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Effect of Thermal Cycles on Flexural Behavior of Al/Al Honeycomb Sandwich Structures

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Abstract: The main attractiveness of honeycomb sandwich structures lies in their high stiffness/weight and strength/weight ratios, which makes them suitable for primary structural aerospace parts such as aileron, elevator and rudder where weight reduction is a primary concern. Honeycomb cores, including nomex and aluminum honeycombs, have been used in the aerospace industry where bending, buckling, impact resistance and fire retardation are required, for example in some primary structural applications like wings and stabilizers. During flight time period, structural parts of an aircraft can be subject to thousands of such thermal cycles. Due to these environmental effects, damages can be occurred, especially at the interface region of core/face sheet. From literature surveys on evaluation of honeycomb sandwich structure flexural properties, it is not easy to find an article about sandwich behaviors under the effects thermal cycling. The information probably exists, as it is used on aircrafts that are submitted to a rigorous certification process to guarantee that they operate under safe conditions. However, this information may be restricted by confidentiality because of military or commercial concerns. In this study, AA3005-H19 aluminum alloy core/AA5754-H22 aluminum alloy face sheet (Al/Al) honeycomb sandwich structures are subjected to thermal cycles (0, 50, 150 and 300 cycles) in a full function environmental test chamber at temperature ranges -30 ^{o}C to +40 ^{o}C for 120 minutes. This paper deals with the determination of flexural properties such as ultimate core shear stress, facing stress, flexural stiffness, transverse shear rigidity and core shear modulus of various thermal cycled Al/Al honeycomb sandwich structures. Three-point bending tests are performed and flexural properties are calculated according to ASTM C393/C393M-16 and ASTM D7250/D7250M-16. After three-point bending tests, damage mechanisms which are occurring in the honeycomb sandwich structures are detected by digital camera images.

Keywords: Honeycomb sandwich structures, Three-point bending tests, Thermal cycles, Damage modes

Introduction

With the development of new materials technology, honeycomb sandwich structures are increasingly used in the aerospace, civil engineering and other fields because of its good performance in lightweight, high strength and stiffness, resistance of fatigue (Ley & Godinez, 2013, pp. 309-336). Due to its outstanding absorbed energy properties, impact resistance and lightweight characteristic with high in-plane and flexural stiffness, honeycomb sandwich structures are widely used on aircraft flight control surfaces such as rudder, aileron, spoiler, and flap. (Bruffey & Shiu, 2016; Han et al., 2020; Lu & Yu, 2003; Zhang, Lu, Ruan, Fei & Duan, 2019).

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Face sheets of honeycomb sandwich structures are made from stainless steel, aluminum alloy, titanium alloy or typically thin composite laminates. On the other hand, the core of the sandwich is mostly honeycomb cell walls and made of nomex, fiberglass or aluminum alloy (Wei, Wu, Gao, & Xiong, 2020; Xie, Jing, Zhou, & Liu, 2020). Aluminium/aluminium (Al/Al) structures are especially preferred in the use of structural parts of the aircraft due to their performance against environmental conditions such as high G forces and high fatigue strength (Jen & Chang, 2008). 5xxx and 3xxx aluminum alloys are preferred as the face sheet and core material in honeycomb sandwich structures for aircraft structural parts due to resistant of atmospheric corrosion. When the literature studies on the mechanical properties of Al/Al honeycomb sandwich structures are investigated, some previous studies are found. Palomba, Crupi & Epasto (2019) performed three-point bending tests at different bending test speeds to determine the flexural properties of AA5754/AA5052 honeycomb sandwich structures. It was determined that the bending moment values of Al/Al honeycomb sandwich structures did not change significantly according to the bending test speed. In addition to this result, it was stated that the highest bending moment value (83 kNm) was obtained in tests with 2 mm/min bending speed. Sun, Huo, Chen & Li (2017) applied three-point bending tests on samples (AA5052/AA3003 honeycomb sandwich structures) with different core thickness (0.04 mm, 0.07 mm and 0.1 mm) in order to examine the effect of core thickness on the flexural properties of honeycomb sandwich structures. The results showed that the increase in core thickness had been increased the maximum force applied to the material and had been consequently improved the strength of the material. Maximum force is about 2000 N at 0.1 mm and about 1000 N at 0.04 mm. In another study, Crupi, Epasto & Guglielmino (2012) investigated the effect of different lower support span distance (55 mm, 70 mm, 80 mm, 125 mm) on the flexural properties of the AA5754/AA5052 honeycomb sandwich structures. It was found that the maximum force (2800 N) had been achieved at the smallest support span distance (55 mm). As the support range increased, the load acting on the support points increased so at longer support distances and more deflection could be applied to the material with less force. Belouettar, Abbadi, Azari, Belouettar & Freres (2009) used the bending test to examine the maximum load-deflection effects of Al/Al honeycomb sandwich structures with different core densities. AA5754 aluminum alloy was used as the face sheet material in the sample, and an aluminum alloy having different densities (55 kg/m^3 and 82 kg/m^3) was used as the core material. It was determined that an increase in core density had increased the hardness of aluminum honeycomb sandwich structures. As a result, the increase in core density made the damage load value of the material higher.

