Experimental Investigation and Numerical Simulation of the Mechanical Behavior of a Novel Honeycomb Core Sandwich Panels Formed by Hydroforming Process

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Abstract
Sandwich panel with central core honeycomb aluminum as one of the main shielding structures because of their high strength-to-weight ratio and improved energy absorption capacity, has been attracted the attention of many researchers and practitioners in recent years. This paper initiates and presents a new type of central core honeycomb formed by hydroforming process. The study is augmented by a numerical and experimental work on flexural behavior of sandwich panel structures made of aluminum alloy and different cores such as aluminum, polyurethane foams, PVC, silicone and carbon fiber. Firstly a numerical simulation by ABAQUS software was run, then prepared samples were tested and related force-displacement diagrams were depicted from results. Comparing the corresponding diagrams obtained from simulation with that of the results of experimental investigation, high flexural strength of the sandwich panels with proposed honeycomb core relative to a three-layer sheet as well as a very high flexural strength of suggested sandwich panel with honeycomb core filled with carbon fiber against other samples of honeycomb was observed. Finally, comparing the experimental results with numerical simulations indicates acceptable conformity.

1. Introduction
Sandwich panels with aluminum honeycomb core are known as one of the main shielding structures having high strength to weight ratio and having high energy absorption capacity, which in recent years have been the focus of attention of researchers and practitioners. Due to the increased demand for lightening of structures weight, for example in construction of flying objects such as aircrafts, drones, etc., automotive, high-speed trains and ships in the transportation industry, design and construction of these structures are quite different from those of its predecessors. The proper use of these materials in different applications requires more developed knowledge of their mechanical behavior. A few sample applications of sandwich panels are shown in Figure 1.

Figure1. Applications of Sandwich panels [1]

Traditional and common method for honeycomb core construction is shown in Figure 2. This method is very time consuming and needs to spend much time for both production and assembly of discrete structures.
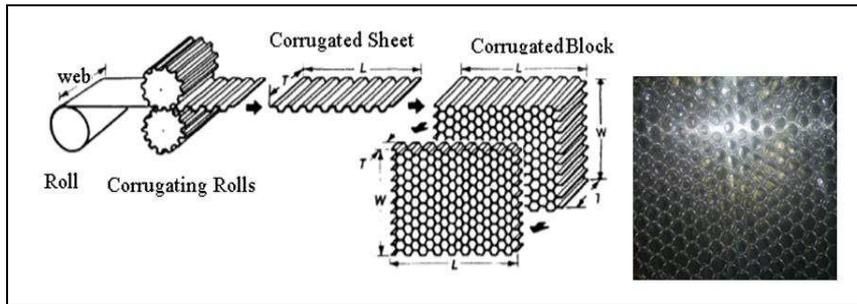

Figure2. Usual method of production of honeycomb core for sandwich structures [2]

Hydroforming or hydraulic forming is one of the main processes of forming metal sheets, which was used before the Second World War II. Nowadays this method as an alternative to the processes of Pines - Traditional matrix and welding of parts is recommended. This method can reduce part weight, minimize materials waste and contribute to building stronger and more resistant parts that require less welding. Figure 3 shows the production process of a piece of sheet hydroforming process and Figure 4 shows two honeycomb samples, one formed by hydroforming process (a) and another shaped by traditional process (b).
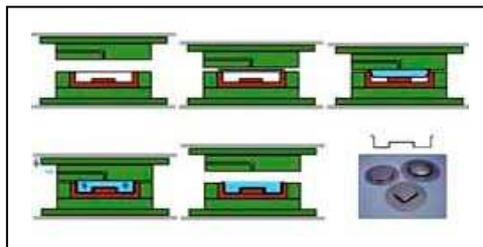

Figure3. Various stages of production parts by sheet hydroforming process [3]

Figure4. (a)The proposed middle core formed by hydroforming process,(b) Traditional sample [4]

Lihui Lang et al. [5] examined the experimental and numerical study in sheet hydroforming process of multilayer plate with a very thin layer in middle. Based on the proposed HDD with uniform pressure onto the blank, the triple-layer structure with the very thin layer in the middle was hydroformed successfully to contribute to the realization of functional gradient structure forming. The formability of the thin middle layer has been improved significantly, and the wrinkling and the fracture are totally avoided although the middle layer is extremely thin. Aluminum alloy metal sheet hydroforming process is described by Novotny and Hein [6]. Using appropriate mechanical properties of aluminum for lightweight structures, they studied alloy AA 6016-T4 and also examined different ways to increase the ductility of this material in the hydroforming process. Gedikli et al. [7] have examined hot hydroforming for sheet aluminum alloy AA5754-O practically and theoretically. Using finite element method, they compared the numerical and practical results. For the numerical solution, several different sizes and types of mesh were used.

