STATIC AND FATIGUE ANALYSIS OF AUXETIC RE-ENTRANT SANDWICH PANELS BASED ON THREE POINTS BENDING TEST

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ABSTRACT

In this study Static and Fatigue behaviour of re-entrant sandwich structures produced by 3D printing were investigated to evaluate the energy dissipation ability and durability of sandwich structures. The core structures having different thicknesses but the same mass were considered for the study. Both finite element analysis and experiments were performed based on three-point bending tests. The mechanical properties of the core structures were obtained from the static analysis by performing the tensile test, first. As a secondly, three-point bending test was performed to obtain the some parameters needed for fatigue analysis. Fatigue behaviour of core structures were obtained from the dynamic analysis. In this part, fatigue analysis was done using three-point bending test method. Failure load obtained from the static analysis was applied in the fatigue studies and loading ratiowas 80 %. It is seen according to the static and fatigue analysis results that energy absorbation capabilities of the structures increased when the thickness of the structure increased. It is observed that the finite element analysis results and experimental results were good agreement.

Keywords: Fatigue, re-entrant, 3D printing, sandwich, three-point bending, failure load

1. INTRODUCTION

Compared to conventional materials, the need of cheaper and strengthten materials day by day has been very important. Scientists are studying and seeking about such materials. Auxetic structures are attracting researcher's attention recently. It has different application in industry. Sandwich panel structures composed of auxetic materials have become very common in the automotive, defense and aerospace industries in recent years. The core structures of sandwich panel differ due to many factors such as production method and production material. It is well known that manufacturing by 3D printer is very easy thus it is a candidate to be common production method. This production method is very suitable to produce auxetic sandwich

structures [1]. Samples in auxetic structures can be produced by many methods such as additive manufacturing [2]. Using a 3D printer production method does not require many features, both in terms of cost and experience [3,4]. In addition, 3D printers are one of the rapid prototyping methods and are used in scientific as well as industries [5].

In recent years, with the increase in people's communication with technology, the orientation towards composite structures has increased considerably. Weight, cost reduction, which has become the need of the aerospace, defense and automotive sectors, has gained high importance [6]. Sandwich structures have responded to the need at this point [7,8]. In addition to the weight and cost effects of these structures, their high specific bending stiffness and high energy absorption have pushed engineers to this field [9,10]. It has been necessary to examine the static and fatigue performances of sandwich structures which are increasingly used in these areas [11-13]. It is very important to examine these structures which can break off from the lower and upper covers of sandwich structures, under static and dynamic loads. It has been proven that there is a change in the hardness and damping ratios of these samples depending on the usage condition and environment [14-16]

In addition to many mechanical properties of auxetic materials, their effects on Poisson's ratio are also important properties [17,18]. The formation of these structures is called "Designable Materials", in other words "Metamaterials" [19]. The most beautiful visual non-auxetic and auxetic materials are given in Figure 1.1.

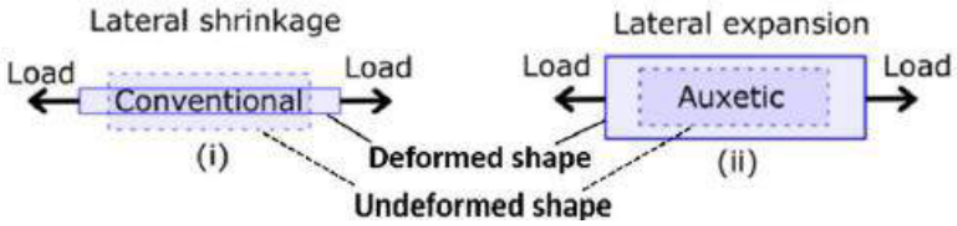

Figure 1.1: (i) non-auxetic material, (ii) auxetic material, [20]

Mechanical behaviour of structures are very important for the design and manufacturing. Structures should be tested in terms of their mechanical behaviour before design stage. One of the most important test is fatigue. Fatigue behaviour is the most important index for auxetic structures as well as non-auxetic structures. Fatigue causes about 78% of plane crashes [21, 22]. For this reason, fatigue behavior is an important issue that should be taken into account in all structures [23]. The fatigue of a honeycomb structure which is one of the auxetic structures has been investigated before [24]. In the study, it has been determined that parameters such as the size of the cell in the honeycomb structure and the loading interval are effective. In addition, the number of loading cycles required for crack initiation varies between samples. For crack propagation, the number of loading cycles up to the breaking of the first cell varied and corresponds to the low cycle fatigue regime. In addition, the effect of dynamic loading on the

mechanical properties was investigated and the effects of energy distribution on the core structure were reported. In addition to sandwich panels, composites were also studied with three-point bending test [25]. In fatigue tests, it was found that the bending modulus changed according to the production method during the first cycles. The effects of the production method on the stiffness and the lowest breaking strength in fatigue resistance were investigated. Finally, the most important fatigue life is calculated and the difference between the structures can be commented. There is not much research for additively produced sandwich composites for these new structures.

It is very important to check the safety of usage of auxetic materials and to determine their capacity of energy absorbing during usage. For this reason, the main purpose of the study is to examine the fatigue behavior of sandwich panels consisting of the re-entrant core structure and to evaluate the energy distributions according to their durability. The auxiliary structure was checked with different thicknesses, different angles and different relative densities in three groups. First, static three-point bending tests of each configuration were performed, then experimental bending cyclic fatigue tests were performed. Thus, the effect of sandwich structures on their stiffness, energy absorption and damping ratio was determined.

2. STRUCTURAL DESIGN

Recently, sandwich structures have become very popular in the automotive and aerospace industries. The designers' need to reduce weight, costs and absorb energy have pushed sandwich structures. An example of this solution is shown in Figure 2.1. Another feature of these structures is that they can be controlled for different purposes. Sandwich structures consist of two basic elements. The first element consists of thin hard layers above and below, and the second one consists of the auxetic structure between two hard surfaces.

