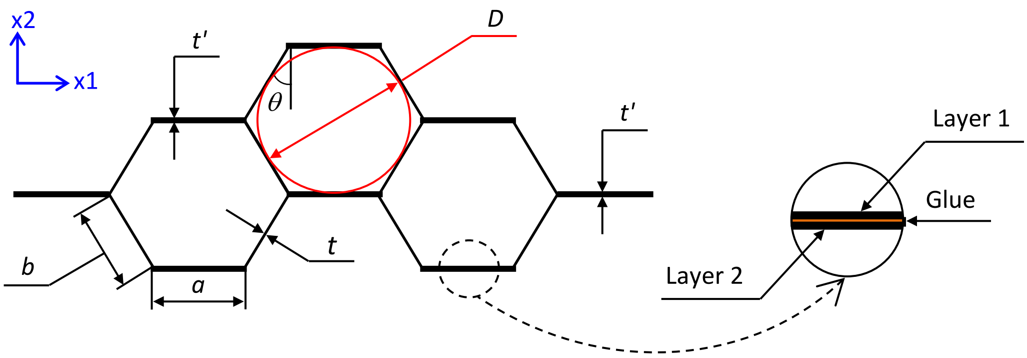


Fig. 2. Honeycomb cell description

Table 1. Composite mechanical properties [31]

	Material property	**Value**
Aramid core	Cell size	3.2 mm
	Density	148 kg/m^3
	Shear resistance (L direction)	3.5 MPa
	Shear Modulus (L direction)	130 MPa
	Compressive strength (L direction)	15.5 MPa
Aluminium Skins	Young's modulus	70000
	Fracture resistance	270 MPa
	Tensile strength	370 MPa
	Elongation to break	13%
	Poisson coefficient	0.33

Testing scheme. The tested sample is mounted in the support fixture. The edges of the panels were mounted between two rounded purlins. In order to avoid horizontal test tubes moving, a pretension F_{min} is applied to each level, which generates an arrow f_{min}. Figure 3 shows the load application points, the method of fastening and the point at which the displacements are measured.

F_0 is the force applied to the specimen at the beginning of the fatigue test. Its value represents a percentage of the maximum force determined during the static test (F_{el}). This percentage defines the selected three loading levels (90%, 80%, and 70%) under a loading frequency of 5 Hz.

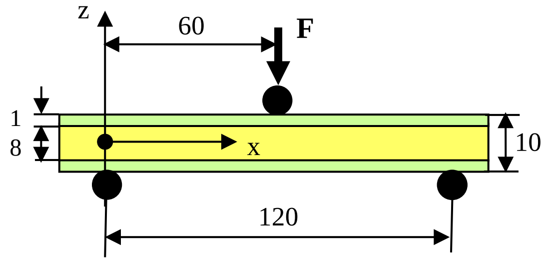


Fig. 3. Assembly of the specimen

3. Static tests

Procedure. Static bending tests were performed on a WDW-5 computer-controlled universal testing machine (Fig. 4), with a load cell of 50 kN. This machine was manufactured in China by Jinan (Shandong).

On the basis of three test tubes, the static bending experiments were carried out. Graphical results obtained show the loading force as a function of displacement (Fig. 5.1). A curve magnification in the elastic zone makes it possible to better discern the experimental results (Fig. 5.2).

Test conditions
Number of tests: 4
Speed: 5 mm/mn
Standard ANSI A208-2: L = 120 mm
Temperature: 27°C

Fig. 4. Static bending test machine: Universal Machine WDW-5

Analysis of static results. As illustrated by static bending tests (Fig. 5.1), the structural response of the sandwich panels investigated can be considered linear until the first failure occurs during in-plane compression loading. The equation below for Young's modulus, E_e, describes the effective structural response:

$$E_e = \frac{1}{2\text{tf} + \text{c}}\left(2\text{tf}\, E_f + \text{c}\, E_c\right).$$

Material and geometrical properties are expressed in the above equation by skin and core thicknesses *tf* and *c*, and, respectively, E_f and E_c the moduli in the load direction of the skins and core.

