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Experimental Investigation on the Fatigue Behavior on Honeycomb Sandwich Composite Panels

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Abstract: This paper aims to study the dynamic behaviors of particular sandwich panels manufactured using three specifications of aluminum honeycomb core with fiberglass or aluminum face-sheet materials. Three groups of panels were designed and manufactured, each including three different sorts of samples, all fabricated with the same thickness. A cantilever fatigue test was conducted on specimens, and the results were collected and presented in curves to detect the factors that affect the panel's endurance. The finding showed that the specimens with aluminum skin had more probability of face-sheet/core delamination. Samples of fiberglass covers showed face-sheets cracks or cores cracks more than delamination failure, while samples of epoxy-filled cores experienced the specimen's global crack. Generally, specimens with aluminum covers and epoxy-filled cores resisted fatigue load more than other specimens. The larger honeycomb cell-size specimens showed more probability to face-sheet/core delamination failures than samples with smaller cell-size cores.

دراسة عملية لسلوك التعب على الالواح المركبة ذات النواة على شكل قرص العسل

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الخلاصة

تهدف هذه الورقة إلى دراسة السلوكيات الديناميكية لأنواع معينة من الألواح المركبة، وقد تم تصنيعها باستخدام ثلاث مواصفات مختلفة من قلب الألومنيوم مع مواد تقوية من الفايبرجلاس او الالمنيوم. تم تصميم وتصنيع ثلاث مجموعات من الألواح، كل منها يشتمل على ثلاثة أنواع مختلفة من العينات، وجميعها مصنعة بنفس السمك. تم إجراء اختبار إجهاد التعب الناتئ على العينات. تم جمع النتائج وتمثيلها بواسطة منحنيات لاكتشاف التباين في المواصفات الميكانيكية بين العينات وكذلك العوامل التي تؤثر على قدرة التحمل للالواح المركبة .اظهرت النتائج أن العينات ذات اغطية الألومنيوم لديها احتمالية أكبر للتفكك بين الغطاء والوجه، وأظهرت عينات من أغطية الألياف الزجاجية تشققات في صفائح الوجه أو تشققات في القلب أكثر من عيوب التفكك ، في حين أن عينات النوى المملوءة بالإيبوكسي تعرضت بشكل اكبر الى كسر شامل. . ، بشكل عام ، أظهرت عينات أغطية الألمنيوم وتلك التي تحتوي على نوى مملوءة بالإيبوكسي مقاومة أكبر لحمل التعب ، وتظهر العينات ذات الحجم الأكبر لخلية قرص العسل احتمالا اكبر لفشل تفكك الصفيحة عن النواة أكثر من العينات التي تستعمل خلايا اصغر لنواتها.

الكلمات الدالة: لوحات، قرص العسل، طبقة الوجه، النوى، اجهاد.