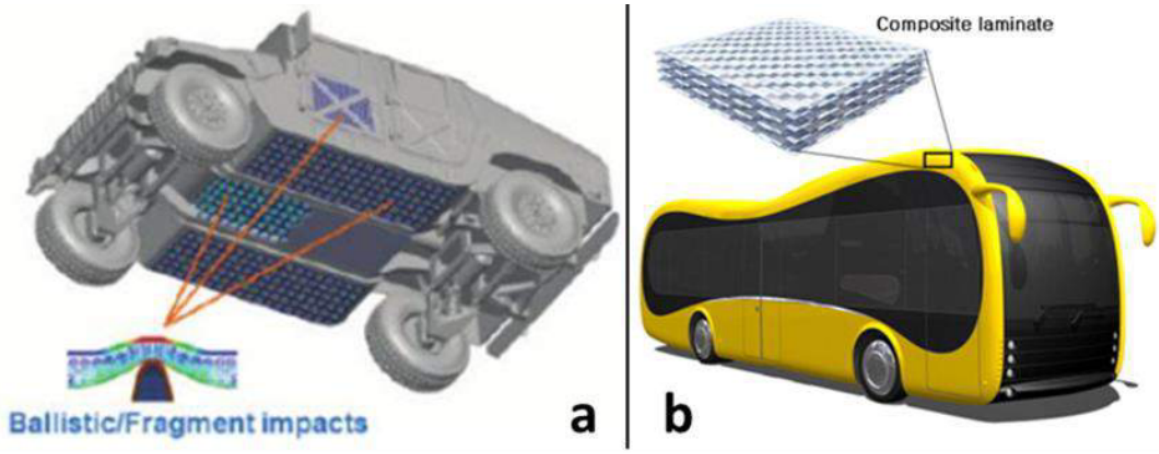

Figure 2.1: Auxetic Sandwich Panels a) Localised Impact Resistance, [26] b) Low Floor Bus, [27]

Core Structures are divided into five in their own group. These are Honeycomb, Corrugated, Foam, Lattice and Auxetic Structures. Appropriate core structure is preferred according to usage conditions and costs [28]. Auxetic materials have additional mechanical properties compared to conventional materials. In addition, they are preferred due to their lightweight characteristic. In this study, re-entrant core structure was chosen from the auxetic material group because it is easy to manufacture.

Four kinds of specimens were designed by Solidworks software. The sandwich core structure considered is shown in Figure 2.2

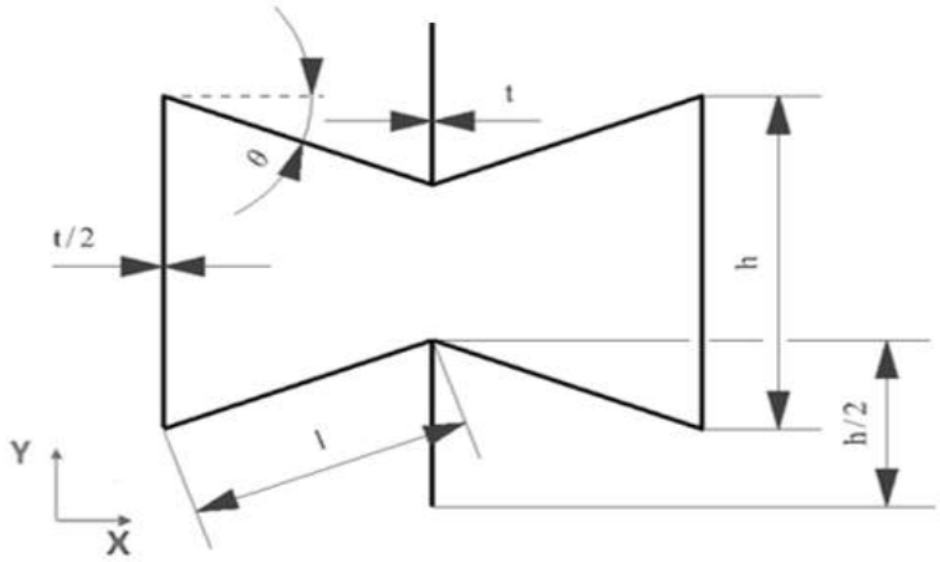

Figure 2.2: Design of Unit Cell of Auxetic Structure

In the design stage, when the thickness(t) changes, the distances of h and l also change inversely. Thus, the same volume is created in the design of the all four samples. The structural parameters of the samples are given in Table 2.1. The width of all samples is 50 mm and the thickness is 7 mm (1 mm plates, 5 mm cell). The length of the structure is set at 125 mm. The designed panel structure is shown in Figure 2.4.

Table 2.1 Design Parameters of Auxetic Core

Cells in width	l (mm)	h (mm)	θ (°)	t (mm)	b (mm)
2 cells	13.3	17.04	– 20	2.4	5
4 cells	6.65	8.52	– 20	1.2	5
6 cells	4.433	5.68	– 20	0.8	5
8 cells	3.325	4.26	– 20	0.6	5