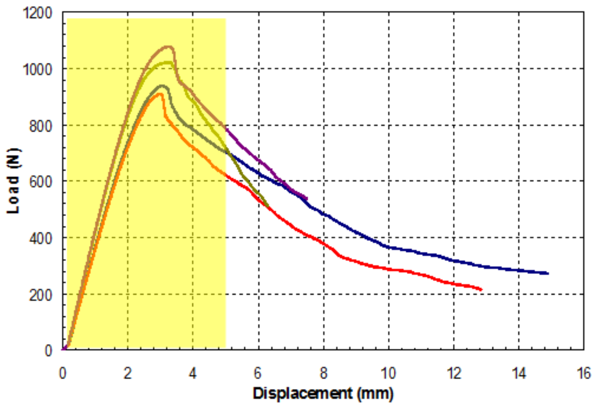


Fig. 5.1. Static bending tests

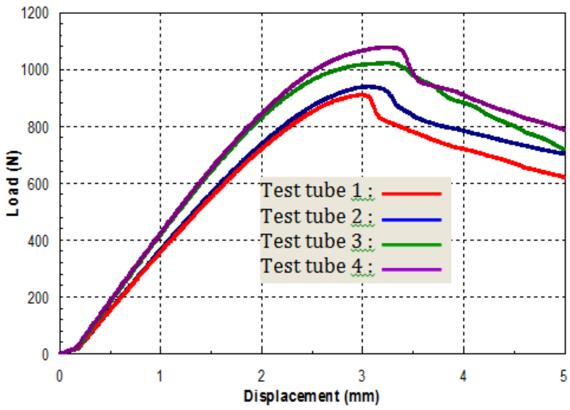


Fig. 5.2. Zoom in elastic zone (in yellow)

When compressed in the in-plane direction, the load is mainly carried by the face-sheets of the sandwich, whereas the core stabilizes the structure and prohibits premature buckling of the face-sheets.

The start of loading causes compression of the core, in particular the adhesive, due to its viscoelastic property. In our opinion, the appearance of a small slope at the beginning of curves is due to imperfect test conditions; there is elimination of gaps, backlashes, etc. If the compression of the structure is continued after the initial failure, the damage will start to propagate through inelastic deformation until the core damage.

In Figure 5, one can make a distinction between two deformation zones:

- A linear zone corresponding to elastic deformation up to the limit value, F_{el} = 720 N.

- A non-linear zone representing plastic deformation up to the maximum value, F_{max} = 960 N.

It is necessary to maintain the stresses to which the material will be subjected in the elastic range. So that the maximum value of the applied force F_0 tends to the elastic limit force F_{el}.

4. Fatigue tests

Procedure. The bending fatigue experiments were carried out on the testing machine INSTRON 4400 (Fig. 6) with a load cell of 250 daN of imposed arrow. A force sensor, mounted on the cell, transmits the measurements to a connected computer-assisted navigation (CAN), equipped with processing software. This machine was manufactured in China by Beijing Jinshengxin Testing Machine Co., Ltd.

Three-point bending fatigue tests were performed for 3 loading levels of the elastic limit force F_{el} (F_0 = 648 N, F_0 = 576 N, and F_0 = 504 N). As this fatigue machine is of constant deformation, it is necessary to determine the maximum deflection corresponding to F_0 for each level.

Three tests were carried out with loading levels of 90%, 80%, and 70% of the maximum elastic stress amplitude (F_{el}). The frequency (*fr*) was set at 5 Hz and the load ratio (*R*) at 0.2. Sample tests were conducted by determining the displacements and measuring the forces required for them. The displacement, expressed below, corresponds to an arrow difference (Δf) caused by the initial load force (F_0) and a pretension force (F_{min}).

