Investigation of Static and Fatigue Behavior of Honeycomb Sandwich Structures Under Bending Load

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Abstract-The static and fatigue failure behavior of honeycomb sandwich structures have been experimentally investigated in this paper. Three point bending static and fatigue tests were used for assesment of flexural rigidity and fatigue life. Under displacement control monotonic load, the load and mid span displacement response corresponds to five different phases. The fatigue life of the panel is evaluated by performing the constant amplitude load at the several loading levels. The results show that fatigue life increases as the stress level decreases. The visual and optical analysis were performed to analyze static and fatigue failure behavior. The fracture modes were analyzed using Scanning Electron Microscope (SEM). It was investigated that the sandwich structures subjected to three point bending load fail in various ways including face yield, compression of face sheet, core shear failure and delamination at core and face sheet interface depending upon the loading conditions. However it is concluded that the final failure under static load occurs due to the compression of face sheet at the loading area and under fatigue load the failure is due to the compression of facing as well as debonding at core and face sheet interface.

Keywords-Three Point Bending, Scanning Electron Microscope, Bending Stiffness, Fatigue Life, Core Indentation, Face Yielding.

I. INTRODUCTION

Sandwich structures are formed by bonding a thin layer of high strength and stiff face sheet to both side of the thick, flexible and light weight core [i], [ii].The adhesive provides the adhesion to the face sheet and core to transfer the load and also to work properly as a sandwich structure [iii]. The primary function of face-sheet is to resist the compression and tensile loading while the core is meant to resist transverse shear loads [iv], [v]. The use of core increases the moment of inertia of the complete structure with little increase in weight, thus making the sandwich structure ideal for light weight applications [vi], [vii].These structures have a high bending stiffness, significant heat resistance, high resistant to corrosion and outstanding energy absorption abilities [viii-x] and used for making the aeronautical structures, racing cars and high speed marines and civil engineering structures [xi], [xii].

The strength and stiffness of sandwich structures mainly depends upon the types of materials used for facing and core [xiii]. The face sheet of sandwich structure can be made of metal or any other composite laminates. The most widely used face sheets are glass fibers, carbon fibers, aluminum, stainless steel, aramid fibers, plywood, Concrete, foam and flax. The core may be of made of any material but generally there are four types; honeycomb core, web core, foam or solid core, corrugated or truss core [iii], [xiv]. Aluminum, aramid fiber, carbon fiber, foam, composite, steel, wood, concrete and glass fiber is used as a core material.

The particular failure mode depends on the material properties of core and face, loading arrangement and the geometry of sandwich structure [xv], [xvi]. Compression facing wrinkling, face yielding, core shear and crushing, local indentation and intra-cell buckling, bending of cell walls, delamination of core/face interface are the major failures observed in sandwich structures subjected to bending and shear load [xvii-xix]. Following paragraphs provides a brief literature review of previous studies on fatigue and static behavior of composite structures.

The fatigue behavior of undamaged and damaged specimens of foam core sandwich beams haven been already discussed in previous studies [xx], [xxi]. It was proposed that 90% of the fatigue life comprised of crack initiation and crack is initiated in the region of high shear stresses. Three and four point bending arrangements are used for the assessment of strength and life of panels. As three point bending test is performed to determine the bending stiffness of composite sandwich structures of carbon fiber face sheets and aluminum honeycomb core with and without the Kevlar fiber Interfacial toughening [xxii]. It was observed that the bending strength of sandwich structure improves in the presence of Kevlar fiber.

Similarly in a study [xxiii] four point bending test is performed on two kinds of sandwich structures having aluminum 5754 faces and aluminum 3003 and aramid core one with defect and other without the defect. It was found that the presence of defect have no influence on monotonic response of the structure.

Several studies have been carried out for the investigation of failure behavior of sandwich structures. The behavior of sandwich structures with Airex C70.30 core and glass/epoxy and aramid/epoxy fabrics face sheets under monotonic and fatigue loading is investigated in a study [xxiv]. It was found that the core shear failure increases at a higher rate near failure. However the core contributes very less in flexural stiffness. Four point bending testing is performed [xxv]to investigate the static and fatigue failure behavior of aluminum honeycomb sandwich structure on the basis of different range of temperature. The results showed that the flexural strength as well as failure mode changes with the increase of temperature. The static and fatigue response of GFRP sandwich structures with foam core[xxvi] show that the initiation of failure starts because of the small shear crack in core and the propagation of crack causes the interfacial de-bonding and rupture of fiber insertion. However a theoretical model is developed [xxvii] to predict the failure modes in case of three point bending testing. It was found that the initiation of failure occurs due to face yielding, core shear or core indentation.