Thermal cycling (TC) is a very important phenomenon in aviation. Aircraft structural components are exposed to different temperature due to changes in the altitude. There are a few studies on the thermal cycles of Al/Al honeycomb sandwich structures in the literature. Zaoutsos (2019) aimed to determine the mechanical properties of honeycomb sandwich structures exposed to bending loading in low temperature applications. They applied four different temperatures of 23 °C, 0 °C, -40 °C and -70 °C to honeycomb sandwiches having face material aluminum 3000 series and core material aluminum 3003 alloy. Three-point bending tests were carried out on specimens made of aluminum sandwich panels according to ASTM C-393 in order to study the bending behavior of the sandwich panel. Ultimate tensile strength and yield strength are not affected from changes of temperature; while in the case of compression loading the respective values of strength seem to be decreased as temperature decreases. Bending strength is concerned by the values of ultimate strength and yield strength are not affected by the temperature. The experimental data can be used for the selection of lighter and stiffer combination of sandwich panels according to the temperatures and loading conditions. Due to limited studies in literature, it is necessary to investigate the bending behavior of such honeycomb composites used in structural parts especially in the aviation industry by also concerning the effect of thermal aging. In all mission profiles of an aircraft including taxi, flexural loading occurs in the moving parts of the aircraft due to environmental conditions. This situation is also an issue that needs to be investigated.

In this study, flexural behaviors of Al/Al honeycomb sandwich structures subjected to different thermal cycles (0, 50, 150 and 300 cycles) are investigated. Ultimate core shear stress, facing stress, flexural stiffness, transverse shear rigidity and core shear modulus of AA5754-H22/AA3005-H19 honeycomb sandwich structures are investigated by applying three-point bending test. After mechanical tests, failure modes which were occurred in the material are visualized with digital camera.

Materials and Methods

Materials

Honeycomb sandwich panels used in this study are made of aluminum alloy face sheet (5754-H22) and honeycomb core (3005-H19), which were bonded together using the double layer polyurethane. The layup including aluminum based face sheets, polyurethane adhesive and the aluminum based honeycomb core was cocured under atmospheric pressure at the recommended cure temperature of 80 ^{o}C for 15 min. The dimensions of test specimens (200 mm x 28.7 mm x 14.5 mm) were cut from the manufactured sandwich panel for three-point bending tests according to the ASTM C393/C393M standard (American Society for Testing and Materials [ASTM], 2016). L is the total length of the sandwich panel (200 mm) and W is the total width of the sandwich panel (28.7 mm). The schematic views of honeycomb sandwich structures are given in Fig. 1 where H is the total thickness of the sandwich panel (14.5 mm), b is the cell size (6.78 mm), d1 and d2 are upper and lower face sheet thickness (0.5 mm). In addition, the material properties of core and face sheet are given in Table 1.