The produced samples with 0° orientation by 3D printer are shown in Figure 2.3

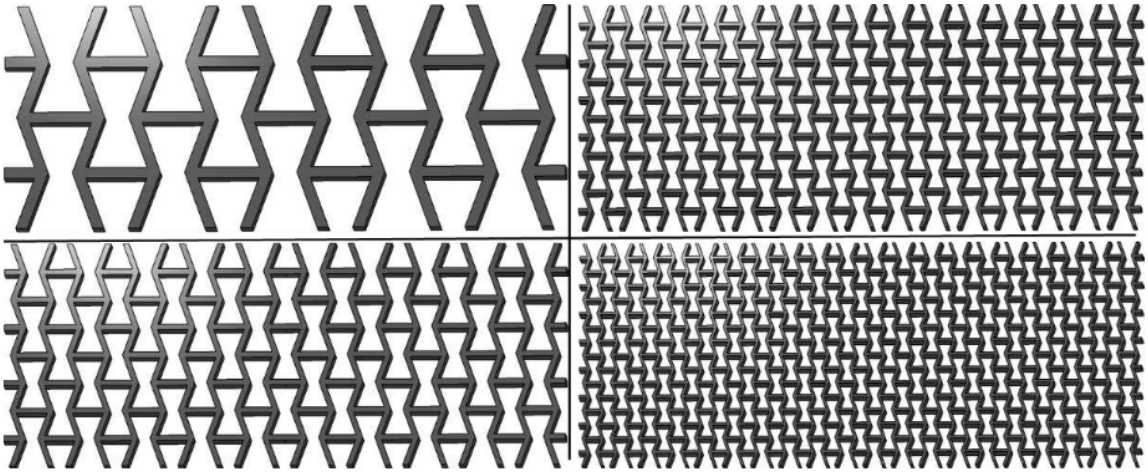

Figure 2.3: The sandwich cores before adhesion

The sandwich panel consists of the core, upper plate, and lower plate. The compact sandwich panel is constructed bonding the core with the upper and lower plates. Epoxy adhesive was used for bonding the lower and upper plates. A template was made to use the same adhesive in all samples.

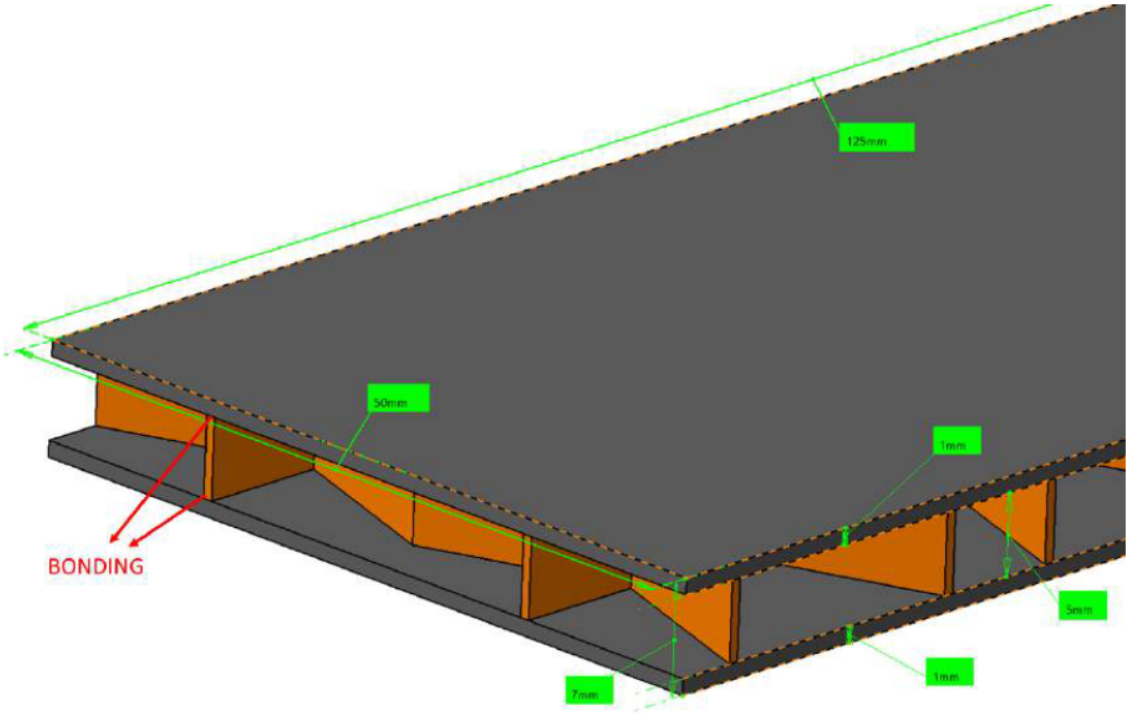

Figure 2.4: Sandwich panel dimensions

A stuck sandwich panel is shown in Figure 2.5. A mold sample was made for sticking the parts. Thanks to this, the amount of adhesive and the slipping of the sample during adhesion are prevented. It is important that the adhesive should not overflow and to be controlled its level. In case of errors that may occur, different results are obtained in the samples.



Figure 2.5: Sandwich Panel After Adhesion; a) Front view, b) Top view c) Side view

3. EXPERIMENTAL ANALYSIS

In this section, the best manufacturing method of the re-entrant core structure was determined first. Then, the material characteristic of the PLA material used in the 3D printer has been determined. The analytical approach of the re-entrant core structure was carried out after determining of the material characteristics. After that, numeric approach required for re-entrant core structure has been applied. All these analytical and numerical studies were also carried out with experiental test.

3.1 Sample Preparation

All of the sandwich structures were produced with the Ender-3 V2 3D printer device. The 3D printer device allows additive manufacturing with many materials such as ABS and, PLA. PLA material was preferred due to both cost and ease of production. Static testing is required to obtain the data to be used in the fatigue test. Mechanical properties of PLA material differ from one manufacturer to other one in terms of homogeneity. Besides, the production method and ambient conditions are also important factors. The tensile test was applied to determine the characteristic feature of the material. Three types of specimens were designed and produced by 3D printing styles corresponding the angles of 0°, 45°, and 90° as shown Figure 3.1. Each one

was subjected to the tensile test to obtain the specimen's characteristic and to be defined the specimen having the best characteristic. Universal testing machine inspekt table 50 kN was used for the testing. Tests were performed according to ASTM D638 standard. The tests were carried out under the load of 50 kN and the velocity of 5 mm/min.