The mechanical and fatigue failure behavior of composite sandwich panels have been reasonably well analyzed. But the performance of all types of honeycomb sandwich structures especially under fatigue loading, is still not completely understood because of the large number of types of materials used for core and facing. Glass fiber is slightly more flexible than carbon fiber and also have lower tensile modulus which allows it to bend and take more strain without breaking. Because of the excellent corrosion resistance and low cost of fiber glass, aluminum honeycomb sandwich structure having face sheets of glass fiber not only used in same industries as sandwich structures having carbon fiber; it also have further applications. The fatigue failure mechanism of aluminum honeycomb sandwich structures having glass fiber face sheets have not been well investigated.

The primary objective of the paper is to investigate the monotonic and the cyclic failure of composite sandwich structures having glass fiber face sheets and aluminum skins. The secondary objective of this research is to investigate the fracture mode under static and fatigue loadings using scanning electron microscope (SEM) and optical microscopy.

II. Experimental Program

A. Test Specimens

The face-sheet of the sandwich panel was made of woven glass fabric as reinforcement and epoxy as matrix. Honeycomb Core is made of Aluminum 5052-H32. Mechanical properties of core and face sheet are given in Table I. The specimens were cut from the panel using hacksaw. The geometrical dimensions of specimens are shown in Fig. 1.

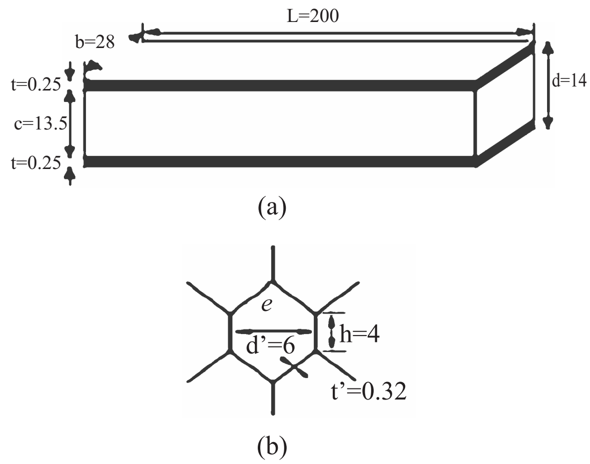


Fig. 1. Geometrical Dimensions in mm
(a) Honeycomb panel (b) Honeycomb cell

TABLE I
MECHANICAL PROPERTIES OF CORE AND FACE SHEETS

Properties	Core wall Aluminum 5052-H32	Face sheet Woven glass fiber
Density	83 kg/m^3	0. 47 kg/m^2
Poisson's ratio	0.33	0.125
Elongation (%)	13	4.8
Tensile Modulus (Gpa)	70.3	20
Compressive Modulus (GPa)	1.31	17

B. Experimental Procedure

Both static and fatigue tests were carried out through a three point bending testing fixture using the Material Testing System (MTS-810). MTS is an indispensable resource to obtain the information about the characterization of all types of materials and available in Fracture Mechanics lab of UET Taxila. The three point loading configuration based on ASTM C-393 [xxvii] is shown in Fig. 2. The static test was carried out by loading specimen under bending until the failure of specimen. The fatigue tests were carried out at several loading levels obtained from 65% to 95% of ultimate load in monotonic tests. The constant amplitude sinusoidal waveform loading was selected. The ratio of minimum applied load to maximum load R was considered 0.1 in all fatigue tests. The operating frequency was set to 2 Hz.

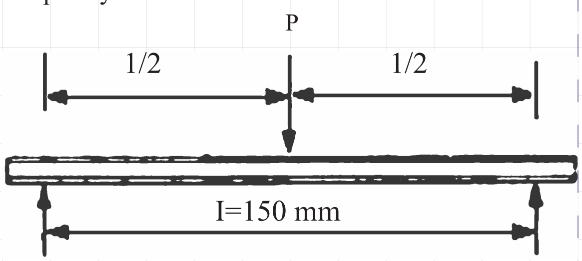


Fig. 2. Three point loading configuration

To determine the failure behavior of sandwich panels Scanning Electron Microscope (SEM) has been used. For this purpose only a defective portion of a composite sandwich structure have been separated from specimen. SEM is used for the microscopic surface study of conductive materials. Because of non-conductivity of fiber glass first of all face sheets of fiber was coated by ultra-thin layer (2-20nm) of conducting metal Gold (Au) using Sputter Coater.