1.INTRODUCTION

Sandwiches are structures with low-density cores between thin faces (skins), which are highly stiff and relatively lightweight. The core represents the ability to carry shear loads well. The sandwich's core gives lightness and solidity [1]. One of the most structurally effective cores, particularly in rigidity-critical applications, is the honeycomb core, the hexagonal cells [2]. A honeycomb material is composed of identical cyclically repeating arrays of hexagonal cells, and its thick low-density core material provides shear strength and toughness. Honeycomb is used in many industries due to its stiffness compared to weight, insulation quality, and design flexibility. These characteristics are just a few distinctive properties that make honeycomb structures a popular option for rigidity-critical applications [3]. Many industries employ sandwiches as wind turbines, which are the most sensitive and significant because they require high durability and are lightweight. Modern, clean energy instructions have grown widely [4]. The utilization of the basic materials that manufactured the sandwich must be considered. Glass fiber and carbon fiber are two of the strongest and lightest materials that may be used for composing the face sheets. Glass fibers are used [5] because of their durable properties; therefore, they are used recently in aspects of civil engineering to share the steel material, which implies both high durability and widespread for such materials. Sandwiches with honeycomb cores are affected by the foil thickness (wall thickness), cell size, and cell height. Besides the face sheet thickness, the composite sandwich materials' strength is influenced by the previously mentioned properties [6]. Several researchers have studied the influence of the fatigue bending test on hexagonal honeycomb sandwiches regarding malformation and adhesive failures, which are the most frequent damage types when creating honeycomb sandwich composites [7]. Jen et al. [8] numerically and experimentally analyzed honeycomb sandwich composites' four-point bending fatigue behaviors with different face sheet thicknesses. The damage that later developed in the specimens due to fatigue was caused by delamination between the core and the face sheets. Abbadi et al. [9] studied the fatigue behaviors of both damaged and un-damaged specimens when subjected to four-point bending stresses. They showed that the specimens' static strength was unaffected by the damage. It was asserted that drilling a hole significantly affected the fatigue life of honeycomb sandwich panels compared to a Brinell fault. Belingardi [10] used a four-point bending test to examine how the initial defect would affect composite sandwich panels' fatigue life and bending stiffness; the author found that the initial damage was drastically lower than these metrics, according to the investigation on the adhesive failure impact between cores and face sheet material on the fatigue life of honeycomb sandwich composites, core crushing was noted in the locations of adhesive failure. The relationship between the crack growth rate and stress intensity component was found by Shipsha et al. [11,12] by examining the fatigue crack growth behavior between the face and core of a sandwich panel. Zen Kert et al. [13] analyzed stress levels to sandwich panel failure types; high loads produced core failures, whereas low loads caused panel failures. To forecast the fatigue life of sandwich panels under block spectrum loads, Clark [14] created a fatigue damage model that used the shear modulus of the sandwich core as the damage parameter. Abbadi [15] investigated the residual strength evolution rule of honeycomb sandwich panels and suggested a nonlinear fatigue damage accumulation model. Wu [16] conducted honeycomb sandwich panel flat compression and bending fatigue tests and made an S-N curve prediction for the fatigue life. Palomba [17] studied sandwiched aluminum honeycomb structures' bending fatigue failure modes. Demelio [18] examined the fatigue on sandwich panels that were fastened together and discovered that the skin material and core thickness influenced the fatigue strength. For Sandwiches made of aluminum for the core and covers. It was found that the area of adhesive failure between the core and face sheet directly influenced the fatigue life. On the other hand, there was no clear correlation between the face sheets' thicknesses and fatigue life under the same applied bending load [8,10]. Specimens examined with cumulative low-to-high fatigue loading would have a longer life than samples analyzed with high-to-low fatigue loading [19,20]. Sandwiches with either aramid or aluminum honeycomb cores covered by aluminum were subjected to a four-point bending fatigue test. Sandwiches with an aramid core were almost more ductile but had a shorter fatigue life than sandwiches with an aluminum honeycomb core [9]. Aluminum honeycomb material for the core was better than aramid regarding fatigue lifetime. Delamination failure for samples made of aluminum honeycomb core and carbon fiber face sheet can be reduced using thin Kevlar fiber tissue between the core and cover [21,22]. The damages to the honeycomb core due to the fatigue test were fatigue shear cracks. As the number of cycles increased, the micro-cracks in the honeycomb core increased. When the specimen's maximum life was reached, these cracks' lengths rapidly increased. The damages caused by fatigue were due to excessive core shear stress for sandwiches using fiberglass material covers (GFRE). Since the life period of the glass fiber was significantly longer than the life period of the entire sample, it is reasonable to assume that the damage caused to the face sheet was due to the matrix's micro-cracks [19,20]. Regarding the face-sheet materials, using a woven E-glass reinforced composite significantly reduced fatigue stress compared to random E-glass fiber material [23]. Also, E-type woven fiberglass/epoxy composite showed superior mechanical durability compared to other composite materials [24]. Abdullah, F. A. [25] studied shot-peening's effects, in manufacturing, on the mechanical characteristics of woven (matt) reinforcing E-fiber glass with matrix epoxy resin materials. The results showed an improvement in fatigue strength. Al-Ameen et al. [26] revealed that adding 2% weight TiO_2 to the fiberglass/epoxy composite resin decreased the crack rate propagation.

2.EXPERIMENTAL WORK

The flow chart in Fig. 1 shows the main steps of the experimental work.