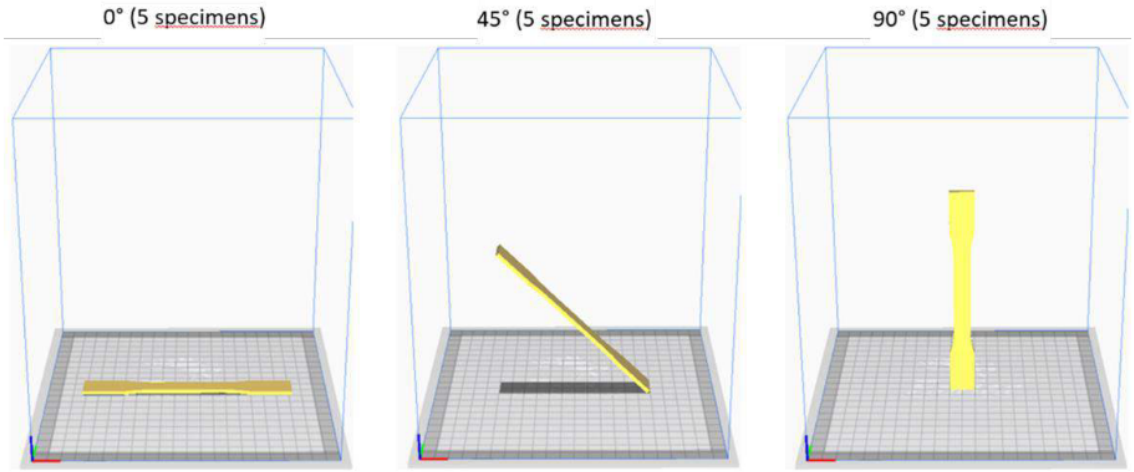

Figure 3.1: Printed specimens at different orientations using FDM

Another important point is the angle of compression. The all designs and sandwich specimens were produced with the same compression angle. The compression angle is given in Figure 3.2. 3D printer features are given in table 3.1.

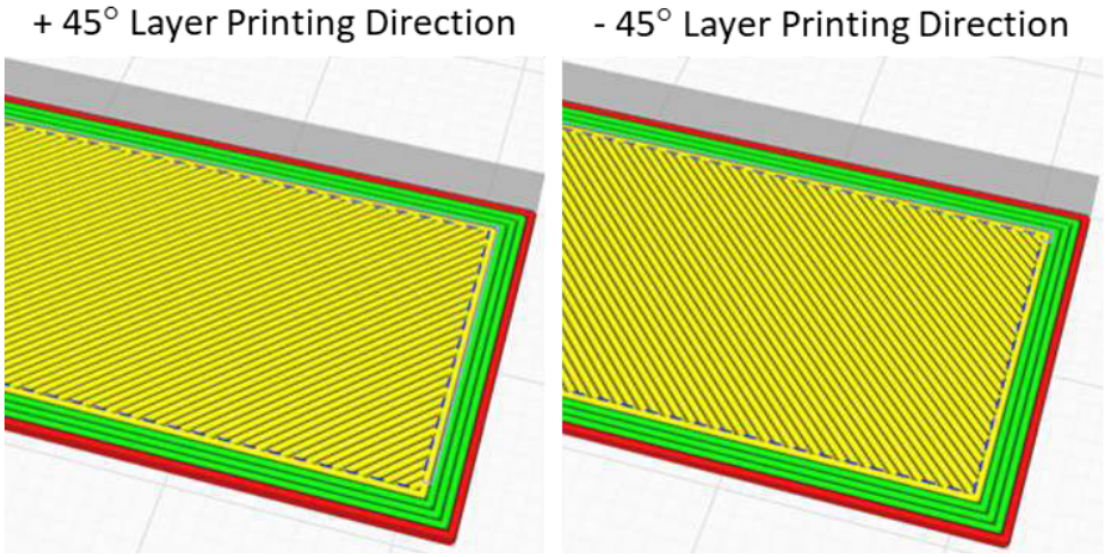

Figure 3.2: + 45° / – 45° layer printing directions followed when producing samples.

Table 3.1 The features of the 3D Printer

Noozle Diameter (mm)	0,4
Nozzle temperature (°C)	225
Solidity ratio (%)	100
Scan angle (°)	+ 45° / – 45°
Table temperature (°C)	70

The tensile test was repeated five times for each specimen for the accuracy. It is seen that the best and worst characteristics were obtained for 45° and 90°, respectively. The results mechanical properties of the PLA material for 90° and 45° are given in tables 3.2 and 3.3, respectively. The best results obtained from 0° orientation is given in table 3.4.

Table 3.2 Mechanical Properties of the PLA Material for 90° orientation

Young Modulus (MPa)	Poisson Ratio	Tensile Stress (MPa)	Maximum Load (N)
E = 1463	$\upsilon = 0.31$	$s_y = 37,34$	$F_{max} = 1295,64$

Table 3.3 Mechanical Properties of the PLA Material for 45° orientation

Young Modulus (MPa)	Poisson Ratio	Tensile Stress (MPa)	Maximum Load (N)
E = 1609	$\upsilon = 0.33$	$s_y = 41,13$	$F_{max} = 1425,20$

Table 3.4 Mechanical Properties of the PLA Material for 0° orientation

Young Modulus (MPa)	Poisson Ratio	Tensile Stress (MPa)	Maximum Load (N)
E = 3376	$\upsilon = 0.33$	$s_y = 48,61$	$F_{max} = 1831,52$

3.2 Analytical Approach

In this section, expression of stress-strain, Poission's ratio, and shear forces depending on the geometry of the structure were derived based on the principles of mechanics. Since the auxetic structures are orthotropic, with the change of the geometric structure of auxetic materials, the characteristic feature of the material also changes. As the most important feature of auxetic materials the negative Poisson ratio is the most important difference in the separation of metals from the re-entrant samples. The way the geometry of the re-entrant structure changes with pressure can be expressed in Figure 3.3.

