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EXPERIMENTAL INVESTIGATION OF CRUSH ENERGY ABSORPTION AND STRENGTH PROPERTIES OF SANDWICH PLATES WITH ALUMINUM FACESHEET/ EXPANDED POLYPROPYLENE FOAM CORE

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Abstract: Due to the developing electric vehicle industry in the last decade, weight reduction studies on vehicle bodies have gained great importance. Foam core sandwich structures stand out as the most ideal materials in terms of providing both weight reduction and strength conditions in the bodies of electric individual and public transportation vehicles. In this study, EPP foams with two different densities were placed between aluminum plates and sandwich structures were obtained by combining the two structures with an EVA-based adhesive. Compression and bending behaviors of the produced sandwich structures were investigated under quasi-static and dynamic loading conditions. With the tests carried out, the strength of the sandwich structures and the amount of energy they absorb were calculated and compared experimentally. According to the results obtained, it was observed that the denser D_2 foam exhibited approximately 1.4 to 2.05 times more strength than the lower density D_1 foam in all tests. In terms of the energy they absorb, the D_2 foam absorbs 1.25 to 2.5 times more energy than the other foam. Contrary to this situation, only the dynamic compression test occurred in the tests performed. When the post-damage behavior of the sandwich structures was examined, it was also observed that the D_2 foam returned to a very similar dimensions to its original size, giving more of the deformation after the damage at the end of 72 hours.

Keywords: Sandwich Composite Structure, Polypropylene Foam, Energy Absorbing Structures, Automotive Lightweighting

Alüminyum Yüzey Plakası / Genişletilmiş Polipropilen Köpük Çekirdekli Sandviç Levhaların Çarpışma Enerjisi Sönümleme ve Mukavemet Özelliklerinin Deneysel Olarak İncelenmesi

Öz: Son on yılda gelişen elektrikli araç endüstrisi nedeniyle araç gövdelerinde ağırlık azaltma çalışmaları büyük önem kazanmıştır. Köpük dolgulu sandviç yapılar, elektrikli bireysel ve toplu taşıma araçlarının gövdelerinde hem ağırlık azaltma hem de mukavemet koşulları sağlaması açısından en ideal malzemeler olarak öne çıkmaktadır. Bu çalışmada, alüminyum levhalar arasına iki farklı yoğunluktaki EPP köpükler yerleştirilmiş ve iki yapının EVA esaslı yapıştırıcı ile birleştirilmesiyle sandviç yapılar elde edilmiştir. Üretilen sandviç yapıların basma ve eğilme davranışları statik ve dinamik yükleme koşulları altında incelenmiştir. Yapılan testler ile sandviç yapıların dayanımları ve absorbe ettikleri enerji miktarları deneysel olarak hesaplanmış ve karşılaştırılmıştır. Elde edilen sonuçlara göre, tüm testlerde daha yoğun olan D_2 köpüğünün, düşük yoğunluklu D_1 köpüğüne göre yaklaşık 1.4 ila 2.05 kat daha fazla mukavemet sergilediği gözlemlenmiştir. D_2 köpüğü absorbe ettiği enerji açısından diğer köpüğe göre 1,25 ila 2,5 kat daha fazla enerji sönümlemiştir. Bu durumun aksi bir davranış yapılan testlerde sadece dinamik basma testinde meydana gelmiştir. Sandviç yapıların hasar sonrası davranışı incelendiğinde, hasarın sonrasındaki 72 saat sonunda D_2 köpüğün orijinal boyutuna çok benzer boyutlara geri döndüğü ve daha fazla deformasyonu geri verdiği gözlemlenmiştir.

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1. INTRODUCTION

Increasing environmental awareness and technological developments in recent years have led the tendency of automotive industry to work on to produce hybrid and electric vehicles that cause less CO_x gas emissions (Güçlü, et al., 2020; Rosenthal, et al. 2020; Baek, et al., 2022). Especially fully electric personal and public transport vehicles constitute a large part of these studies and targets. Compared to other vehicles with internal combustion engines, fully electric vehicles (FEVs) have great advantages in terms of greenhouse gas emissions, which cause air pollution, and thus, they are of great importance in terms of climate change and environmental pollution. One of the most important issues to be considered in the design of FEVs is the design of lightweight vehicles and vehicle parts in order to increase battery efficiency and range capacity (Yu, et al., 2021; Burd, et al., 2021; Li, et al., 2019; Arifurrahman, et al., 2018). In addition, the designed vehicles must be robust enough to meet the safety regulations and meet the pedestrian and passenger safety criteria (Pan, et al., 2020; Xiong, et al., 2018). Sandwich composite structures are materials that can meet all expectations in the automotive industry in the most ideal way, with their high specific strength, specific bending stiffness and superior crash energy absorption capacity (Thiagarajan and Munusamy, 2020; Hung, et al., 2022; Shu, et al., 2018). Moreover, these materials have important advantages as they can be produced in one piece and monocoque in desired part shapes and can also offer sound and heat insulation depending on the characteristics of the core structure used (Wang et al., 2021).