III. Data Analysis

Ashby, M., & Gibson L. [xxviii] explain the analysis for the determination of distributed stresses on the panel under bending load. The mathematical model is identical for all types of bending loading configurations except for the values of geometrical constants. The normal or compressive stresses in the face sheets and core σ_f and σ_c and shear stresses τ_f and τ_c is calculated from the following equations.

$$\sigma_f = \frac{M_y E_f}{BS} = \frac{M}{btc} = \frac{Pl}{Abtc} \quad (1)$$

$$\sigma_c = \frac{M_y E_c}{SS} = \frac{ME_c}{btcE_f} = \frac{PlE_c}{btcE_f} \quad (2)$$

Where M is the bending moment, P is applied load, BS and SS are the bending and shear stiffness of the panel. A is constant depends upon the type of loading. E_c and E_f are the modulus of elasticity of core and facing skins. Where E_c may be determined by:

$$E_c = CE_f\left(\frac{\rho_c}{\rho_f}\right)^2 \quad (3)$$

$$G_c = DE_f\left(\frac{\rho_c}{\rho_f}\right)^2 \quad (4)$$

Where C (~1) and D (~0.4) are constants and ρ_c, ρ_f are the densities of core and faces and G_c is the shear modulus of core in the direction of load. Shear stresses are calculated by:

$$\tau_c = \frac{P}{Bbc} \quad (5)$$

$$\tau_f = \frac{t_c}{2} \quad (6)$$

Where B is also a constant and its value depends upon the type of loading. For 3-Point Central Loading configuration the values of A and B are 4 and 2 respectively.

The maximum Bending stress of sandwich structure[ix] is calculated by:

$$\sigma_b = \frac{M\left[\frac{c}{2}+t\right]}{I_t} \quad (7)$$

Where bending moment is M, and calculated by using the equation: $\sigma_f = \frac{M}{btc}$. I_t is the transformed moment of Inertia along the horizontal axes and calculated by:

$$I_t = 2\left[\frac{bt^3}{12} + bt\left(\frac{c}{2} + \frac{t}{2}\right)^2\right] + \frac{1}{12}bc^3 \quad (8)$$

The strength of beam in bending is estimated from the equivalent flexural rigidity or bending stiffness (BS) of beam, and the equivalent shear rigidity or shear stiffness (SS) of beam.

$$BS = \frac{(E_f btc^2)}{2} \quad (9)$$

$$SS = \frac{(G_c bd^2)}{c} \quad (10)$$

The deflection [iii] is considered as the sum of the shear and bending components, when load is applied.

$$\delta = \delta_b + \delta_s = \frac{PL^3}{24E_f\, btc^2} + \frac{PL}{4bcG_c} \quad (11)$$

IV. Results and Discussion

A. Static Tests

Static tests were carried out to determine the ultimate load and stiffness of the sandwich panel in order to set the amplitude of fatigue loading. Under static load the ultimate static failure load is recorded and on the basis of the information of static failure load and the geometric parameters the average flexural strength and stiffness of the panel is calculated using the data analysis discussed in section III, and is given in Table II. The behavior of the load versus the displacement for the monotonic tests is shown in Fig. 3. Four different phases have been observed during the force and deflection behavior of the sandwich panels.