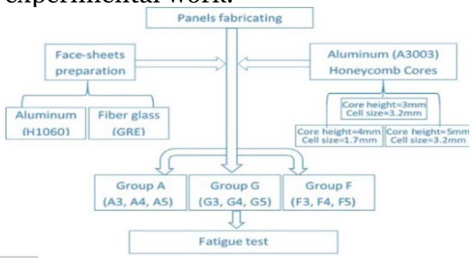
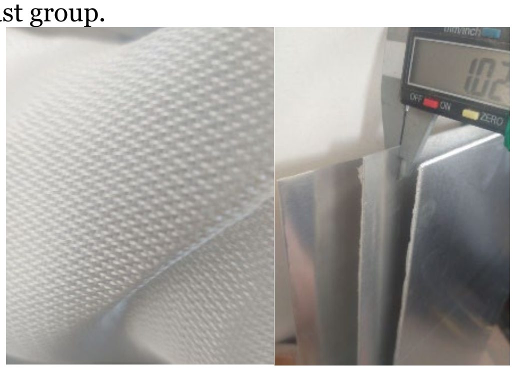


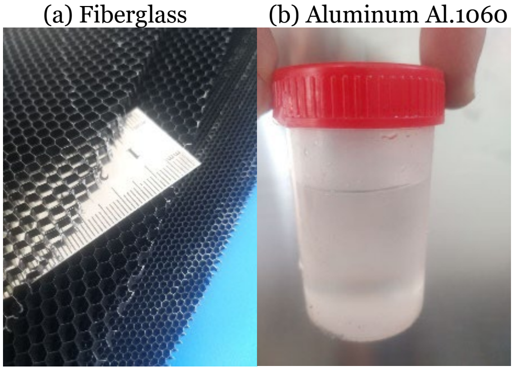
Fig. 1 Flow Chart of the Experimental Design.

2.1.Materials and Samples Preparation

Fig. 2 shows the studied materials, i.e., glass fiber "woven roving E glass," aluminum "1060H16", aluminum hexagonal honeycomb core "A3003", and Epoxy. These materials were used in fabricating three groups of panels, and each group had specific details according to face-sheet materials. All specimens in this study shared the same thickness (6mm), and each group included three samples. Each one had a different core height. All cores have a constant density (0.17 g/cm^3), and the samples were fabricated according to the L direction. The materials and fabricated panels' information and properties are listed in Tables 1–3. For panels of group "A," the epoxy was used to bond the core with the aluminum covers. At the same time, it served as a matrix to form the face-sheet material in groups "G" and "F" fill cores of the last group.



(a) Fiberglass (b) Aluminum Al.1060



(c) Al. Honeycomb (d) Epoxy

Fig. 2 Studied Materials.

Table 1 Mechanical Properties (SI Units) of the Raw Materials Used in the Fabricated Panels.

Material		Specific Gravity g/cm³	Tensile Modulus GPa	Poison's Ratio MPa
Fiberglass		2.54	85	0.20
Aluminum Alloy	AL1060-H16 cover	2.7	68.9	0.33
	AL3003-H16 core		71	
Epoxy		1.12	3.9	0.38

Table 2 Densities (g/cm3) of Panels Components.

Matrix (Epoxy + Hardener)	Fiberglass Tissue	Glass-Epoxy (GRE) Layer	Core
1.08	1.2	1.7	0.17

The three groups of panels were categorized according to the type of face sheet materials and core status; (either epoxy or air-filled). The number of covers' layers for panels varied depending on the core thickness to ensure all panels with the same thicknesses (6mm) for all groups. Fig. 3 shows the main details for each group. The panels have been named according to the first letter of the material that formed the face sheet and the core status. Those letters are followed by a number representing the core thicknesses (A; Aluminum, G; Glass-fiber, F; epoxy-filled core). For example, A3 means the panel or sample is from group A and has an aluminum cover with a 3 mm core thickness. The panels were designed and manufactured with the hand layup method, as shown in Fig. 4. Three groups of panels were produced, A, G, and F, as shown in Fig.5. Each group includes three different types of samples; the samples were prepared for the cantilever fatigue test, designed and cut with a diamond saw. The dimensions depended on the test device specifications of the fatigue test samples, as shown in Fig. 6.