$\Delta f = f_{max} - f_{min}.$

Fig. 6. Bending fatigue machine: INSTRON 4400

Preliminary setting data are as follows:

- At a load level of 90%, the pretension force is set as: F_{min} = 130 N and the fixed displacement is:
Δf = 1.8 – 0.36 = 1.44 mm.

- At a load level of 80%, the pretension force is set as: F_{min} = 115 N and the fixed displacement is:
Δf = 1.57 – 0.32 = 1.25 mm.

- At a load level of 70%, the pretension force is set as: F_{min} = 100 N and the fixed displacement is:
Δf = 1.375 – 0.275 = 1.1 mm.

Table 2. Experimental data with a test end criterion of 90%, R = 0.2, and fr = 5Hz

		Sample 1	**Sample 2**	**Sample 3**
90% Load	N	11750	18250	96050
	F/F_0	0.9		
	Max arrow amplitude (mm)	1.8		
	Deformation amplitude déformation	0.015		
	Stress amplitude (MPa)	1050		
80% Load	N	102050	154550	321050
	F/F_0	0.8		
	Max arrow amplitude (mm)	1.57		
	Deformation amplitude déformation	0.013		
	Stress amplitude (MPa)	918		
70% Load	N	1143050	1435550	2007050
	F/F_0	0.7		
	Max arrow amplitude (mm)	1.375		
	Deformation amplitude déformation	0.013		
	Stress amplitude (MPa)	918		

Table 3. Experimental data with a test end criterion of 75%, R = 0.2, and fr = 5 Hz

		Sample 1	**Sample 2**	**Sample 3**
90% Load	N	16650	22550	114050
	F/F_0	0.9		
	Max arrow amplitude (mm)	1.8		
	Deformation amplitude déformation	0.015		
	Stress amplitude (MPa)	1050		
80% Load	N	120050	175550	394550
	F/F_0	0.8		
	Max arrow amplitude (mm)	1.57		
	Deformation amplitude déformation	0.013		
	Stress amplitude (MPa)	918		
70% Load	N	1435550	2047550	2416550
	F/F_0	0.7		
	Max arrow amplitude (mm)	1.375		
	Deformation amplitude déformation	0.013		
	Stress amplitude (MPa)	918		

Composite design in the case of fatigue loading is usually characterized by an S-N curve, from which one may obtain the Wöhler curve. Thereafter, this can be represented as a curve giving the value of the cyclic stress amplitude. Unfortunately, the software used by the available testing machine uses only forces in the ordinate axis instead of stresses. Nevertheless, we believe that the shape of the obtained curve is very significant and similar to the S-N curves usually presented. To achieve Wöhler curves, the experimental tests were carried out at constant deformation amplitude (CDA) with two test end criteria of 90% and 75%. The loading ratio R and the excitation frequency fr were maintained constant.

The illustrative tables, Table 2 and Table 3, summarize the results obtained for the four sample groups. It can be seen that the load level and the test end criterion have an influence on the necessary number of cycles to obtain a resistance loss of 10% and 25%, respectively.

Ten years ago, Manca et al. [21] examined the fatigue crack growth in foam-cored and E-glass/polyester face sheet sandwich composites using the mixed mode bending (MMB) test method. Fatigue tests were performed at 80% of the static critical load, at load ratios of R = 0.1 and 0.2. Fatigue crack growth results revealed that the main crack propagated in the core or in the face laminate at the debond crack tip.

Analysis of fatigue tests. A series of fatigue tests were conducted on a number of specimens of the material at different stress levels. The stress endured is then plotted against the number of cycles sustained (Fig. 7). The fatigue process is thought to begin at an internal or surface flaw where the stress is concentrated. By choosing lower and lower loading levels, a stress value or load ratio (F/F_0) may be found which will not produce failure, regardless of the number of applied cycles N. This stress value corresponds to the maximum stress amplitude. The applied force varies in amplitude depending on the cycle number resulting from the material resistance loss. The plotted stress-cycle diagrams show no clear fatigue threshold.