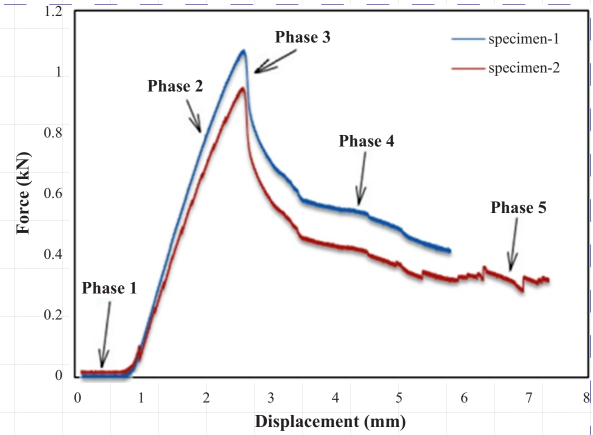


Fig. 3. Evolution of the deflection with respect to force

TABLE II
THEORETICAL CALCULATIONS OF THE AVERAGE FLEXURAL STRENGTH OF PANEL

Properties	Sandwich Panel	
	Face-sheet	Core wall
Compressive Strength (Gpa)	403	5.67
Shear Strength (Mpa)	0.68	1.35
Bending Strength (Mpa)	42	
Bending Stiffness (Flexural Rigidity) (Mnmm^2)	23.6	
Shear Stiffness (Shear Rigidity) (KN)	103	
Beam deflection (mm)	41.8	

Phase 1 shows the very small change of load approximate zero with small deflection. The specimen is shown in Fig. 4 (a). Phase 2 shows the linear elastic behavior of panel until the ultimate load is achieved. During Phase 2, the stiffness of panel reduces because of the face yield as shown in Fig. 4 (b). Phase 3 shows the abrupt decrease of the load followed by the stiffness degradation of honeycomb because of the small core indentation at the loading area as shown in Fig. 4 (c). Phase 4 shows the slightly slow reduction of load corresponding the structural stabilization. Its mean specimen will carry the more load less than maximum failure load with the increase of displacement with time. Phase 5 occurs after the further application of load, load carrying ability of panel reduces and permanent deformation occurred because of the inter laminar shear failure of facing, bending of cell walls and core shear failure as shown in Fig. 4 (d).

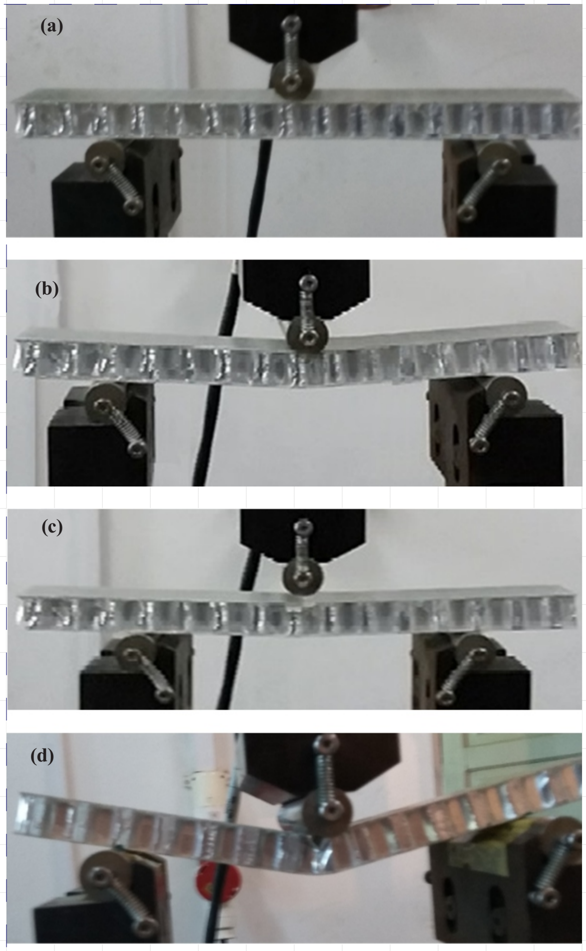


Fig. 4. Different Phases during static tests (a) Start of the test with small load (b) Face yield (c) Small indentation of faces (d) Plastic deformation of facing and bending of cell wall

B. Fatigue Tests

The purpose of fatigue tests is to predict the life of honeycomb as well as the investigation of failure modes. The graph between fatigue deflection and the number of cycle at different loading levels is shown in Fig. 5. It can be seen from the Figure that the deflection is almost constant in the start because of core shear resistance and then increases because of the degradation of stiffness. Initiation of failure is considered where the deflection starts to increase abruptly. The slight increase in defection in the beginning is due to the face yielding. The abrupt increase in deflection is caused by the small indentation and bebonding of honeycomb core and face interface at loading area. It was observed that at higher load the initiation of failure occurs near the final failure because of the face yield and final failure is because of compression of face sheet but in case of small load the initiation of failure occur because of face yield as well as delamination below the loading area and final failure occurs because of indentation.