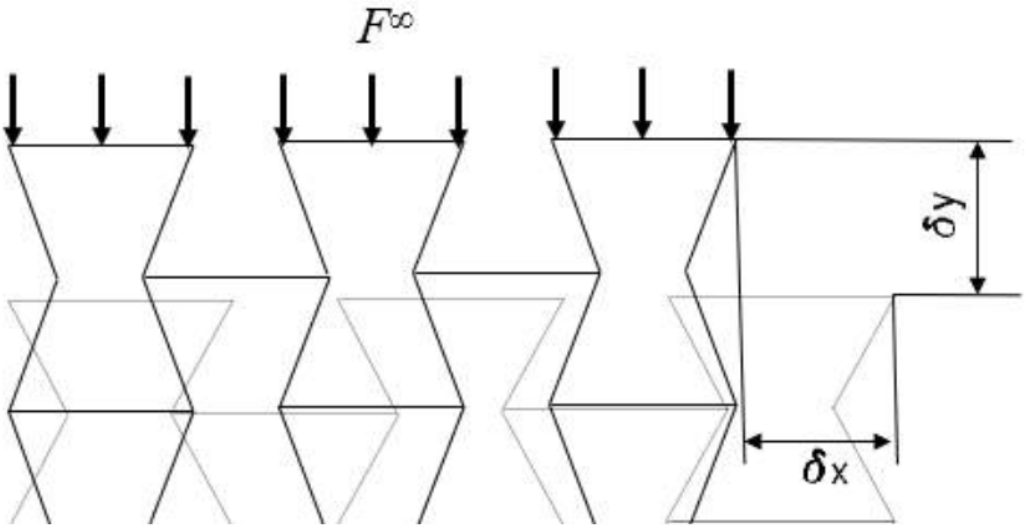

Figure 3.3 Re-entrant lattice structure with affected loading

The loads affecting on the structure are shown in Figure 3.4. Where force and moment expressions N1P and M1P affecting node 1 determines the reactions by the other symmetrical part of the structure. And, the force F, which represents the force of external load. The forces P affecting from the node 1 and 3 used to compensate for the dummy force to be used in calculating the lateral deformation.

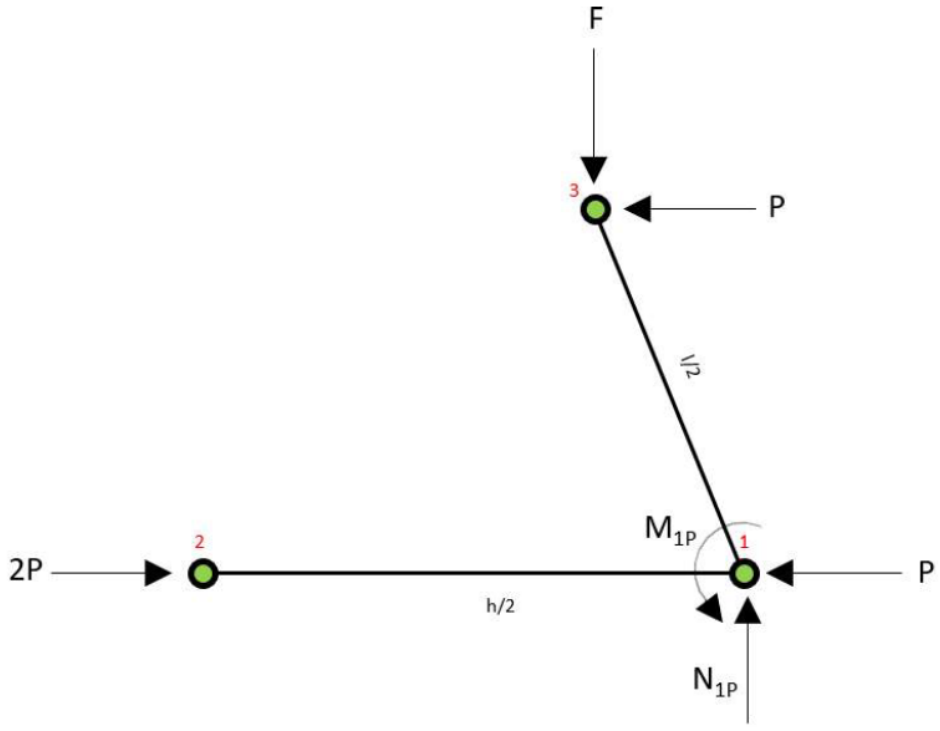

Figure 3.4 Free body diagram of the re-entrant structure

Thanks to all the equations made, the following equations are obtained. Re-entrant structures exhibit orthotropic properties in terms of structure. This proof has been made with the equations

to be obtained orthotopically of the isotropic matrix. The stress-strain relationship of the structure considered can be obtained using Hooke's law as given equation (1) and (2).

$$E_{xx} = E\left(\frac{t}{l}\right)^3 \frac{\left(\frac{h}{l} - \cos\theta\right)}{\left(1 + \left(\cot^2\theta + \frac{h}{l}\csc^2\theta\right)\left(\frac{t}{l}\right)^2\right)\sin^3\theta} \tag{1}$$

$$E_{yy} = E\left(\frac{t}{l}\right)^3 \frac{1}{\sin\theta\left(\frac{h}{l} - \cos\theta\right)\left(\cot^2\theta + \left(\frac{t}{l}\right)^2\right)} \tag{2}$$

Eq (1) and (2) provide the change in Young's modulus corresponding the geometrical change in the structure.

The structure of displacement ratios gives the Poisson's ratio as expressed in Eq (3).

$$v_{12} = -\frac{\cos\theta\left(1 - \left(\frac{t}{l}\right)^2\right)\left(\frac{h}{l} - \cos\theta\right)}{(\sin^2\theta)\left(1 + \left((\cot^2\theta + \csc^2\theta)\left(\frac{h}{l}\right)\right)\left(\frac{t}{l}\right)^2\right)} \tag{3}$$

The third important expressions are about shear modulus appeared in the structure. Equation (4), (5), and (6) state the shear modulus took place x-y plane, x-z plane, and y-z plane, respectively.

$$G_{12} = E\left(\frac{t}{l}\right)^3 \frac{1}{\left(\frac{h}{l}\right)\left(1 + 2\frac{h}{l}\right)\sin\theta} \tag{4}$$

$$G_{13} = G\left(\frac{\left(\frac{t}{l}\right)}{2\sin\theta}\right)\left(\frac{\frac{h}{l} - \cos\theta}{1 + 2\frac{h}{l}} + \frac{\frac{h}{l} + 2\cos^2\theta}{2\left(\frac{h}{l} - \cos\theta\right)}\right) \tag{5}$$

$$G_{23} = G\left(\frac{t}{l}\right)\frac{\sin\theta}{\left(\frac{h}{l} - \cos\theta\right)} \tag{6}$$

3.3 Finite Element Analysis (FEA)

Finite element analysis is widely used in many engineering fields. It enables to solve complex structures and provides very accurate solutions. In this study, FEA was used to verify the experimental fatigue study. Abaqus software was used for the modelling and analysis. It is suitable for analysis of anisotropic, orthotropic structures. As explained in the section 2.2, the solid models of the re-entrant structures were created by Solidworks. In the next step, it was arranged according to the Abaqus program for fatigue analysis.