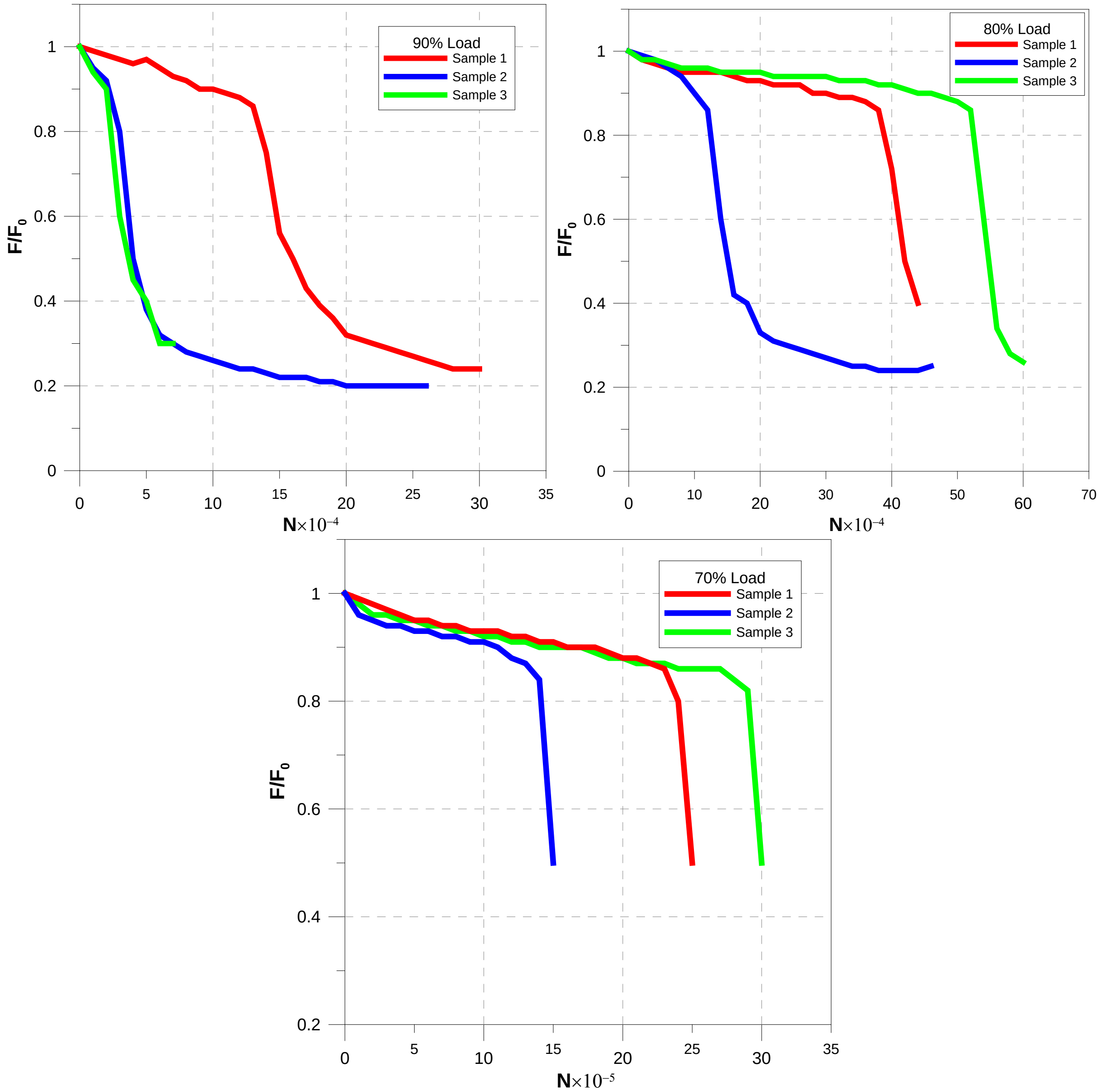


Fig. 7. Resistance loss curves for different loading levels

The discrepancies in the fatigue test results obtained for identical samples are due to the unevenness of the adhesive film of the interface between the skins and the core, as well as to the different positions of the section plane of the specimens relative to the core cells. The debonding of the adhesive between the face sheet and the core was identified as the major failure mode when analyzing the four-point bending fatigue strengths of aluminum honeycomb sandwich beams with cores of various relative densities [22].

The possibility of predicting the durability of an adhesive bitumen mix with mineral components of asphalt concrete has been proved [23]. It was established that due to thermostating, the quality of the adhesive bonding of bitumen can be significantly improved, which can provide increased strength, durability, and wear resistance.

The resistance loss presents distortions due to the different positions of the specimen's cutting plane relative to the extreme cell contours that modify the sole section and, consequently, its quadratic moment on the one hand, and the irregularity of the adhesive film between skins and core on the other hand (Fig. 7). In fact, previous experimental results revealed that the main failure mode of sandwich panels made of Nomex and carbon fiber reinforced polymer (CFRP) was the fracture in the honeycomb wall. Sandwich structures in the form of L-joints have been tested under bending load to investigate the mechanical performance during structural deformation and damage evolution [24]. Moreover, the hexagonal honeycomb cells were characterized in an FE model with an elasto-plastic constitutive model and damage criterion in detail during impact [25].