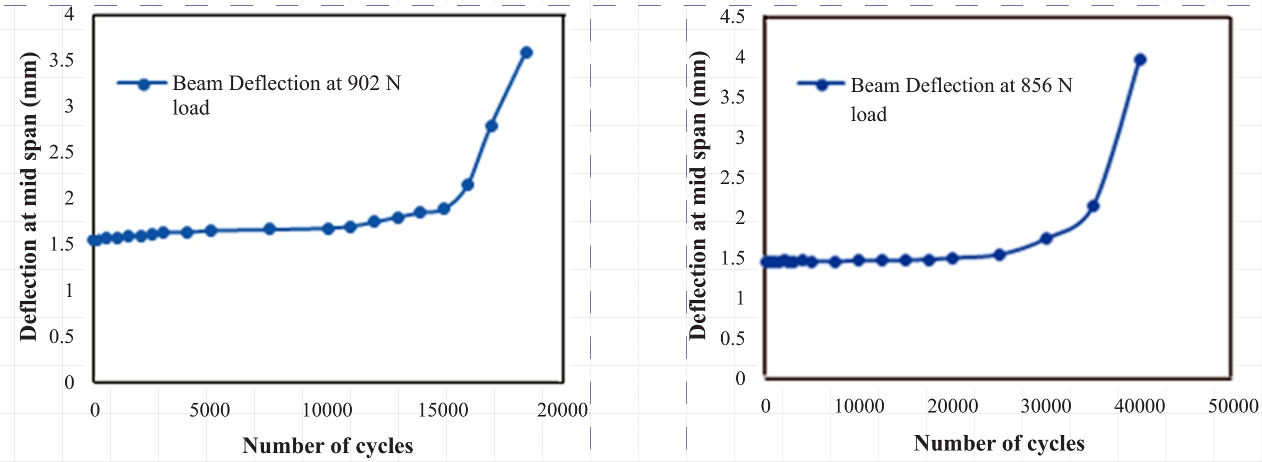


Fig. 5. Fatigue deflection and number of cycle behavior. (a) Beam deflection at 902N load (b) Beam deflection at 856 N load

The fatigue life is predicted in terms of applied load and number of cycles as shown in Fig. 6 (a). It has been observed that the fatigue life of sandwich structures increases with the reduction of applied load. So for cyclic loading the specimen is suitable at the 60 to 70% of ultimate load. The behavior between bending stress and number of cycle (S/N curve) is shown in Fig. 6 (b). The results show the increase of fatigue life at lower stress level.