Table 3 Panels Specification.

Group Name	Sample Name	Face-sheet material	Face sheet Thickness (mm) (single-side)	Honeycomb core (mm) AL.3003-H16 Cell size	Core height	Foil (wall-thickness)
A	A3	AL 1060-H16	1.5	3.2	3	0.10
	A4		1	3.2	4	0.05
	A5		0.5	1.7	5	0.10
G	G3	Epoxy Fiberglass (GFRE)	1.5	3.2	3	0.10
	G4		1	3.2	4	0.05
	G5		0.5	1.7	5	0.10
F Core filled with Epoxy	F3		1.5	3.2	3	0.10
	F4		1	3.2	4	0.05
	F5		0.5	1.7	5	0.10

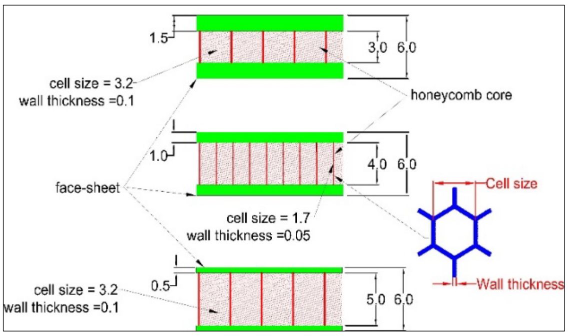


Fig. 3 Panels Design (mm).

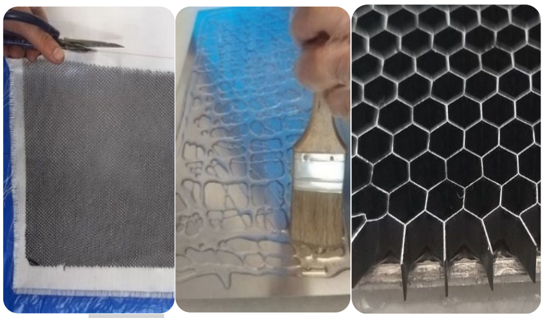


Fig. 4 Panels Preparation Steps.

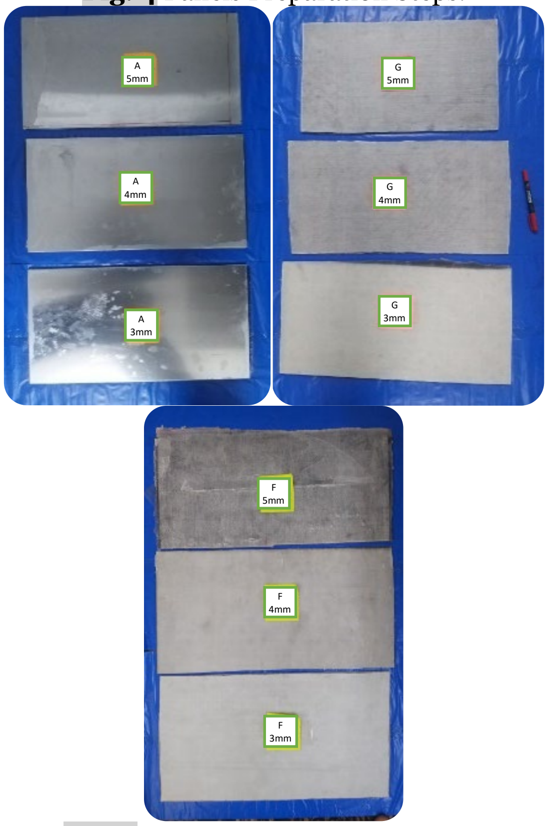


Fig. 5 Manufactured Panel Groups.