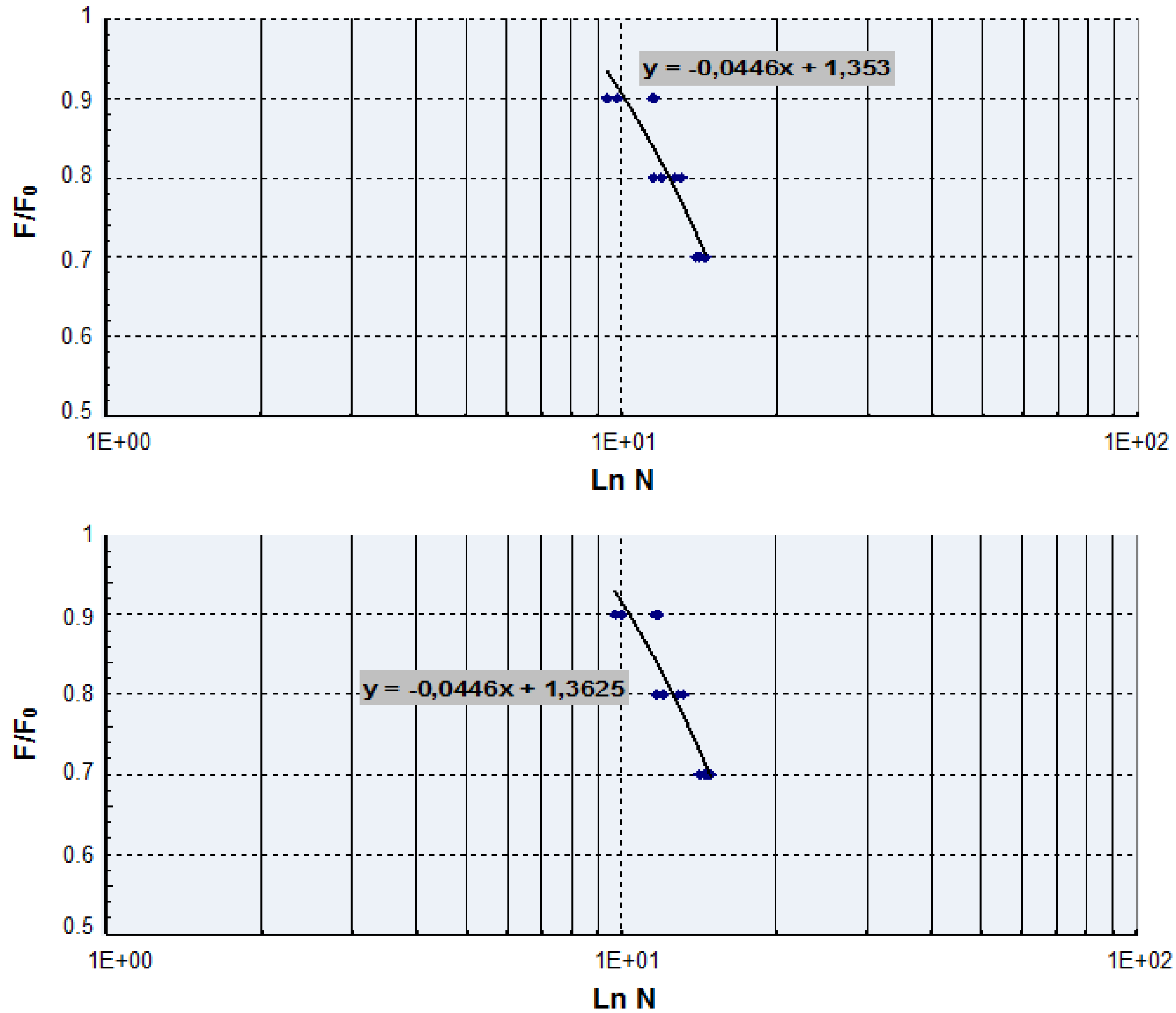


Fig. 8. Fatigue testing results

It can be seen that the curve shape (Fig. 8) tends to a constant slope. In fact, the last points show that it will be asymptotic at the value of F/F_0 = 0.7, representing the fatigue threshold. According to Wöhler curves (Fig. 9), the maximum stress amplitude of this material was reached for the following cycle numbers:

- 2×10^6 for the test end criterion of 90%.
- 3×10^6 for the test end criterion of 75%.

In this context, numerical simulations have been carried out to predict the fatigue life of honeycomb sandwich structures. Experimental characterizations were developed to describe the static and fatigue behaviors of the Nomex honeycomb sandwich under out-of-plane pressure load and bending load. From the strength and stiffness calculated results, critical parameters of fatigue behavior experiments could be set, including the maximum load, stress ratio, and loading frequency [26].