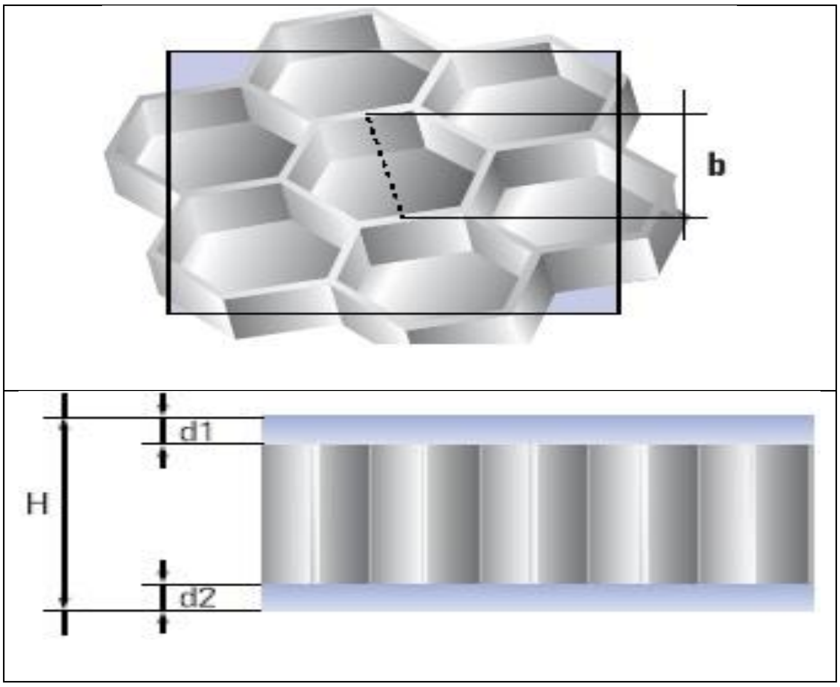


Figure 1. The geometry of honeycomb sandwich structures

Table 1. The properties of core and face sheet material

Properties	Core material (3005-H19)	Face sheet material (5754-H22)
Density	2.8 g/cm^{3}	2.66 g/cm^{3}
Modulus of Elasticity	70 GPa	70.3GPa
Ultimate Tensile Strength	270 MPa	245 MPa
Shear Modulus	26 GPa	25.9 GPa
Shear Strength	150 MPa	150 MPa
Poisson's Ratio	0.33	0.33

Thermal Cycle Condition

For accelerated thermal cycle process, Atlas SC 600 Solar Simulator environmental chamber which is facilitated in TÜBİTAK-MAM was operated. Al/Al honeycomb sandwich structures were subjected to the thermal cycles (0, 50, 150 and 300 cycles) in a full function environmental chamber at a temperature ranges -30 ^{o}C to +40 ^{o}C for 120 minutes. 300 thermal cycles corresponds to typical check interval for military fighter jet F-16C/D maintenance programs. Samples were subjected to cyclic environments with the following controlled factors: the relative humidity (RH) and the surrounding temperature (T). After thermal cycle process, honeycomb sandwich structures were removed from the climatic chamber. Fig.2 illustrates the applied temperature changes during the thermal cycling process. In Fig. 2, one cycle of thermal aging process is 120 minutes according to a flight of a military fighter jet which is serviced routine daily operational flight. In addition, RH was only applied between 0 ^{o}C and +40 ^{o}C. Accelerated thermal cycles imposed on samples at a temperature range of -30 to +40 ^{o}C with 98% RH.