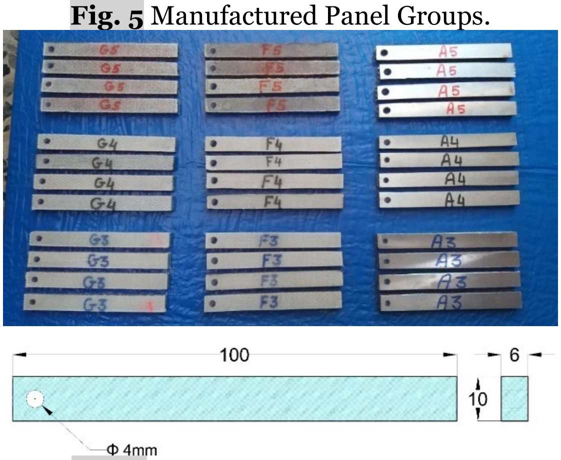


Fig. 6 Fatigue Test Specimens with Dimensions (mm).

3.ENGINEERING ANALYSIS AND MECHANICAL TEST

Fig. 7 shows the fatigue test used, which is a mechanical test used to analyze and evaluate the endurance of the specimens.

By selecting four specimens for each type, the cantilever fatigue test experienced sample endurance within a different range of loads applied according to each sample's specification. Tensile and Three-point flexural tests for all studied panels in the "L" direction were concluded prior. A digital dial gauge was used, and the test was conducted at 25 °C.

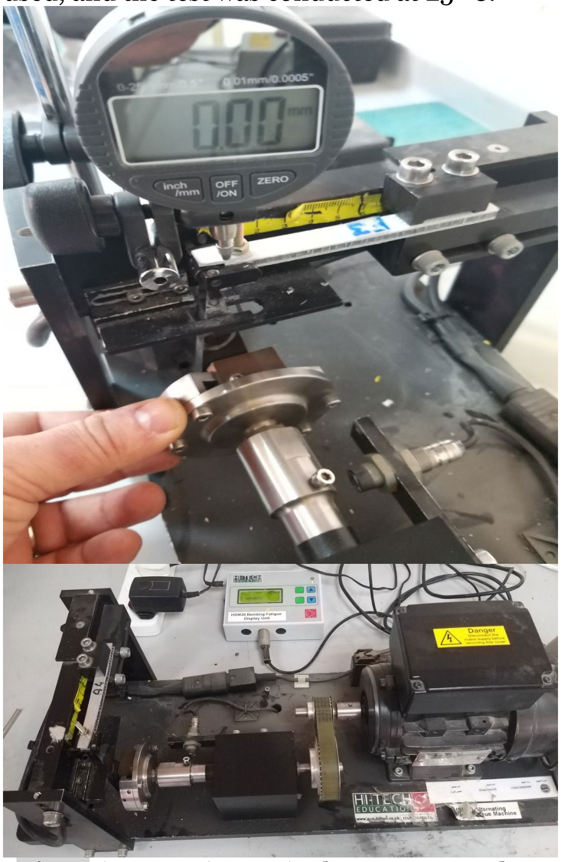


Fig. 7 (HSM20/00495) Alternating Bending Fatigue Machine/UK.

Regarding theories in producing sample fatigue curves, samples' flexural rigidities (EI) were determined using a three-point flexural test (Table. 4). Three samples of each type were examined, and the average values were endorsed.

Table 4 Tensile and Flexural Test Results.

Samples	Yield (MPa)	Yield Extension (%)	Extension to Break (%)	Modulus (GPa)	Flexural Rigidity Pa.m⁴
A3	51.32	0.0175	0.064	2.93	0.42605
A4	34.65	0.0099	0.055	3.50	0.62655
A5	17.43	0.043	0.044	0.40	0.07160
G3	97.24	0.038	0.04	2.55	0.44753
G4	65.8	0.026	0.03	2.53	0.44753
G5	33.28	0.018	0.02	1.84	0.32222
F3	103.35	0.039	0.045	2.65	0.46543
F4	70.7	0.023	0.033	3.07	0.53704
F5	39.4	0.033	0.033	1.19	0.07160
$GRE_{1.5mm}$	190.1	0.037	0.038	5.13	----
$Al1060_{1.5mm}$	101.09	0.0015	7.8	67.4	----

A range of deflections within yield values was applied on samples to conduct the fatigue loads and then estimate the number of cycles for samples' failures, Eqs. (1), (2) are used in the calculations.

$$\text{flexural deflection} = \frac{pL^3}{48EI} \quad \textbf{(1)}$$

$$\text{cantilever deflection} = \frac{pL^3}{3EI} \quad \textbf{(2)}$$

Where

p *is the load applied* (N),

L *is the effective span* (m),

EI *is the flexural rigidity* $(N.m^2)$.