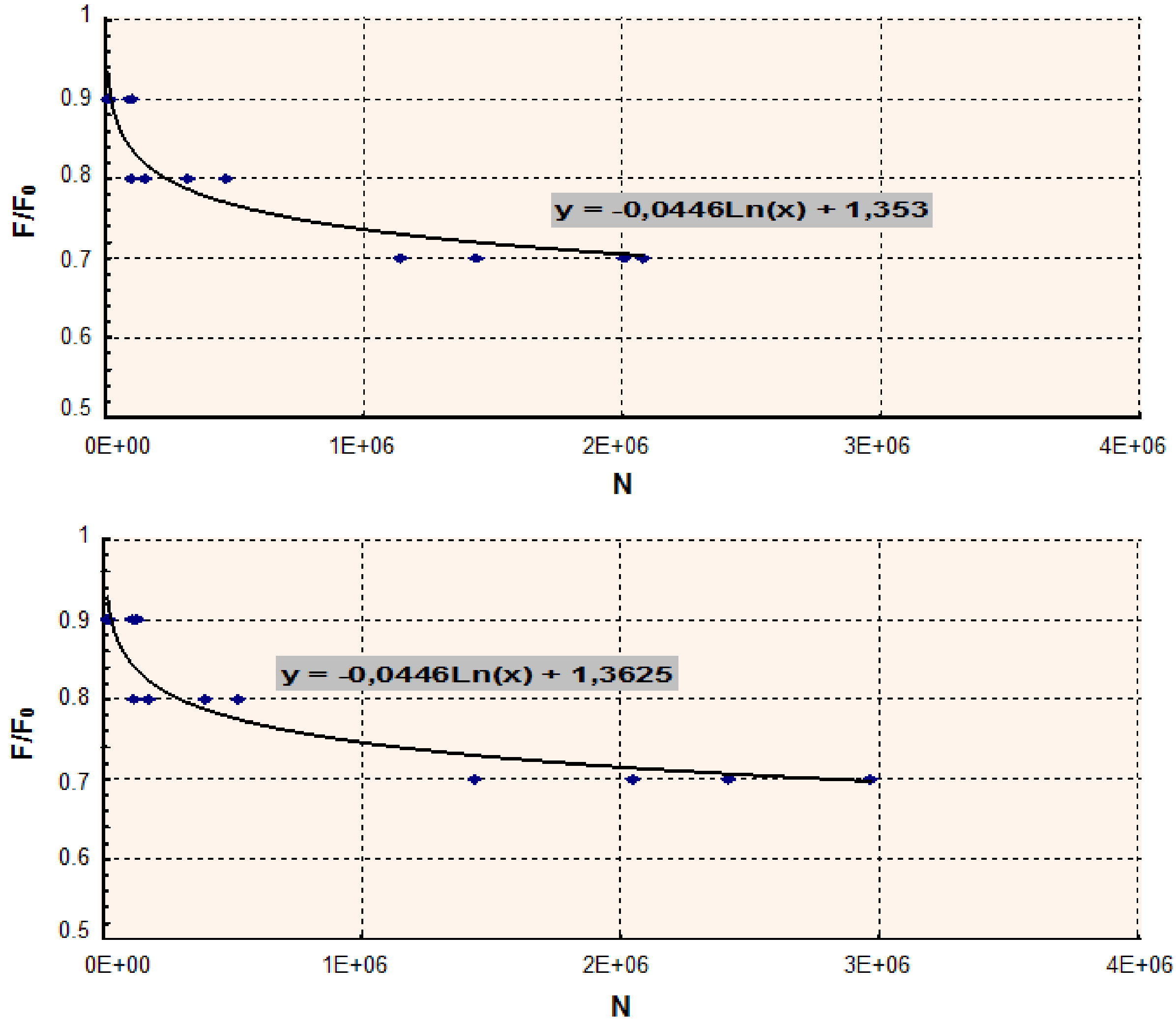


Fig. 9. Wöhler curves

The fatigue response of commercial aluminum honeycomb sandwich panels subjected to three-point bending loading conditions was tested experimentally. Two different collapse mechanisms were detected: for larger supports span, a fracture of the tensioned skin was observed, whereas lower supports span produced core shear [27].

5. Material damage

For the fracture mechanics analyses in fatigue and bending testing (Figs. 10 and 11), an optical microscope together with image analysis is utilized. The equipment consists of three parts: an optical microscope, a macro-observation system, and a PC with software for image analysis.

Observation of the rupture facies in static and cyclic flexion showed the different modes of damage to the skins (indentation) and the honeycomb core (detachment and shear) causing the deterioration of the samples (Figs. 10 and 11). In terms of damage, we can perceive during static bending and fatigue cyclic stress:

- Shearing occurs when the skins are indented and the sole cells burst, as shown by the red circle in Fig. 10.

- The disbond of the core is indicated by the red arrows in Fig. 11.