3.3.1 Static Analysis

The characteristic features of PLA material required for the fatigue analysis were obtained by static analysis. For this purpose firstly, the samples were subjected to axial compression test to obtain Modulus of Elasticity (E), Modulus of Rigidity (G), and Poisson's ratio (ν). Afterwards, a static three-point bending test was applied to get some parameters of the samples required for fatigue analysis.

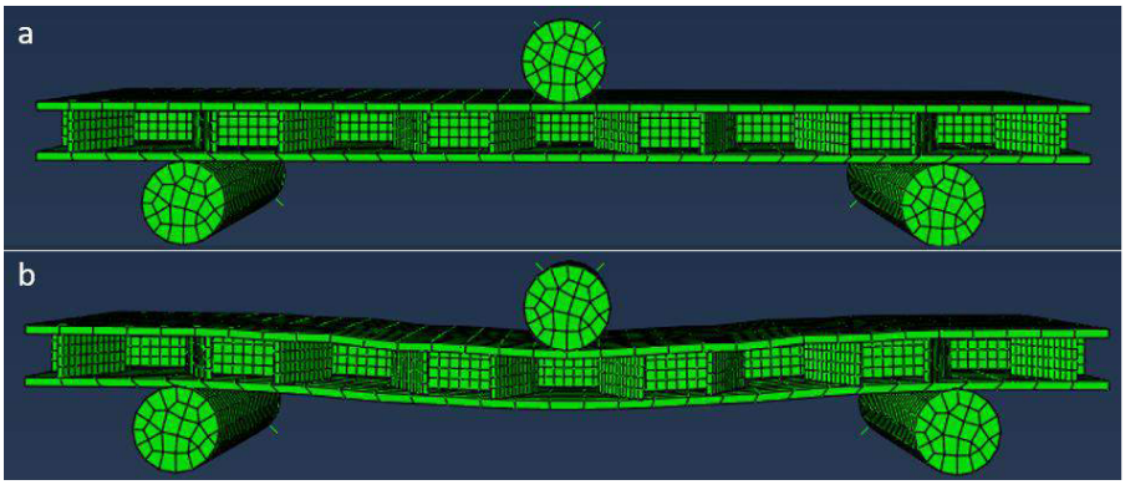

Figure 3.5. a) Before three point testing, b) After three point testing

3.3.2 Fatigue Analysis

Abaqus is a very functional program for finite element analysis on samples with negative Poisson's ratio. Static analysis of samples is needed for fatigue life calculation. Sandwich panel samples designed in Cad programs are transferred to the Abaqus program for each test. Then the material properties obtained from the tensile test for the PLA material were processed in the property section of each part. In the assembly section, the sandwich panel was prepared and the installation of the interfaces in the three-point tilt test was completed. After the assembly, the process of performing the test was prepared in the step section. In the interaction section, the sandwich panel parts were glued and contacted with the interface samples that will serve in the

three-point pressing test. The motion interfaces to be performed in the three-point bending test were defined in the load section. The mesh was applied separately for each sample. The deepest mesh was applied for the core structure of the sandwich panel. The approximate global size for the lattice core structure was defined as 0.6 mm. For shell fragments, this value was defined as 4 mm. After the mesh, the test was initiated.

The folder named ".odb" obtained at the end of the test was added to the Abaqus FEM program. Load and material properties were redefined in the FEM software program. In this section, the fatigue approach is discussed. As showed at the flowchart in Figure 3.6, the stress analysis results, loading conditions and material properties are input parameters for the fatigue analysis. Fatigue analysis was performed according to Goodman's approach.

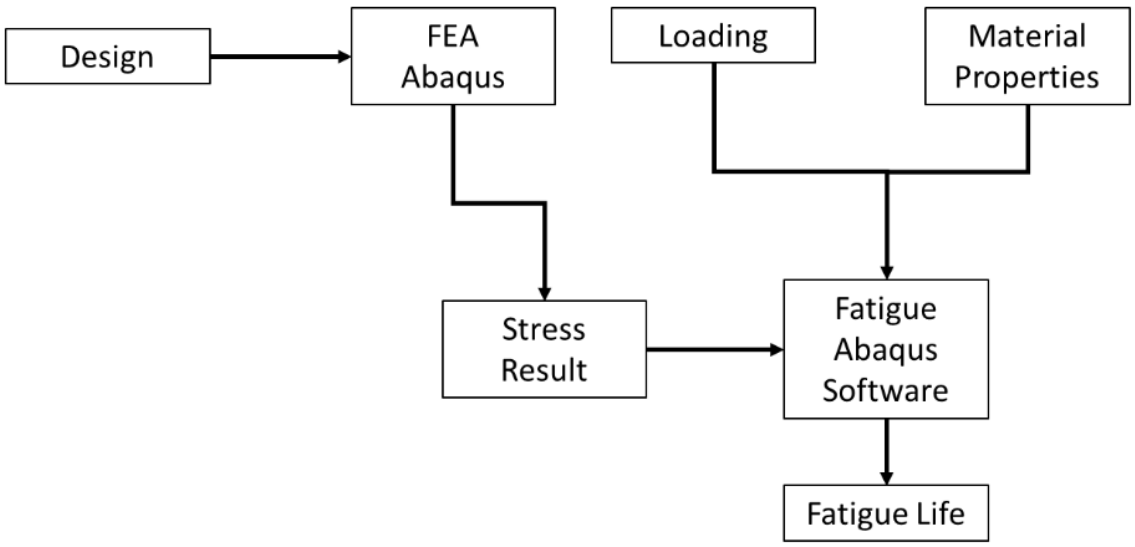

Figure 3.6 Scheme of Fatigue Life Calculation Numerically

The fatigue results obtained from Abaqus software are given in the table 3.5.