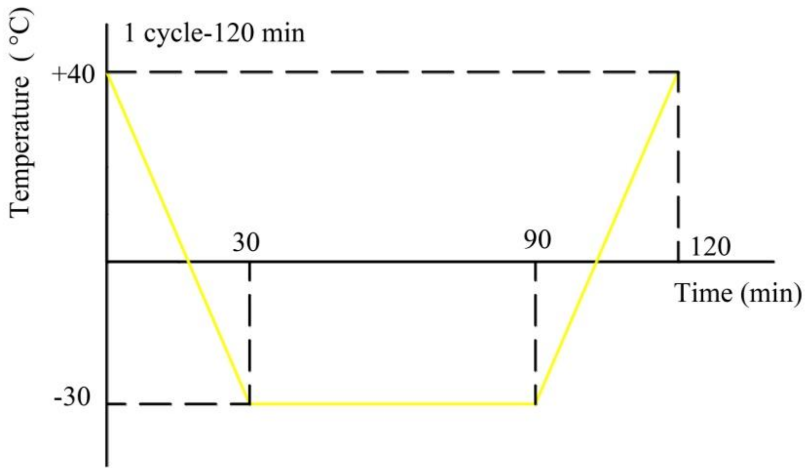


Figure 2. The temperature variations imposed during the accelerated thermal cycling test of honeycomb sandwich structures

Three-Point Bending Tests

After thermal cycling process, three-point bending tests were applied to various thermally aged honeycomb sandwich structures by the guidance of ASTM C393/C393M-16 (ASTM, 2016). MTS universal testing machine and three-point bending apparatus which are facilitated in Composites & Structures Laboratory at Istanbul Technical University was operated for three-point bending tests. Support span length was chosen as 150 mm. Rigid rollers which were used for loading and supporting tools had a diameter of 10 mm. In addition, for preventing the local core damage at support and loading locations of the honeycomb sandwich structures, 25 mm x 30 mm wide flat steel loading blocks which have 4 mm thickness are used between the sandwich surfaces and rigid rollers. Sufficient samples of honeycomb sandwich structures to get significant flexural data were tested with the speed of 4 mm/min for cross head displacement. The load-displacement curves were obtained by using the load and displacement data which were stored by MTS universal testing machine. The flexural properties such as ultimate core shear stress, facing stress, flexural stiffness, transverse shear rigidity and core shear modulus of various thermally aged honeycomb sandwich structures were determined. Average values of tested honeycomb sandwich structures were given. The ultimate core shear stress and facing stress are calculated from the load-displacement curve based on the formulas in ASTM C393/C393M-16 (Eq. 1 and Eq. 2) (ASTM, 2016). The flexural stiffness, transverse shear rigidity and core shear modulus of sandwich structures are obtained by using the formulas and the method of two loading configurations on the same test specimens described in ASTM D7250/D7250M-16 (Eqs. 3-5) (ASTM, 2016). In this method, the data in elastic region of load-displacement curves were used. The support span length for the second loading configuration was described as 120 mm. The flexural stiffness, transverse shear rigidity and core shear modulus of the honeycomb sandwich structures can also be obtained using simple bending theory (ASTM, 2016). However, the effects of thermal cycles and humidity on material properties of face sheet, core and adhesive were not able to be determined. For determining the flexural properties of honeycomb sandwich structures, the formulas of flexural properties are shown in Eqs. 1–5, respectively;

$$F_s^{ult} = \frac{P_{max}}{(d+c)b} \tag{1}$$

$$\sigma = \frac{P_{max}S}{2t(d+c)b} \tag{2}$$

$$D = \frac{P_1\, S_1^3(1-S_2^2/S_1^2)}{48\Delta_1(1-P_1 S_1 \Delta_2/P_2\, S_2 \Delta_1} \tag{3}$$

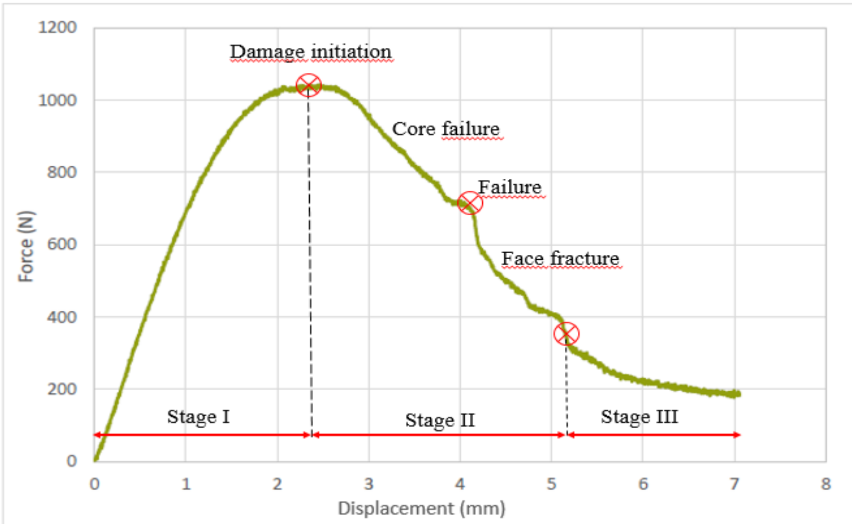
$$U = \frac{P_1 S_1 \left(S_1^2/S_2^2-1\right)}{4\Delta_1\left(\left(P_1 S_1^3 \Delta_2/P_2 S_2^3 \Delta_1\right)-1\right)} \tag{4}$$