Sandwich structures are engineering materials obtained by placing a relatively low density, lightweight and thick core structure between two thin, stiff plates. Many distinctive features of sandwich structures depend on the mechanical and physical properties of the core material used (Wang, et al., 2021). Foam structures are among the most widely used core materials today. The cellular and porous structure they have given these materials the ability to deform to a great extent under the applied load. In this way, they become very good impact energy and shock load absorbing structures (Vinayagar, et al., 2020; Huo, et al., 2020). In addition, they are very light materials, as the majority of their structure consists of air or gas trapped inside the pores. Thanks to its features, they are the most reasonable choice to be the materials of the core of sandwich structures that can be used especially in the energy absorbing elements of vehicles during an accident or crash, in the main bodies of public transport vehicles that will make them lighter and safer, in the structure of battery carriers of new generation FEVs, and in the bodies of cargo cabins of light and heavy commercial vehicles. Expanded Polypropylene foams with closed-cellular structure are recyclable structures and have low density and low production cost, resistant to impact, superior energy absorption capacity. Due to these properties, it is widely used in the automotive industry as padding material in vehicle front bodies, front and rear bumper beams and side door panels (Güçlü, et al., 2020; Evans and Morgan, 1999; Mo, et al., 2018).

Foam materials exhibit large deformation under the load applied on them. Since most of their structures are made of air, they can behave in this way. As there is no space in the cells after the large deformation, they exhibit a behavior like a solid material. Thanks to these deformation mechanisms, they can be used as an ideal energy absorbing structure. Reyes and Borvik (2018) experimentally investigated the crash performance of parts produced with polymer foams placed between steel plates under quasi-static loads. They used extruded polystyrene (XPS) and expanded polypropylene (EPP) foams in their study. As a result of the experiments they revealed that, if maximum energy absorption is first desired in the production of parts for crash in vehicles, XPS foam is more preferable; if the expectation is force reduction or minimum back-plate displacement, EPP foam is more suitable. Güçlü et al. (2020)

investigated the behavior of sandwich structures with EPP foam core, with varying density, placed between self-reinforced PP composite plates under quasi-static 3-point bending and compression load, both experimentally and numerically. Their findings showed that this sandwich structure, consisting entirely of PP, is extremely suitable for the production of durable parts with reduced weight, especially in the automotive industry. Galos and Mouritz (2019), presented an example of the multifunctional use of sandwich structures with polymer foam cores in the automotive industry. Lithium-ion polymer battery cells are placed in the foam material at the core of the load-bearing sandwich structures. They tried to eliminate the need for an extra battery box by placing the vehicle battery cells into the sandwich structures that can be used in the outer bodies of hybrid and electric vehicles. They emphasized that embedding battery cells in sandwich structures does not have any negative effect on the strength of the structure; besides, the bending load -induced deformation of the sandwich structure does not alter the working performance of the battery cells. Rumianek et al. (2021) in their study carried out in 2021, the quasi-static mechanical properties of closed-cell EPP foams with different densities were investigated both experimentally and numerically at different loading rates and varying temperatures. As a result of the experiments and finite element analyzes, it was revealed that the increase in loading rates and foam density increased the compressive strength and energy absorption capacity of the material, while the increase in temperature caused a decrease in these values. They stated that the foam material can be selected according to the need in the automotive part, and the optimum structure can be obtained, and they also emphasized that this material has an important place in automotive weight reduction studies. Apart from these, many studies on foam and sandwich structures with foam core are available in the literature (Höhne, et al., 2022; Volpe, et al., 2019; Nasirzadeh and Sabet, 2014; Wang, et al., 2013).

In this study, a sandwich structure was obtained by combining aluminum (Al) face sheets and closed-cell EPP foam with 2 different densities. When combining the two main components, a flexible adhesive, Ethylene Vinyl Acetate (EVA), which is not very common in previous studies, was used. This material is an adhesive known for having particularly good crack resistance and flexibility. Thanks to these features, when a load is applied to the sandwich structure, it will adapt to the flexibility of the foam material much more than other adhesives, and the structure will become more flexible as a whole. The obtained sandwich structures were subjected to compression and 3-point bending tests under both quasi-static and low-velocity load conditions. As a result of the experiments, it has been revealed that the produced sandwich structures will offer great advantages with high strength and energy absorption capabilities in the use of automotive exterior body, floor and roof sections, especially in line with weight reduction studies.