Table 3.5 Design parameters of sandwich structure for different thickness

Cells in width	2 cells	4 cells	6 cells	8 cells
Number of Cycles	43	79	131	278

3.4 Experimental Fatigue Test

All tests were repeated five times. The tests were carried out with the machine named "INSTRON 8871". It has +-5 kN load capacity in static and fatigue tests. Fatigue tests were carried out according to ASTM D790-86 standard. All tests are based on displacements

measured from the machine's sensor. The test specimens were positioned at 90 mm. In the three-point bending test, the diameter of the parts that will apply the compression force is 10 mm. Statically, the tests were carried out successfully.

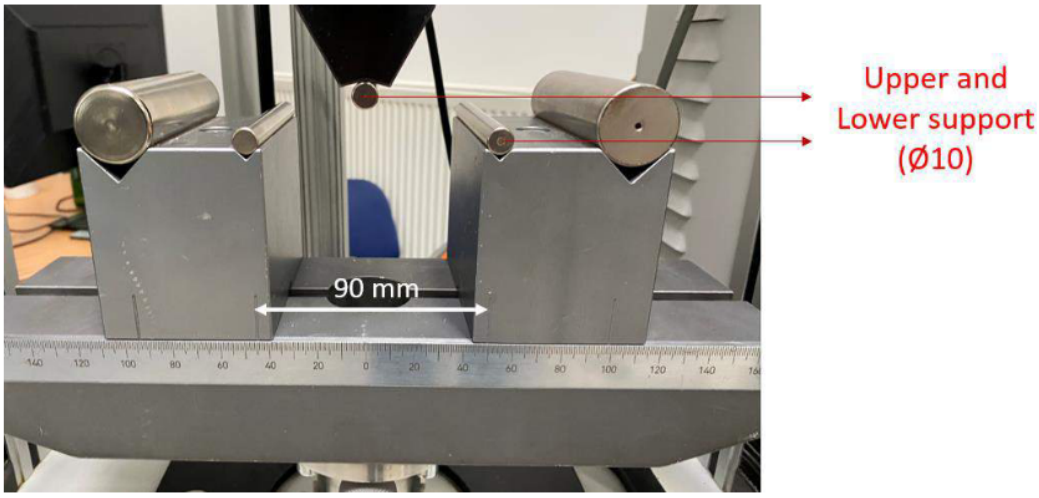

Figure 3.7: Three-point bending test set up

The load-deflection curves with different thickness are shown in Figure 3.8 below.

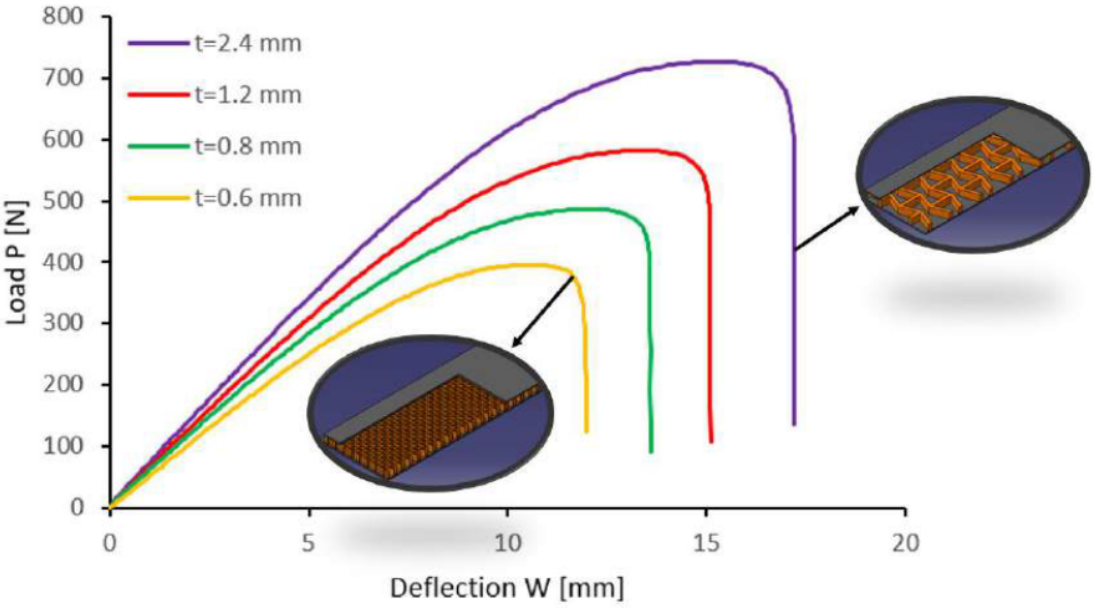

Figure 3.8 Load-deflection curves of sandwich panels with different thickness cores

According to the result to be obtained from the graph, load and deflection increase as the thickness increases in the core structures. This result provides information about the hardness of the material. According to the load deviation curve, observations were made in three regions. The first region presents the linear behavior of the sandwich panel. The second region exhibits

behavior of a nonlinear structure. Bending and compression of the upper layer takes place in this region. The onset of damage occurs in the third region. The end zone represents the failure. Complete fracture takes place in this region.

At the end of the static tests, the fatigue life of the sandwich structure is calculated by subjecting the samples to fatigue tests separately. According to the number of cycles, the development of rigidity in the structure is studied. This is one of the most widely used fatigue calculations. The loading level is made as 80%. The development of the maximum load with the cycle is shown in the curve below. A semi-logarithmic equation is established, thus the curve graph is obtained. The curve is divided into three regions like a static equation. The first zone is conditioned the onset of damage to the sample and crack growth. The second region refers to the decrease in hardness. The end zone represents the decrease in hardness. As the cycle increases, the amount of damage increases. This last region represents the failure in the sample.