Shahbazi Karami et al. [8] examined the effective geometrical and physical parameters in hydroforming of three-layer composite tubes using finite element method. In this paper, single, bi-layered and three-layered tube hydroforming processes were numerically simulated using the finite element method. It was found that the final bulges heights resulted from the models were in good agreement with the experimental results. Three types of modeling were kept with the same geometry, tube material and process parameters to be compared between the obtained hydroformed products (branch height, thickness reduction and wrinkling) using different loading path types. Hosseinzadeh et al. [9] examined effective parameters in a new hydroforming method. In this study, a polyurethanes sheet is used in order to control and reduce wrinkling in the area of the blank flange.

The core section (middle layer) of honeycomb sandwich panels are almost like nests of bees in nature and its name is taken from it. The Chinese were the first people who have created honeycomb papers about 2,000 years ago and used them for making jewelry. One of the first man-made sandwich-shaped structures was tubed shape bridge in Wales's railway line which was built in 1845. In 1919, the first sandwich panel in aircraft where the Mahogany surface layers connected with balsa wood core layer was used. Also in the first and second world wars, wooden covers attached to the core layer were used as the basic structure of the Italian seaplanes.

Full aluminum sandwich panels were not made until 1945. The real success was just before the change of adhesives for connecting the surface layers to core layers. The honeycomb structure is used in numerous applications including energy absorption, directing air flow, thermal panels and acoustic panels.

In the last decade interest in the development of resistant structures is increased. Rahimi et al. [10] examined the Pitch effect on flexural behavior of sandwich structure with composite skins and a corrugated combinatorial core with trapezoidal geometry. In this paper the experimental and numerical study on flexural behavior of new type sandwich structures with glass-epoxy skins and a combinatorial core consist of foam and corrugated composite with trapezoidal geometry was investigated. It has been shown that the flexural stiffness was increased with decreasing in pitch; and the flexural stiffness to mass ratio was increased at first but then was decreased with decreasing in pitch. Finally, the experimental and numerical results were compared and a reasonable agreement between them has been observed.

Xu et al. [11] examined empirically the increased stamina of aluminum honeycomb by trapping air under dynamic load. In this study, it was found that cellular texture of metals is sensitive to strain rate at stretch, but there is no strain augmentative sensitivity. In this study, the reason for increased endurance by focusing on the distribution of trapped air during the compression process is studied. Results showed that the change of trapped air pressure during the dynamic compression is the direct source of aluminum honeycomb strain.

Pirmohamadi et al. [12] experimentally and numerically studied a type of sandwich panel under impact with low-speed that the considered sandwich panel consists of glass-epoxy composite covers and honeycomb core made of aluminum.

This article reviews experimentally and numerically the strength of 6 samples of composite sandwich structures with aluminum foil covers and different central cores and also pays to ultimate flexural strength check and experimental and numerical results were compared with each other.

2. Experiments

2.1 Materials properties

Sandwich structures are usually made in sheets with standard dimensions and with respect to considered application are made integrally by putting these sheets near each other. One of the materials that have many applications in production of sandwich panels is aluminum alloy. In this study with respect to properties of aluminum alloy 5000 series such as in welding and super-plasticity, aluminum alloy 5754 in order to build the proposed honeycomb core and shell is used. Table 1 shows the physical and mechanical properties of aluminum alloy AA 5754, also Figure 6 indicates its stress-strain curve according to the tensile test based on ASTM-E8/E8M-13a standard. The Sample of tensile test is shown in Figure 5.

Table1. Physical and Mechanical properties of aluminum alloy AA 5754

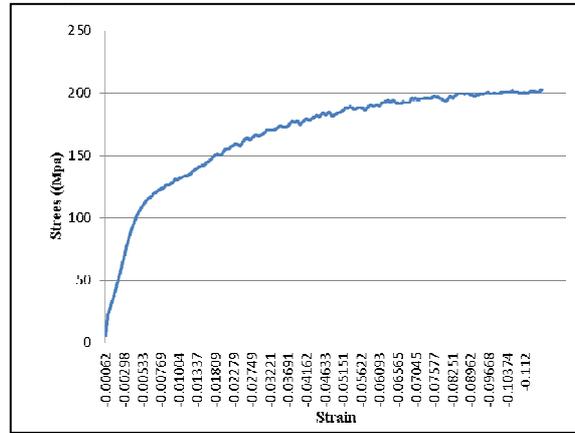| Property	Value
Density	2.66 g/cm^3
Modulus of Elasticity	68 GPa
Passion Ratio	0.34
Property	Value
Standard give up strength	Minimum 130 MPa
Strain resistance	220-270 MPa
Hardness Brinel	63 HB

Figure5.The sample of tensile test

Figure6.Stress-strain curve of tensile test

2.2 Development of the sample

2.2.1 Three - layer sheet of aluminum

One of the most important cases in making sandwich panels is to choose the appropriate and applied adhesive which has high resistance and strength, in our study industrial Bell glue based on CR is used. Bell industrial adhesives product is tested and known as highly resistant and fast adhesive that is produced by combination of rubber polymers, industrial resins and stabilizers in a mixture of solvents. It is polymer-based adhesive CR that is used to stick all levels that should fit with speed and strength to each other. Connected surfaces have high tensile strength.