Fig. 8 shows the samples deviations and the load values calculated based on the above calculations.

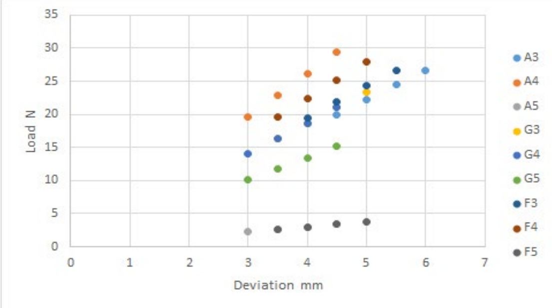


Fig. 8 Load-Deviation for All Studied Samples.

4.RESULTS AND DISCUSSIONS

The S.N curves for specimens with the same core thickness are shown in Figs. (9–11). It can be noted that the samples with thicker face sheets and samples with smaller cell sizes of honeycomb core resisted more fatigue Loads than specimens with a thinner face sheet or larger cell size core because specimens with thicker face sheets had higher bending stress. Also, the samples with smaller cell-size cores bonded firmly to the face sheet. According to Fig. 10, specimens A4 and F4 reached the highest fatigue load compared to other specimens by about 8% and 650%, respectively, as shown in Figs. (9, 11). Because samples with 3.2 mm-cell size cores (that were smaller by half, i.e., 1.7 mm, than the cores' cells of samples in Figs. (9, 11), there was more considerable core flexibility for smaller cell sizes than larger cell-size structures. As a result, the chance of flaws in samples with smaller cell sizes would be less. Regarding specimens in Fig. 10 with a 4mm core height, G4 showed less fatigue load than F4 and A4 by 30-40 %, respectively, because G4 had a non-filled core, and epoxy-filled core strengthened the sample by 33-38% to fatigue load. Specimens of aluminum cover with suitable thickness were more flexible than those with the same fiberglass thickness. Fiberglass showed a higher probability of developing cracks than aluminum during the fatigue test. The damage caused to the fiberglass face sheet was due to the matrix's micro cracks. As shown in Figs. (9, 10), the fiberglass samples with an un-filled core G3 and G4 showed a reduction in the fatigue load compared to A3 and F3 by about 10% and 40%, respectively, yet only for the face-sheet thickness 1-1.5 mm. Samples in Fig. 11, with 0.5 mm face-sheet thicknesses, showed an inverse relationship. The specimen with a fiberglass cover and unfilled core G5 exhibited a higher fatigue load by about three times than A5 and F5. Figs. (12–14) are classified according to each group's type of cover material. The three curves for the fatigue force varied within samples in mentioned figures. Specimens in this study were intended to be 6 mm thick. The samples with thinner skins necessarily had thicker cores; all fabricated samples had the same thicknesses. Compared to those with a thinner core and a thicker cover, specimens with thinner and thicker cover and core skins experienced higher stresses during a fatigue test, which caused them to fail quickly at a low fatigue load.

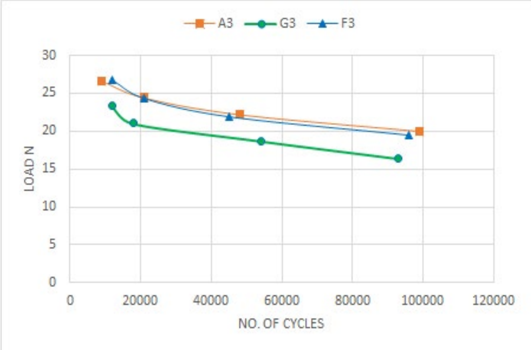


Fig. 9 F.N. Curves of Samples with 3mm-Core Height.