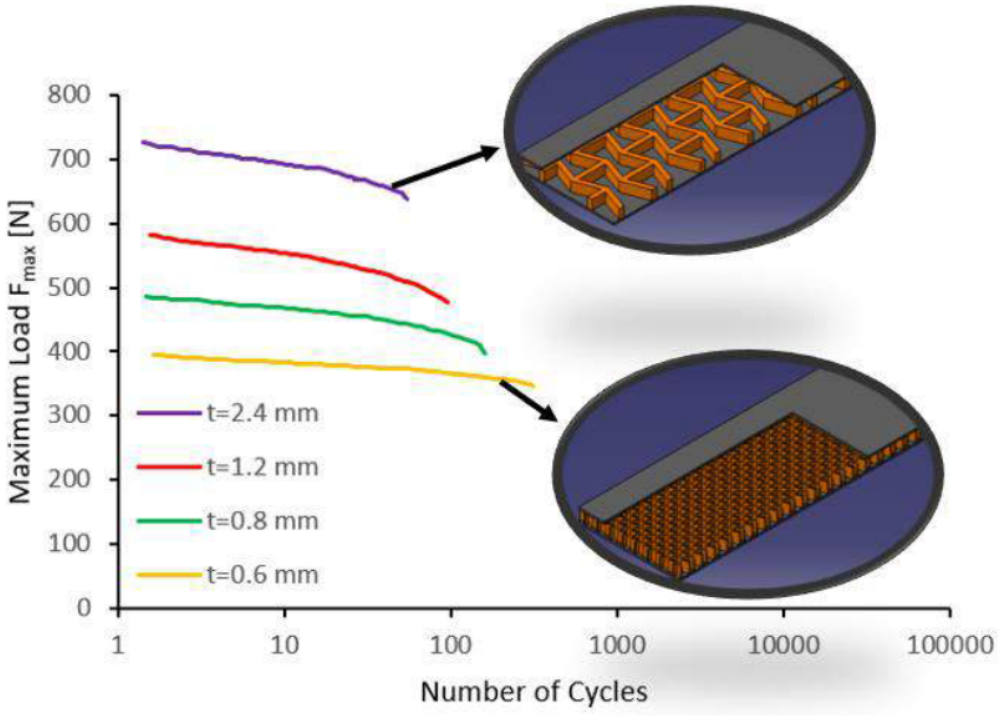

Figure 3.9 Maximum load - number of cycles sandwich panels with different thickness cores

The deterioration in hardness is affected by the change in the geometry of the core part in the sandwich structure. It is observed that the rate of decrease in their rigidity is similar in structures. the sample with a thickness of 2.4 mm also shows a certain difference. it is safer in terms of surface contact because its 0.6 mm thick structure has more adhesion to the surface in places. This is a remarkable case for surface shear stress transfer. The breaking of the sandwich panel with an excessive thickness occurs earlier than the sample with a low thickness.

RESULTS

Examination of the re-entrant structure, which is one of the auxiliary materials, by repeated bending tests is very important for the purposes of using. Factors such as the type of materials that make up the sandwich panel structure and loading levels have an important place in their failure. As the number of cells in the core structure increases, the shear fracture of the sandwich panel structure decreases. In sandwich panel structures, the lower shell sample resists cracking, while the upper part resists compression. The first cleft in the lower shell sample occurs with Deceleration of rigidity between the first cycles. It is observed that the effect of fatigue transfer on the core structure and rigidity distortions differ in each sample. The re-entrant core structure and shell structures produced with a 3D printer may vary depending on factors such as printing angle, temperature, printing speed, adhesion, and ambient conditions. It is aimed to provide the same conditions for each sample in order to be minimally affected by these factors.

Statically, the partial load of the sandwich panel sample of 0.6 mm is lower than that of the sandwich panel sample of 2.4 mm. the 0.6mm sandwich panel sample shows that it has more hardness than the other one. The increase in the distance in the thickness layers of the samples, the increases in load fluctuations also increase. Thus, it can be stated that the part with the lowest thickness is the best for shear stress. The samples required for the fatigue test are obtained from this static test. The homogeneity differences in the formation of PLA material also bring the necessity of tensile testing. It is not possible to use standard static values due to the orthotropic material structure. Figure 3.9, obtained from the fatigue test, expresses the curve of the change of the maximum load with fatigue cycles. The maximum load obtained according to the static value is the maximum in the 2.4 mm sample. However, the minimum number of cycles was obtained from this sample. It changes in inverse proportion with the decrease in thickness in core structures in sandwich panel structure. Thus, the resistance of the samples against hardness can be mentioned through the samples. It is expected that there will be differences in the number of cycles between the numerical results and the test results. There are many reasons why there should be no difference. Factors such as the adhesion rate, adhesion type, ambient conditions, curing time with the cores and shells of the sandwich panel structure can be said.

CONCLUSION

In this study, static and fatigue behaviors of sandwich panels with different geometric re-entrant core structure were examined by three-point bending tests. In the study, the Young's modulus and Poisson's ratio were calculated analytically and numerically according to the geometric structure of the re-entrant core structure. The cores of Sandwich panel structures show orthotropic properties. Tensile testing was performed with a standard sample produced from a 3D printer for the static parameters of the test sample. PLA material has been used in the 3D printer because it is cost effective and easy to manufacture. According to the best data obtained, an adjustment was made on a 3-D printer, and sandwich panel samples were made according to

this adjustment. The core structure and shell samples of the Sandwich panel structure were designed with the Catia program. 3D printer samples were prepared with the Cura program. The 3D data of each sandwich panel sample is integrated into the Abaqus program. The FEA Abaqus software program was used for Fatigue tests. PLA material was used in the 3D printer.

As a result, the geometry of the sandwich panel structure has a great influence on static and dynamic loads. It has been shown that the hardness change in the structures can be selected in sandwich panel structures. In particular, the good load distribution on the samples ensures that auxiliary materials are preferred. The distribution of damage on the lower shell of the sandwich panel creates a certain reduction in their hardness. The first crack in the sandwich panel samples occurred in the lower shell part. It has been observed that the energy distribution is higher in the sample with a greater thickness in the core structure.

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