To stick surfaces with this adhesive, first all surfaces must be dried and cleaned of any grease and dust. Using a brush or any other means, uniformly imbrue surfaces with adhesive substances and for15 to 20 minutes are kept separately layers of glue to dry slightly, then press the two surfaces to each other and wait until surfaces to stick together perfectly. The more pressure of surfaces, the greater adhesion strength, drying time for industrial adhesives based on CR, is 15 to 20 minutes and the solvent is toluene that is in liquid honey form.

External diameter of aluminum sheet for sides and core is 140 mm and a thickness of 1.5 which are stuck together by Bell industrial adhesives and it leads to a total of sandwich panels with a diameter of 140 mm.

2.2.2 Proposed honeycomb sandwich panel

As it was mentioned earlier, in this research aluminum alloy 5754 with sheet diameter of 140mm and thickness of 1.5mm was used in order to fabricate honeycomb core and also honeycomb face sheets.

Design of geometry of honeycomb core is shown in Figure 8. The hydroforming machine, modeling and manufacturing the mold are shown in the Figure 7.

At first, honeycomb face sheets and cores are completely cleaned and soaked in industrial adhesive and compressed together using manual press tool and put the collection under compression of manual press tool for a few hours in order to let the adhesive reach its ultimate stiffness and strength as shown in Figure 9.

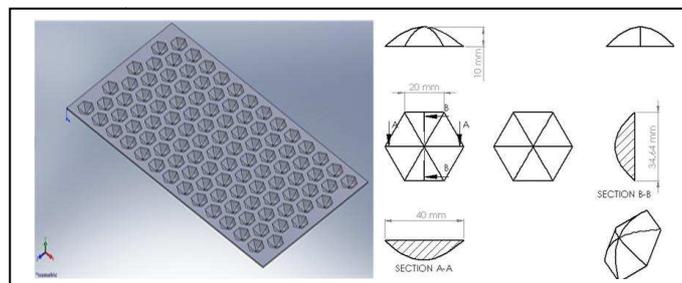Figure7. The mold and sets machine hydroforming [4]

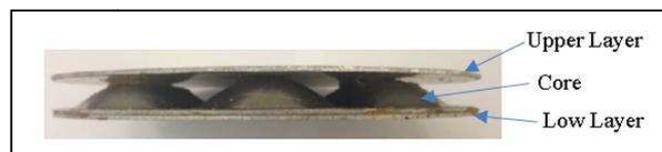Figure8. The geometry shapes of designed new honeycomb

Figure9. The layers of proposed honeycomb sandwich panels

2.2.3 Proposed honeycomb sandwich panel filled with hard polyurethane foam
In manufacturing this type of honeycomb sandwich panel, hard polyurethane foam has been injected into sandwich panel core in order to enhance flexural, tensile, compressive strength and also insulating properties of the proposed sandwich panel, which its manufacturing process will be

expressed later. Proposed honeycomb sandwich panel filled with polyurethane foam is circular with 140mm in diameter as same as empty honeycomb sandwich panel.

Polyurethane foam is developed by mixing two fluids called Polyol and Isocyanate.

In a way that Polyol is first poured into the intended container, and then Isocyanate is poured on it, in the following, these two fluids are stirred with a mixer and are completely mixed. In this study, this task is done using a drill and manufactured mixer series.

In formation process of rigid polyurethane foam, consists of three important time steps called cream time, gel time and rise time. Cream time ranges from the beginning time of mixing by mixer to the beginning moment of the increase in mixture volume. From the beginning time of mixing by mixer until the moment of evolve of the first polyurethane yarn from the growing foam mass is called gel time. From the beginning time of mixing by mixer until the last moment of polyurethane foam mass growth is called Rise time. In Table2 a summary of obtained times during the formation process of polyurethane foam in this study is reported.

Table2.Information of required time for manufacturing process of used polyurethane foam

Time of final formation (s)	Time of gelation (s)	Time of cream (s)
205	53	15

At first, honeycomb holes are filled with Polyurethane foam and then the first face sheet is compressed to the honeycomb core layer using manual press to be quite tightened on each other and honeycomb holes become filled with hard polyurethane foam. In the following, after opening the manual press, the second sheet is fixed on the core and first sheet, and they are placed on each other firmly by manual press, then outer perimeter of sandwich panel becomes enclosed and polyurethane foam is injected into sandwich panel in the cream stage to completely fill inner space of sandwich panel. Figure10is representative of the proposed honeycomb sandwich panel filled with polyurethane foam.