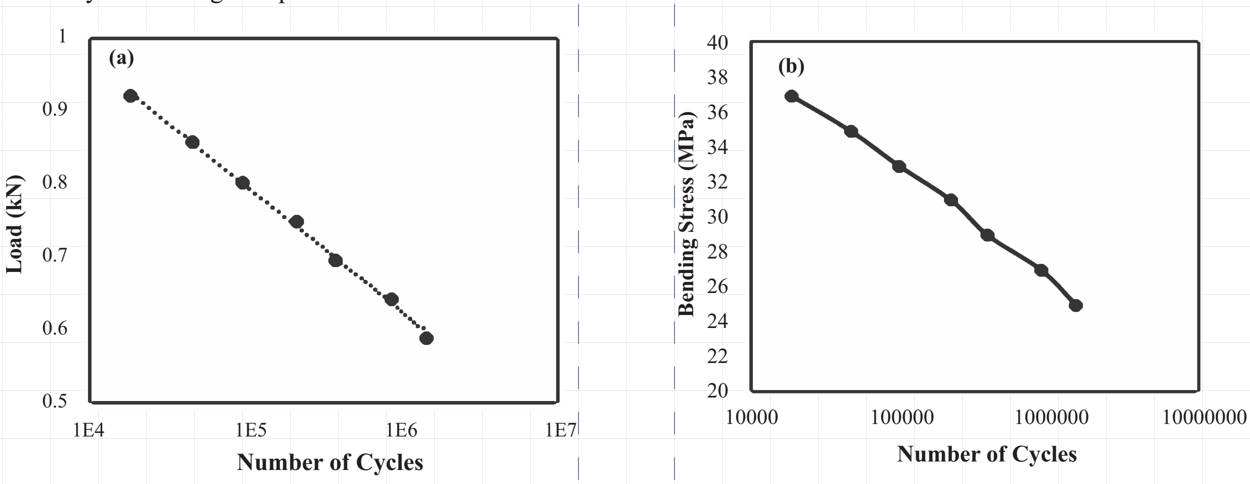
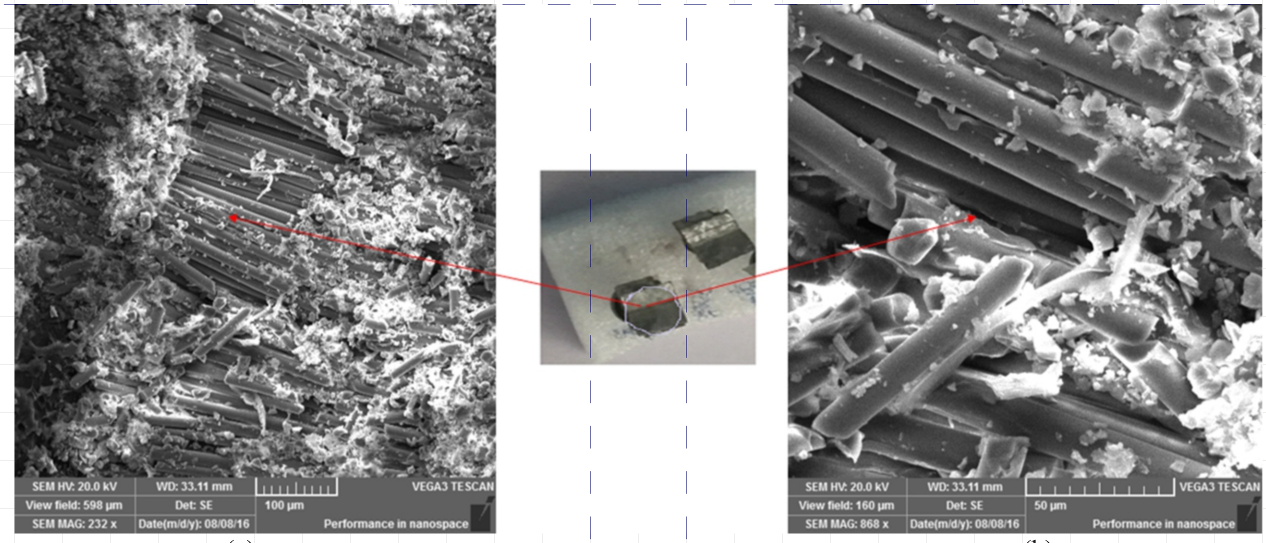


Fig. 6. Fatigue load and number of cycle response(a) Load versus number of cycles (b) Bending stress versus number of cycle

C. Static and Fatigue Failure Modes

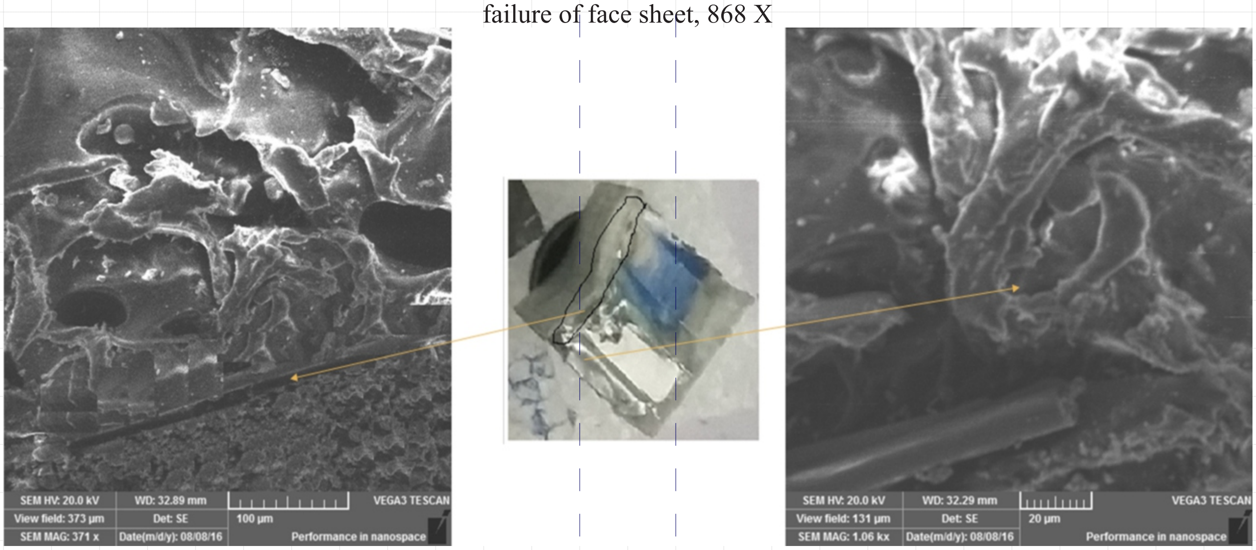
Visual and optical microscopy analysis show that failure occurs because of face yield and indentation, core shear and debonding. Further failure modes after higher loads were observed using SEM analysis.