$$G = \frac{U(d-2t)}{(d-t)^2 b} \tag{5}$$

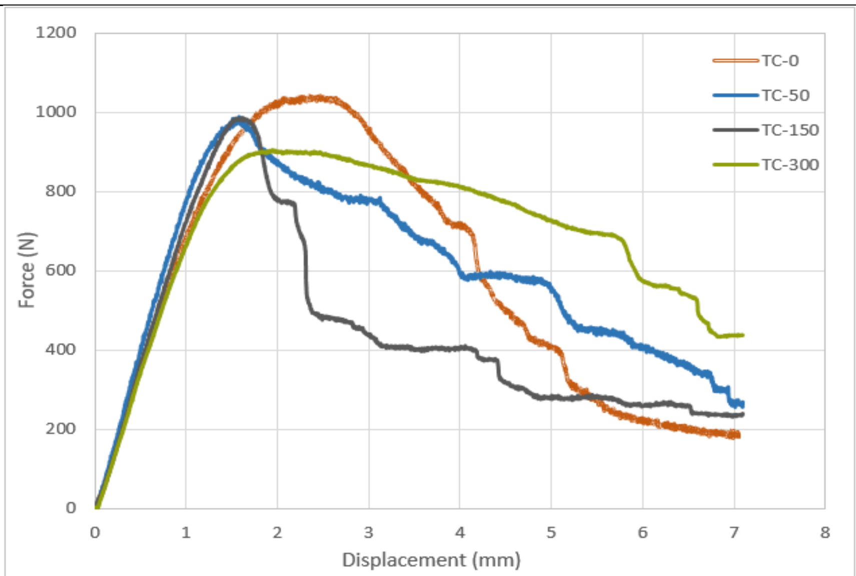
where P_{max} is maximum load prior to failure (N), d is sandwich thickness (mm), c is core thickness (mm), b is sandwich width (mm), S is support span length (mm), t is face thickness (mm), Δ is mid-span deflection(mm), F_s^{ult} is core shear ultimate strength (MPa), σ is facing stress (MPa), D is sandwich flexural stiffness (Nmm^2), U is transverse shear rigidity (N), G is core shear modulus (MPa). After three-point bending tests, damage mechanisms which are occurring in the honeycomb sandwich structures are detected by digital camera images.

Results and Discussions

The load-displacement curves of various thermally aged honeycomb sandwich structures were obtained to investigate the effect of the thermal cycle numbers on the flexural behavior of the samples. Obtained load-displacement curves of various thermally aged honeycomb sandwich structures and conventional unaged load-displacement curve are given. Damage process of honeycomb sandwich structures under three-point bending test were illustrated in Fig. 3.



(a) Typical force-displacement curve and damage process of honeycomb sandwich structures under three-point bending test (He et al., 2019).