Figure10. Proposed honeycomb sandwich panels filled with polyurethane foam

2.2.4 Proposed honeycomb sandwich panel filled with PVC foam

In manufacturing this type of honeycomb sandwich panel, PVC foam is used in sandwich panel core in order to increase strength coefficient and insulating properties.

At first, PVC sheets are combined with specific resin and hardener and then are combined with the proposed honeycomb core. Afterwards, combined face sheets and core layers with PVC foam are compressed using manual press and are completely tightened and attached on each other. Figure 11 is representative of the proposed honeycomb sandwich panel manufactured with PVC foam.
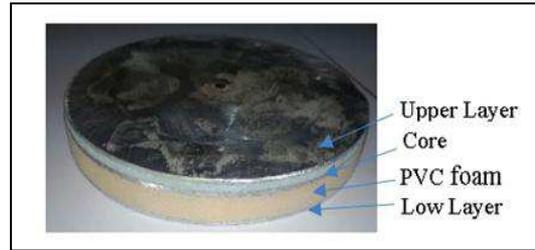
Figure11. Proposed Honeycomb sandwich panel filled with PVC foam

2.2.5 Proposed honeycomb sandwich panel filled with silicon foam

In this type of sandwich panel, silicon was used in combination with the proposed honeycomb core due to its properties like proper insulating properties.

At first, silicon is combined with its specific hardener, and because silicon combination is liquid, a wooden mold is prepared with the same sizes of sandwich panel in order to place the sandwich panel in it and fill it with silicon foam.

honeycomb holes are at first filled with silicon foam and the first face sheet is compressed to core layer using manual press to be placed firmly on each other and the core be filled with foam, then the second sheet is compressed and tightened on the core and first sheet, and outer perimeter and free space of sandwich panel is again filled with foam, and sandwich panel is tightened in the mold by press, after a few hours the desired sample is removed from the mold. Figure 12 is indicative of sandwich panel made by silicon foam.
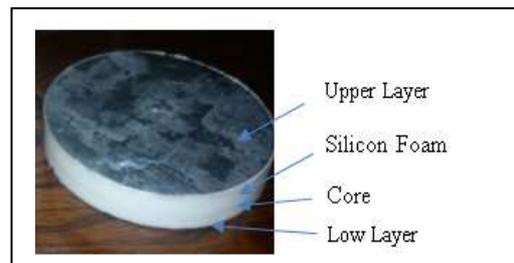

Figure12. Proposed honeycomb sandwich panel filled with silicon foam

2.2.6 Proposed honeycomb sandwich panel filled with carbon fibers

Carbon fibers are used due to high strength, low weight and as a proper insulation in manufacturing this type of sandwich panels.

Each layer of carbon fibers are impregnated with resin and the proposed sandwich panel core is filled with carbon fibers using manual layer clipping method. In Figure13,a sample sandwich panel prepared by this method is displayed.
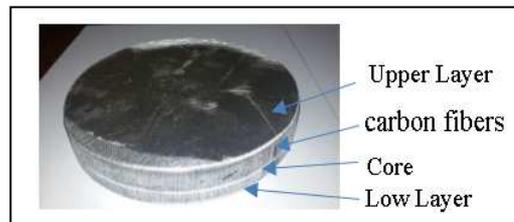
Figure13. Proposed honeycomb sandwich panel filled with carbon fibers

3. Three point flexural test

The purpose of three point flexural test is investigating flexural strength properties in materials. STM-150 machine (SANTAM 15 ton) was used to conduct three point flexural test. In Figure 14, an example of force sensors and jaws of this machine are shown to conduct the test. In this stage, according to the point that, one of our purposes is to show the strength enhancement of this honeycomb sandwich panel, this test is conducted empirically and experimentally on six specimens.

3.1. Three point flexural test procedures

At first, the manufactured sandwich panel sample is placed on the supports of three point flexural test machine and according to numerical simulation, the specimen is placed outside the both sides of the supports; this value has a distance equal to 38.66022 mm measured from sandwich panel center to its both ends, and this value is set by adjustable supports. Also, the jaw is applying the force in the middle of the specimen, and this force is exerted with rate of 2 mm per second. In Figure 15, test performing procedures are shown in order.
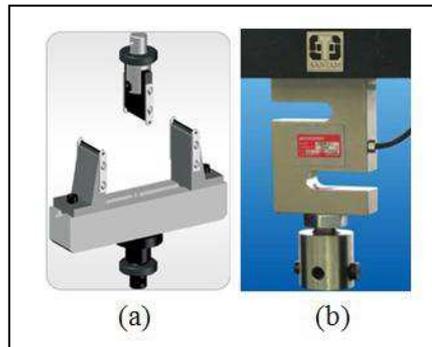