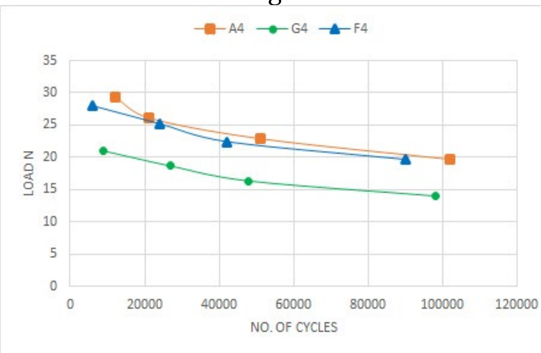


Fig. 10 F.N. Curves of Samples (4mm-Core Height).

Fig. 11 F.N. Curves of Samples (5mm-Core Height).

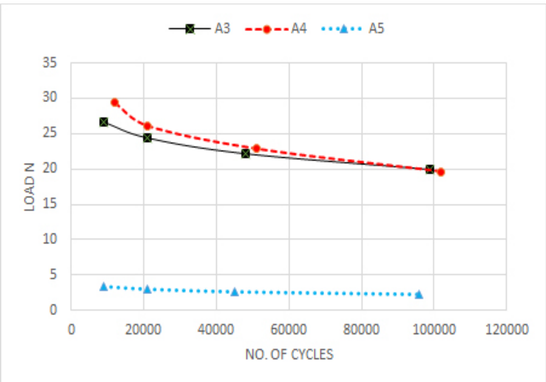


Fig. 12 F.N. Curves for Samples of Group A.

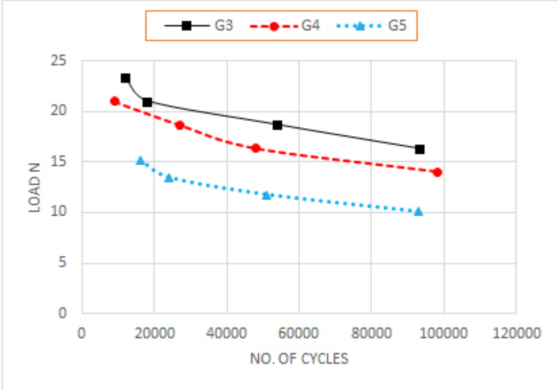


Fig. 13 F.N. Curves for Samples of Group G.

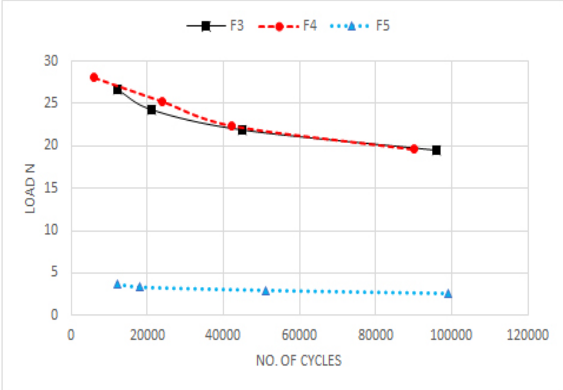


Fig. 14 F.N. Curves for Samples of Group F.

As noted, samples with thicker covers resisted more face-sheet defects because stress decreased on thicker shells. Excluding G4, samples with a smaller honeycomb cell size can bear more fatigue load than those with a larger cell-size core, as shown in Figs. (12–14). A3 and F3 samples with larger cell size cores showed slight descending to fatigue load compared to those of smaller cell size cores, i.e., A4 and F4, as shown in Figs. (12–14). In Fig. 13, the G5 sample exhibited a reduced fatigue load compared to G3 and G4 by about 60% and 40%, respectively. While a sample of a larger cell size core, i.e., G3, showed an increase in fatigue load compared to smaller cell size samples, i.e., G4, by 15%. In contrast to specimens with a 5mm core thickness showing a sharp decrease in fatigue load, the curves for samples of 4mm and 3mm core thick converged. The significant reduction in fatigue stress for A5 and F5 samples occurred due to having larger cell sizes and thinner skin cores. Fig. 15. shows two samples, having cores with different cell sizes with the same material for the face sheet; both used an equal density of the core. During the fatigue test, the probability of delamination between the core and covers for the upper sample was more than the lower one, which had a smaller cells size of honeycomb core, because the upper sample had less contact area between the core and the face-sheet by half. The number of cell wall pillars for the sample using a smaller cell size core compared to the upper sample was twice, and the bonding contacting area was proportional to the cell size of the core.