(b) Force-displacement curves of various thermally aged honeycomb sandwich structures

Figure 3. (a) Typical force-displacement curve and damage process of honeycomb sandwich structures under three-point bending test (He et al., 2019), (b) Load-displacement curves of various thermally aged honeycomb sandwich structures

From Fig.3(a), depending on the drop points the load-displacement curves can be divided into three distinct stages: the initial elastic stage (Stage I), the core or face sheet failure stage (Stage II), and global failure stage (Stage III). In Stage I, the specimen deforms elastically in the initial phase of bending and the corresponding load value has a nearly linear increase almost up to the peak load. However, for the core failure case, there is a little non-linearity in the load-displacement curve prior to peak load, indicating some plastic buckling of the core occurring under the indenter. In Stage II, there are two main damage modes (core failure and face sheet failure), and the trend change is closely associated with the competing failure patterns of sandwich panel. After the top face sheet complete fracture, there is a relative stable load plateau until the final rupture of the panel in Stage III.

In this stage, the prominent failure patterns are core crushing under the indenter and further delamination of the fracture section in the top face sheet (He et al., 2019). From Fig. 3(b), it was determined that all of the thermally aged honeycomb sandwich structures exhibited a similar general trend in the load–displacement curve. First of all, damage initiation occurred at maximum load values, after this point core failure and face sheet failure determined for all thermally aged honeycomb sandwich structures. It was easily determined that displacement values at maximum load also sharply decreased with the increment of thermal cycle numbers. At last, catastrophic damages occurred as core crushing and delamination at all thermally aged honeycomb sandwich structures. Average values of maximum load, core shear ultimate stress, facing stress, flexural stiffness, transverse shear rigidity and core shear modulus for all cases are shown in Table 2.

Table 2. Obtained flexural properties of various thermally aged honeycomb sandwich structures from load-displacement curves

Sample Codes	Maximum Load (N)	Core Shear Ultimate Stress (MPa)	Facing Stress (MPa)	Flexural Stiffness (Nm2)	Core Shear Modulus (MPa)	Transverse Shear Rigidity (kN)
TC-0	1042,49	1,296	194,46	105,92	123,22	51,4
TC-50	989,84	1,232	184,76	209,34	100,72	41,97
TC-150	984,59	1,226	183,91	224,2	89,48	34,85
TC-300	905,26	1,129	169,33	157,13	83,70	37,21

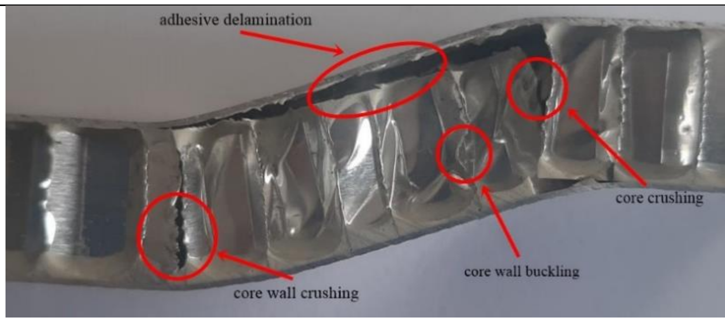
The results of the three-point bending test show a clear reduction trend in the flexural properties such as core shear ultimate stress, facing stress and core shear modulus values as the number of thermal cycles increased (Table 2). Core shear ultimate stress, facing stress and core shear modulus values of thermally aged honeycomb sandwich structures (TC-300) decreased approximately %13, %13 and %32 according to the original honeycomb sandwich structures (TC-0), respectively. At this point, there is a sharp decrement at core shear modulus values for thermally aged honeycomb sandwich structures with 300 thermal cycles. This trend was observed due to the effects of the shear stresses occurring on the fracture of the core during loading. The high value of the shear stress caused deformation and fracture of the core in a shear mode. In the three-point bending test, crack propagation in the core was significant along the neutral axis, which caused the strength of the core to play an important role in determining the mechanical properties of the honeycomb sandwich structures. The fracture of the core relieved the local stress in the material as similar to Ref. (Antony Arul Prakash, Jagannatha Guptha, Sharma, & Mohan 2012).