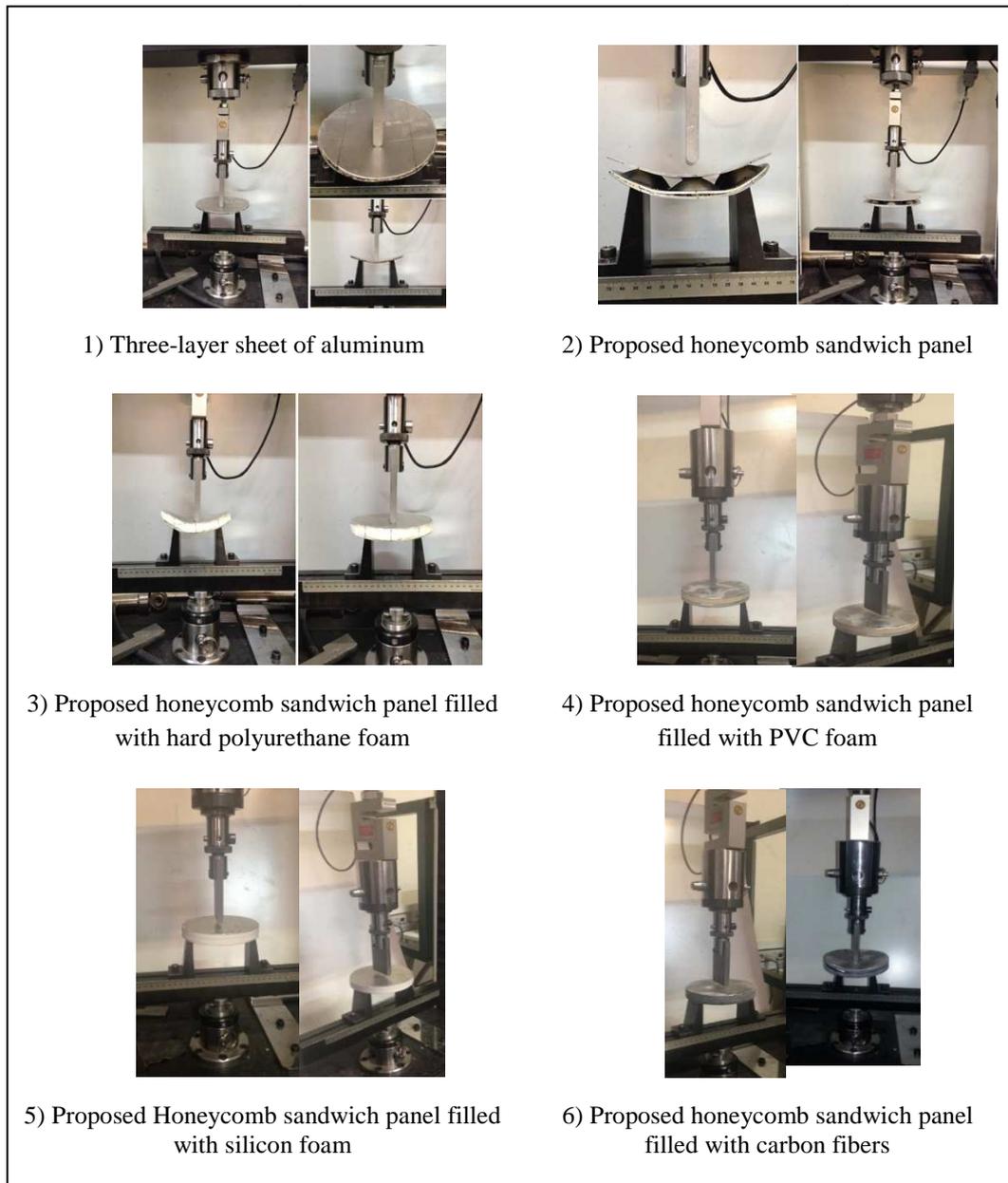Figure14. (a) Load Cell, (b) jaws of three point flexural test