Fig. 10. Shearing of the core walls

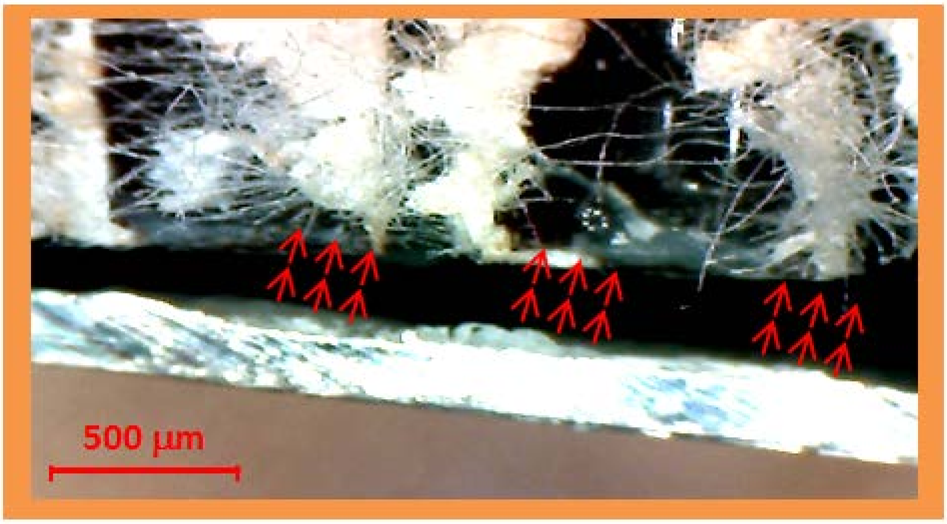


Fig. 11. Disbond of the core

The damage propagation due to core disbond in honeycomb sandwich structures was investigated numerically and experimentally, and a two-dimensional finite element model was presented [28]. The effects of geometry parameters, material properties of the face sheet, and material properties of the honeycomb core on the energy release rate have been considered.

A non-destructive evaluation (NDE) method was proposed to determine the debonding location and size of the damaged honeycomb sandwich beam under predetermined parameters [29]. The method proposed utilizes the frequency response function (FRF) measured at one point. It was demonstrated experimentally that the method can inverse damage parameters with acceptable precision.

6. Conclusion and perspective

In many of the honeycomb panel's applications, in-service conditions produce fatigue loading; as a result, safer use of aluminum honeycomb sandwich structures requires a deep knowledge of their fatigue response in order to provide a quantitative tool for aluminum honeycomb sandwich structure design.

The undertaken experimental study considers the design investigation of a composite material under physical properties solicitations. It is necessary to select the optimum honeycomb sandwich structure for each application on the basis of flexural rigidity per unit weight, fatigue life, and failure behavior.

The results that emerge from this study show that sandwich panels with a honeycomb core have mechanical characteristics comparable to homogeneous materials. The loss of resistance becomes significant for a large number of cycles. Indeed, for moderate cyclic loading at average frequencies (from 1 to 10 Hz), the loss of resistance presents a late manifestation. Therefore, they can replace the usual materials by benefiting from their lightness and low cost.

Two damage types are detected:

- The ruin of the sole, which is manifested by the cell walls' shearing and/or the separation of the sole.
- The indentation of the skin is soft during fatigue and hard during static bending.

One notes that the ruin of the sole occurs prematurely in accordance to the skin's ruin, which omits the abrupt and fatal nature of the damage.

The phenomena involved in the static bending response of aluminum honeycomb sandwich structures are mainly dependent on the cell walls buckling. Failure occurred suddenly, and this should be taken into consideration in industrial applications. To overcome this issue, an analytical model was applied to predict fatigue collapse modes and limit loads based on a detailed parametric study to design and achieve the most efficient uniaxial graded auxetic damper (UGAD) [30]. The achieved graded auxetic system has led to a wide plateau region and a variant strength range (1-10 MPa), which justify the superior performance of the UGAD under different blast levels.

The development of modern technologies requires the use of materials with high mechanical properties specific to their use, but with low densities. In fact, it is necessary not only to study the long-term behavior of their fatigue but also to define reliable non-destructive mechanical testing procedures and standardize production methods.

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