Compression failure of face sheet occursin both monotonic as well as fatigue loading occurs at loading area when the load increases from the compressive strength of the core as shown in Fig. 7 (a). It has been observed that the stiffness degradation of panel starts after the compression of core and face sheet and further application of load causes the inter-laminar shear failure in facing that is shown in Fig. 7 (b). Fig. 8 show the SEM examination of core and face interface. The small delamination due to fatigue loading is shown in Fig. 8 (a). The core shear failure may be observed from Fig. 8. The cell walls of the core were failed due to higher shear stresses. The bending of the cell wall due to shear failure can be seen from the SEM image shown in Fig. 9.



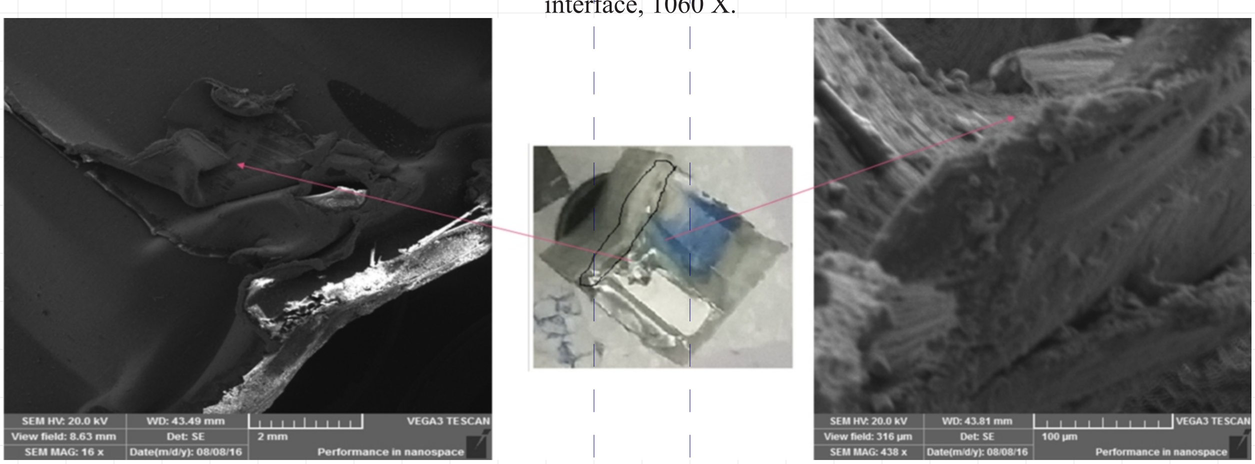
(a) (b)

Fig. 7. Fractography of glass fiber face sheet using SEM. (a) Compression failure of facing, 232 X (b) Inter shear failure of face sheet, 868 X



(a) (b)

Fig. 8. Surface study of core and face sheet interface. (a) Interfacial de-bonding, 371 X (b) shear failure of interface, 1060 X.