1) Three-layer sheet of aluminum

2) Proposed honeycomb sandwich panel

3) Proposed honeycomb sandwich panel filled with hard polyurethane foam

4) Proposed honeycomb sandwich panel filled with PVC foam

5) Proposed Honeycomb sandwich panel filled with silicon foam

6) Proposed honeycomb sandwich panel filled with carbon fibers

Figure15. Performance Steps of Three point flexural test

4. Experimental results

In this research, force-displacement curve regarding each specimen is obtained at the end of three point flexural test. Figure16is representative of force-displacement curve of the first three specimens tested, including three-layer sheet of aluminum, proposed honeycomb sandwich panel and proposed honeycomb sandwich panel filled with polyurethane foam.
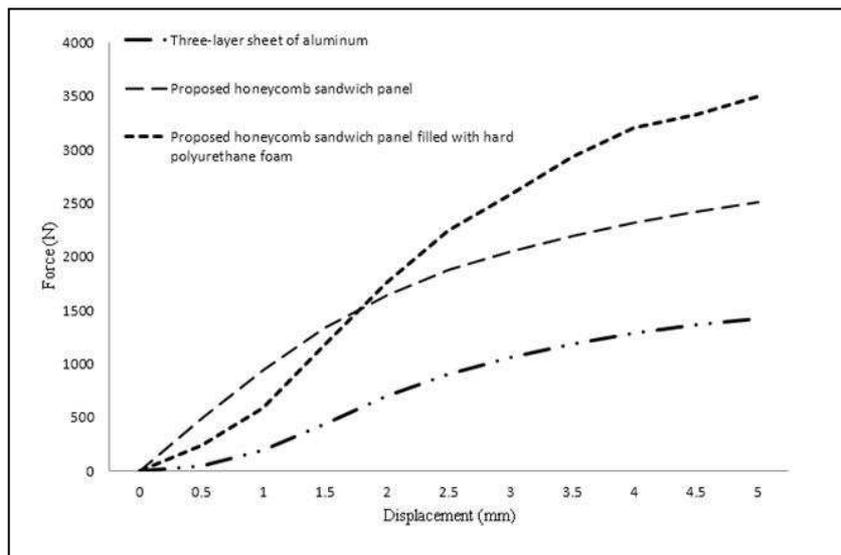
Figure16. Force-displacement diagrams

In this stage, results from comparison of force-displacement curves of the first three specimens are investigated. As diagram of Figure 16displays, force-displacement curves of three compared specimens and table 3which is representative of flexural strength ratio of three specimens, are prepared.

Table3. Ratio of flexural strength

NO	Experimental samples	Weight (N)	Force tolerated (N)	Ratio strength to weight
1	Three-layer sheet of aluminum	1.66	1400	843.37
2	Proposed honeycomb sandwich panel	1.66	2500	1506
3	Proposed honeycomb sandwich panel filled with hard polyurethane foam	1.96	3500	1785.7

Study of Figure 16 and Table 3 show that flexural strength of honeycomb sandwich panel is improved considerably and due to the fabrication of designed core layer, its flexural strength has increased by approximately 80% compared to a three-layer aluminum sheet with the same material and dimensions, which reflects success and applicability of use of this sandwich panel, also, by using hard polyurethane foam, we can increase flexural strength of the proposed honeycomb sandwich panel.

Figure 17 is representative of force-displacement curves resulted from three point flexural test on three other specimens including proposed sandwich panel filled with PVC foam, proposed sandwich panel filled with silicon foam and proposed sandwich panel filled with carbon fibers.
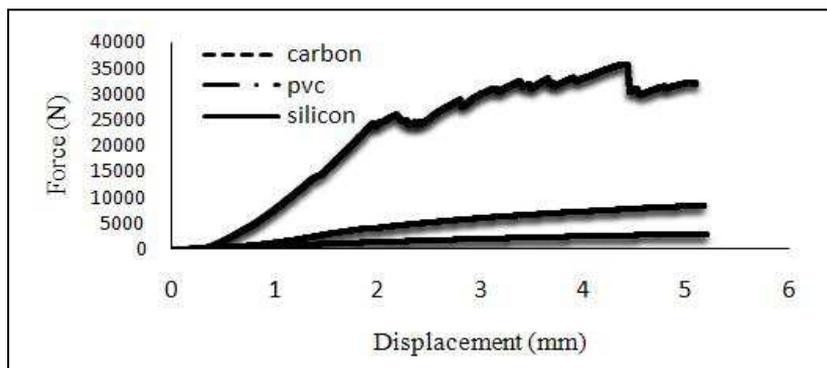
Figure17. Force-displacement diagrams

In this stage, results from comparison of force-displacement curves of the three other specimens are investigated which are shown in Figure 17 and Table 4 is representative of flexural strength ratio of these three specimens.

Table4. The ratio of flexural strength

NO	Experimental samples	Weight (N)	Force tolerated(N)	Ratio Strength to weight
1	Proposed honeycomb sandwich panel filled with PVC foam	2.35	8200	3489.36
2	proposed honeycomb sandwich panel filled with silicon foam	4.11	2850	693.43
3	proposed honeycomb sandwich panel filled with carbon fibers	4.11	32000	7785.88

After investigating diagram of Figure 17 and Table 4, it can be realized that flexural strength of honeycomb sandwich panel filled with carbon fibers is very high and due to the fabrication of this core layer, its flexural strength has an approximately %123increase compared to the specimens filled with PVC foam and an approximately %1022 increase compared to the specimens filled with silicon foam, with the same dimensions.