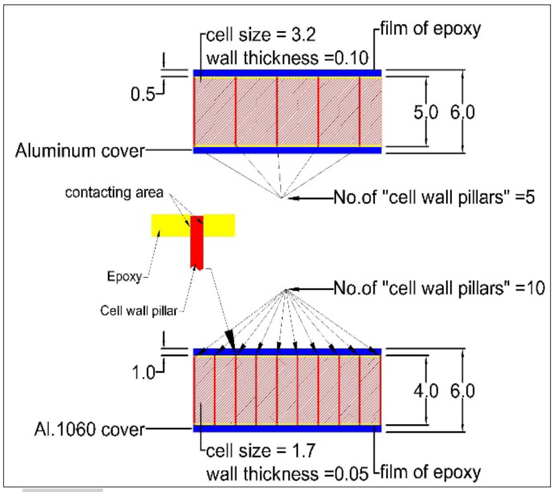


Fig.15 Samples Details with Different Cells Size Core.

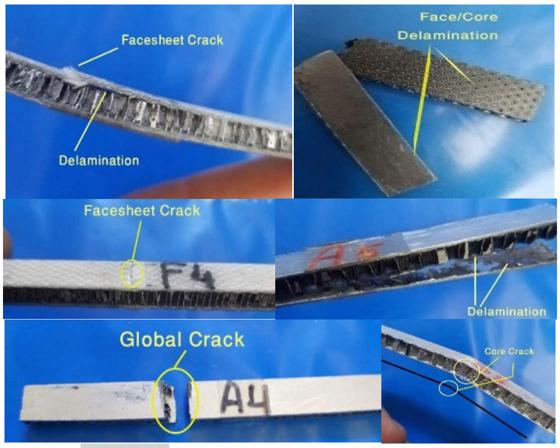


Fig. 16 Samples of Defect Modes.

So, bonding between the core of smaller cells size structure and covers showed significant resistance against delamination during fatigue tests at a particular load. The failure mode depended essentially on the face sheet material and honeycomb cell size, and the delamination was more often for samples that employed aluminum material for the face sheet. The sandwich's resistance against debonding for samples with smaller cells size was significantly large. The primary failure mode for samples with larger cell-size cores was delamination between core and cover, while fatigue shear crack was more common in samples with smaller cell-size cores.

5.CONCLUSIONS

The following points were concluded from this study:

1. Debonding between core and covers, cracks in upper or lower face sheets, cracks in honeycomb cores, and global cracks are examples of specimen defects caused by cantilever fatigue tests (Fig. 16).
2. For studied samples, the composite sandwich stiffness decreased when face-sheet thickness increased. Still, the load to failure increased, and sandwich panels with aluminum covers were almost more ductile than the samples that used fiberglass material.
3. During the fatigue test, the primary defect was the deboning between the core and covers for samples using aluminum face sheets, while cracks were more often in covers for those using fiberglass face sheets.
4. Delamination failure was less in smaller cell-size cores samples than in larger ones.
5. Damage to the honeycomb core due to fatigue shear cracks was more common in samples with thinner face-sheet, while face-sheet damages occurred for samples using a thinner core.
6. Core cracks often occurred in smaller cell-size core samples more than others using larger cell-size cores, while the probability of core-covers debonding was more pronounced with larger cell-size cores samples.
7. For future work recommendations, aluminum face sheets with rough surfaces should be used for aluminum panels to increase the core/cover bonding strength. Using better adhesive materials rather than epoxy is recommended. Utilizing some welding techniques is also applicable to eliminate face/core delamination defects. For fiberglass panels, employing the shot peening process for the fiberglass covers might increase the face-sheet fatigue strength, and nano-powder additions to the resin of the Fiberglass/Epoxy composite (face-sheet) would reduce crake rate propagation.

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