At higher support span length (≥ 70 mm), the collapse mode was different because it was accompanied the mid-plane and by the formation of a plastic hinge also in the tensioned face. By this way, at higher deflections boardened peak occured (Fig. 3-b) as similar to Ref. (Crupi et al.,(2012). For the transverse shear rigidity as a flexural property shown in Table 2, a similar reduction trend with other properties above observed as the number of thermal cycles increased from 0 to 150 cycles. No significant reduction in 300 cycles detected according to 150 cycles. Lastly, a regular reduction pattern was not observed for flexural stiffness while the thermal cycles were increased. It has an increased trend except for 300 cycles. This can be because of flexural stiffness is generally related to strength of face sheets while the others are related to shear performance of core and adhesive. It is possible that the thermal cycle effect could be increase the strength of the face sheets as so-called heat treatment effect on a metallic material.

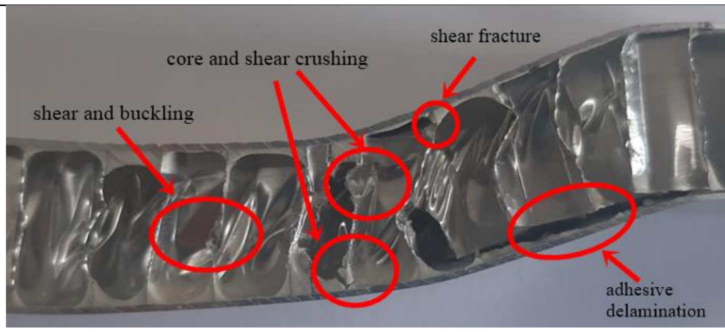
Failure modes of various thermally aged honeycomb sandwich structures after three-point bending tests were given in Fig.4. The between face sheet and core which were strong enough to bear the bending and shear load result in the adhesive delamination mode.

(a) the original honeycomb sandwich structures- TC-0

(b) thermally aged honeycomb sandwich structures -TC-50



(c) thermally aged honeycomb sandwich structures- TC-150



(d) thermally aged honeycomb sandwich structures- TC-300

Figure 4. Failure modes of various thermally aged honeycomb sandwich structures after three-point bending tests

This situation observed as damage with each thermal cycle tested. Fig. 4(a) shows that the main failure mode observed is face sheet indentation and adhesive delamination. However, adhesive delamination collapse mode observed is between core and face sheet (Jen & Lin, 2013). In Figure 4 (b-c), no different from each other collapse modes detected. In addition to the original sample, core wall fracture and buckling were observed. When the load reaches the peak value, the core under the face sheet is began to crush. In Fig 4(d), five competing failure modes were observed, including shear buckling, shear fracture, adhesive delamination, core crushing and core buckling. Significant core and shear crushing is observed in thermal cycle followed by fracture of core walls. This sample is after the core failed by shear fracture, debonding occurred as the cracks propagated in the adhesive layer. The reason for this is the more deformation of the sample due to the increase in thermal cycling. The decrease in flexural properties such as core shear ultimate stress, exposure stress and core shear modulus values was also observed in digital images (Anandan, Dhaliwal, Ganguly & Chandrashekhara, 2020; Wang et al, 2018).

Conclusions

In this study, flexural behaviors of Al/Al honeycomb sandwich structures subjected to different thermal cycles were investigated. From the obtained experimental results, it was possible to draw some conclusions on the behaviour of investigated honeycomb sandwich structures:

1. Maximum load, core shear ultimate stress, facing stress and core shear modulus values of thermally aged honeycomb sandwich structures (TC-300) decreased approximately %14, %13, %13 and %32 according to the original honeycomb sandwich structures (TC-0), respectively.
2. Flexural stiffness of values of thermally aged honeycomb sandwich structures (TC-300) increased approximately %50 according to the original honeycomb sandwich structures (TC-0).
3. Transverse shear rigidity values of thermally aged honeycomb sandwich structures (TC-300) decreased approximately %27 according to the original honeycomb sandwich structures (TC-0).
4. Failure of cell walls due to local buckling was observed in the honeycomb sandwich structures due to the thermal cycles.
5. Differently shear fracture, core and shear crushing, shear and buckling of thermally aged honeycomb sandwich structures (TC-300) were observed according to the original honeycomb sandwich structures (TC-0).

As a result, the decrease due to thermal cycles in flexural properties such as core shear ultimate stress, exposure stress and core shear modulus values was observed.

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