5. Finite element analysis

The concept of virtual production has been developed as an effective method to reduce production time and enhance products quality, due to the increase in industrial applications. Numerical simulation of metal forming processes plays an important role in reduction of performance time. Finite element method is one of the most pervasive numerical methods for simulating, which is widely used at the moment. Sheet metal forming processes are one of the most functional processes of industry, thus, material modeling is a strategic step in production of the desired parts. ABAQUS is very powerful simulation software to analyze engineering problems which can analyze a wide range of engineering problems. Problem-solving steps are respectively as follows: developing geometry of model, defining material properties, assembling parts on each other (mold and raw sheet), defining solving steps, defining contact type of mold and sheet, applying boundary and loading conditions and grid generation which are considered as steps of preprocessing and then

simulating and finally obtaining and displaying desired outputs in order to design the intended machine.

At first, it is intended to draw geometry of model and then it was generated a grid for the geometry of problem. Properties of the desired material which is aluminum alloy 5754 in the proposed honeycomb sandwich panel were defined in ABAQUS software in order to be solved. In this simulation Dynamic/Explicit model is used to simulate three point flexural tests in ABAQUS software. To simulate three point flexural test, it is require to consider two supports beneath the honeycomb sandwich panel in order to hold the test sample and also to flange three point flexural test machine in order to apply pressure on the sample, thus three rod-shaped cylinders with diameter of 10 mm and length of 150 mm were used where each one of them were defined 3-dimensional in term of geometry and Rigid.
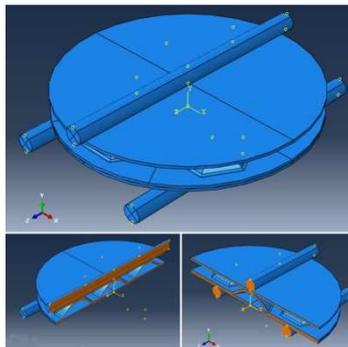

Figure18. The simulation geometry in three-point bending test

In the case of contact between honeycomb core and face sheets and also contact between supports and flange and face sheets, a friction coefficient equal to 0.1 was used and also contact between them is chosen as normal behavior hard contact.

In order to simulate three point flexural tests accurately, boundary conditions were defined as follows:

1. Selecting ENCASTRE boundary condition for both bottom supports in order to consider them fixed.
2. Selecting moving boundary condition for flange in order to consider pressure exertion on the specimen

After applying the mentioned settings, the problem is solved and we are going to report important parameters such as stress distribution and displacement in the simulated compression test.

6. Finite element analysis results
In this section, finite element results of three point flexural test are presented according to several parameters such as displacement and stress distribution.

6.1. Displacement variations of three point flexural test
Displacement variation\ is one of important parameters in physics analysis of the problem. In Figures 19 and 20, displacement contours of honeycomb sandwich panel under three point flexural test are shown.
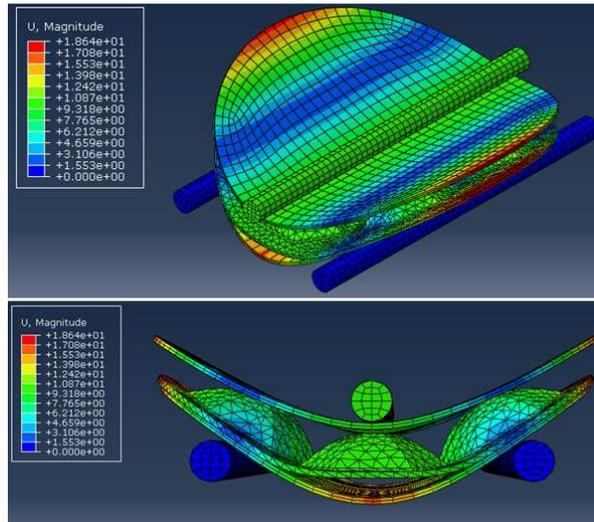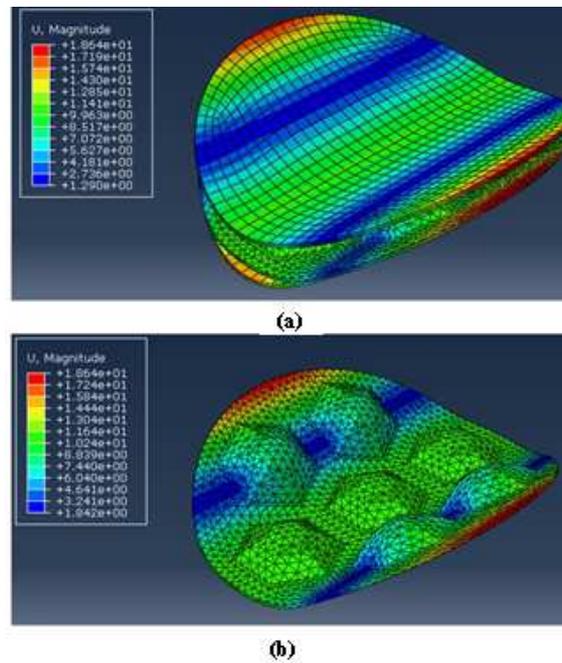
Figure19. Displacement contour of three point flexural test