(a) (b)

Fig. 9. Side view of aluminum honeycomb cell wall. (a) Bending of cell walls (b) core shear failure

V. Discussion

In static testing the initial phase shows a meager load approximated to zero causes the small deflection along the x-axes is due the elastic behavior of panels. When we found its relevance with the literature [xxii], [xxiii], [xxix] it was found that no one has made any significant headway over this phase and neglected this phase. But in this study the data is recorded precisely and this phase is not neglected to investigate the actual response before the failure of specimens. Due to the bending and compressive strength of the core the linear increases of load is observed in phase 2, until the load reaches to its maximum level 1.07 KN and 0.963 N respectively for both tests. This behavior is same for all types of sandwich structures having the face sheets of fabrics. The abrupt drop in load is due to the face sheets of fabric laminates [iv].However in case of face sheets of metals the fluctuations of load is recorded in previous studies and load carrying ability of panel increases even after the yield point. After the sudden drop of load a little increase of load due to the shear resistance of core is observed in phase 4 and structures again gains a small stabilization. The 5th phase show that even that after the appearance of different failure modes in facing and core the panels have ability to carry the load but deflection along the span length increases continuously.

Fatigue testing was performed on several constant loading levels and behavior is compared with previous studies [xxiv], [xxx], [xxxi]. In all tests very small fluctuation in deflection is observed still the thousands number of cycles depending upon the loading levels. After the thousands number of cycles the abrupt increase in deflection is observed. This point is assumed the starting point of failure. After the different number of cycles depending upon the load level the compression of face sheet is investigated and this point is assumed the failure of the panel. The displacement along the span length depends upon the materials used for facing and core and in case of face sheets of more elastic materials such as aluminum the deflection is greater as compared to the face sheet of fabrics. The displacement along the span length increases gradually because of the stiffness degradation of the panel due to face yield and the reduction of compressive strength of face sheets. So start of failure is probed due to face yield and final failure is due to the compression of face sheet. The number of cycles at which increase in deflection and compression of face sheet is observed recorded for each loading level. The results show that deflection increases with the rise of number of cycles and deflection is higher at higher loading levels.

The plot between loading levels (ratio of fatigue load to ultimate load) and cycles to failure is used to find the life of panels. It was recorded that at loading levels such as at 0.95, 0.90, 0.85 and 0.80 the number of cycles to failure are 18494, 45500, 95158 and 215000 respectively. This show that life of honeycomb increases many times with the little decrease of load. It was recorded that at lower loading level in between 0.65 and 0.75 the life of panel becomes millions of cycles. Hence it was concluded that honeycomb panel is suitable at lower operating loading level. Same data of above mentioned loading levels is converted in bending stress and a plot between bending stress and number of cycles is used to predict the life of panels in standard S/N curve. It reveals that with the little depletion in applied bending stress life of panel increased manifolds. The behaviour was compared with relevant studies [viii], [xxxii].

The investigation of failure modes show that the initiation and final failure modes of panels depends upon the types of materials used for core and facing as well as the types of loading. It was also found that the initiation of failure occur because of the face yield as shown in figure as predicted in a study [xv] under three point load. The increase in deflection is also the result of face yield. It was discussed that after the initiation of failure the load carrying ability of panel decreases abruptly. This abrupt reduction of stiffness and strength is because of core indentation and this behavior is validated from the studies [v], [xxxiii]. The further application of load also causes the other different failure modes such as core shear, the bending and failure of cells [xxxiv], [xxxv]. The delamination of core and face sheet is observed only in fatigue loading that is more prominent at lower load levels. But in both types of loading the final failure is because of compression of facing.

VI. Conclusion

The bending strength, stiffness and fatigue life of honeycomb panel is experimentally predicted in this study. In static loading, the load and mid span displacement corresponds to several phases. The initiation of failure occurs due to the face yielding effect and permanent deformation is due to the compression of face sheet. It is also found that in static loading the panel have ability to carry the more load after the failure. It is due to the fact that in case of static loading failure occurs only in loading area and no effect of load is found on the remaining panel. However the further application of load causes the more effects such as core shear and bending of cell walls.

During the fatigue testing the beam deflection at several constant amplitude loading levels is recorded. The fatigue life and stress levels are linearly related and it was concluded that at the higher load levels the beginning of failure is only due the face yielding, however at lower loading level the failure occurs due to the delamination of the core and face sheet interface and face yielding effect. The final failure of the panels is because of the compression of face sheet. The fatigue results show that the fatigue life of the material linearly decreases with stress level.

Because of the importance of honeycomb panels in many areas it is necessary to proceed this study by considering the variation in design parameters and physical properties. The use of SEM and three dimensional digital image correlation is highly recommended for failure analysis. It is need to select the optimum honeycomb sandwich structure for each application on the bases of flexural rigidity per unit weight, fatigue life and failure behavior.

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