(a) Proposed honeycomb sandwich panel
(b) Sandwich panel core
Figure20. Displacement contour of three point flexural test

6.2 Stress variations of three point flexural test

In this section, stress results from three point flexural test simulation are investigated. Stress results are the most important analytical results of this simulation. In Figures 21 and 22, stress distribution contours are shown in three point flexural test simulation.
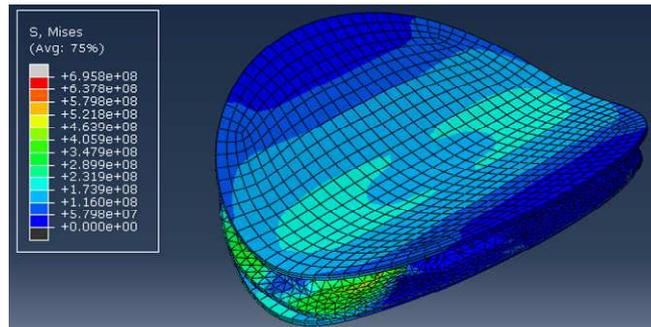
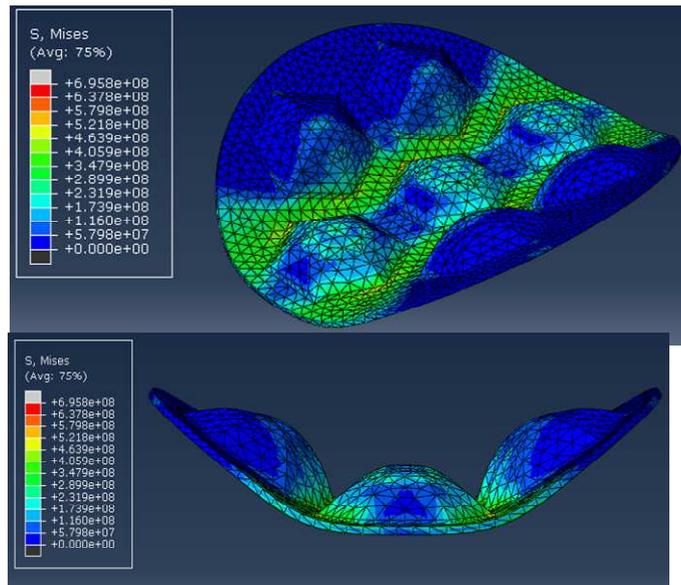Figure21. Stress distribution contour in the proposed honeycomb sandwich panel

Figure22. Stress distribution contour in the sandwich panel core

7. Verification of experimental and finite element analysis results

As it is shown in Figure 23 and Table 5, examination of results is indicative of a good match between results from numerical simulation by ABAQUS software and experimental tests conducted on the proposed sandwich panel. Thus based on needs, results from numerical simulation in order to optimize application can be used.
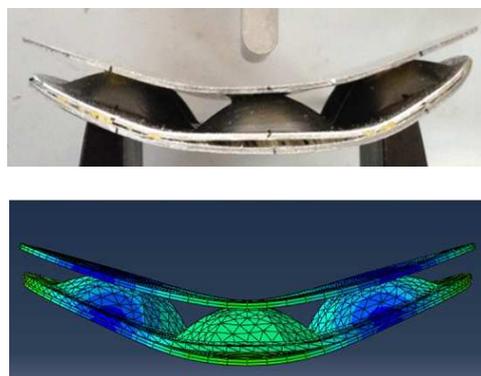

Figure23. Comparison of experimental and finite element analysis

Table5. Validation of finite element simulation

NO	Structure type	Tolerated force in experimental test (kg)	Tolerated force in finite element analysis (kg)	Error(%)
1	Three-layer sheet of aluminum	140	138	%1.4
2	Proposed honeycomb sandwich panel	250	244	%2.4

8. Conclusion

In this paper, flexural behavior of a proposed composite structure filled with different materials has been studied and results are compared with that of flexural behavior of a three-layered sheet of aluminum. Selected substances as filling materials are polyurethane foams, PVC, silicone and carbon fiber. Remarkable findings are as follows:

- Flexural behavior of proposed sandwich panel has shown good improvement in comparison with three-layered sheet of aluminum about 80% increase in flexural strength.
- An increase of 19% in flexural strength of proposed sandwich panel filled with polyurethane in comparison with proposed structure filled with no material.
- Flexural strength enhancement about 132% of proposed sandwich panel filled with PVC foam in comparison with proposed structure filled with no material.
- An increase of 417% in flexural strength of proposed sandwich panel filled with carbon fiber foam in comparison with proposed structure filled with no material.
- High conformity of experimental results with that of obtained from the finite element simulation with at most 2.4% error.
- Proposed sandwich panel can be used as a strong shield structure in aircraft, automotive and other advanced industries.

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