2. EXPERIMENTAL

2.1. Materials

Two different density EPP foams were cut off from a block, thus, it was ensured that the samples were more homogeneous and cell defects were prevented. The densities of the EPP foams used in the production of the samples were measured as 0,365 g/cm^3 (D_1) and 0,657 g/cm^3 (D_2). The mechanical properties of the foams were determined by the experiments carried out (Güçlü, et al., 2020) in previous study. Samples of certain sizes were cut from the foams and these samples were weighed with precision scales. In this way, the densities of the foam structures were determined. The face plates were obtained by 1mm thick Al 1050 H14 commercial material. This type of Al is generally in the group of "commercially pure" Al materials and has a density of 2,71 g/cm^3. An EVA-based adhesive was applied between the core and facesheets to connect both parts to form a sandwich structure. This adhesive is a commercially available hot melt adhesive with a density of 1 g/cm^3. The assembly process of the parts is shown in the figure 1 below. Each face sheet is individually and sequentially bonded to the core material. In order for the bonding process to show the desired effect, when the two pieces are brought together, a 5kg load is placed on them. It was waited for about 5 minutes in order for the adhesive to cool down and to ensure the full bonding. This load does not cause any damage to the foam and does not cause any damage to the operation of the foam. The foam material does not receive any damage that goes out of the elastic region with this load.

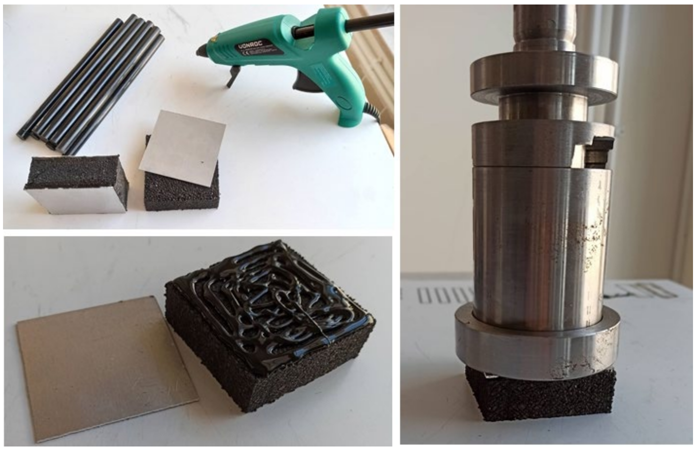


Figure 1: *Building of Sandwich Structure by Combining Components.*

The wall thickness of the EPP foam materials used in the core was measured as 26±0.5 mm. Al facesheets have a thickness of 1±0.1 mm. The sandwich structures produced were determined by the measurements to have a thickness of 30 ±0.3 mm. As it can be understood from the measurements made, an adhesive layer with an average thickness of 1 mm was formed between both upper and lower facesheets and the core structure. The total thickness of the sandwich structure, the thickness of the core materials and the thickness of the Al plate were measured and the difference was determined as the adhesive thickness. Figure 2 show the dimension of designed sandwich structure.

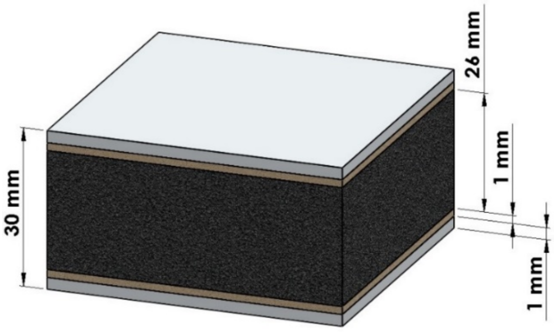


Figure 2: *Thicknesses of the Elements That Constitute the Sandwich Structure.*

Compression and 3-point bending test specimens, in which foam material with two different densities form the core structure, were produced in accordance with the dimensions specified in the standards (ASTM C365/C365M -16 and ASTM C393/C393M -20 respectively). In accordance with the specified standards, the compression test specimens were prepared 75mm x 75mm x 30mm; 3-point bending specimens were also prepared with dimensions of 200mm x 50mm x 30mm. Both tests specimens' dimensions given in figure 3 below.

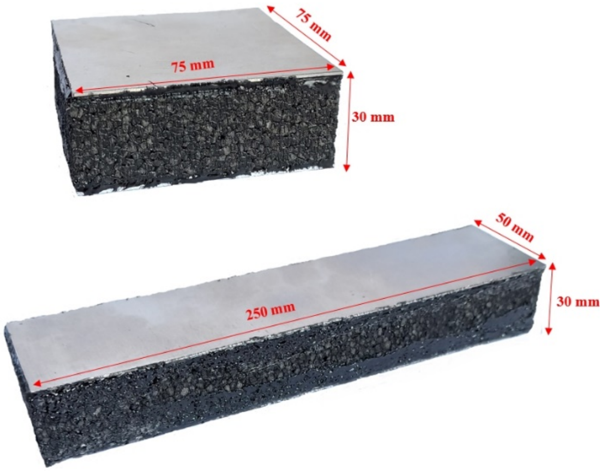


Figure 3: *Compression and 3-Point Bending Test Specimens and Dimensions.*

2.2. Characterization

2.2.1. Quasi-Static Compression and 3-Point Bending Tests

Quasi-static 3-point bending and compression tests were made to obtain energy absorbing capabilities of sandwich structures under static loads. Tests were carried out by Shimadzu AGS-X Universal test device with a test speed of 10 mm/min in a laboratory environment of 23± 2 °C. The setups for experiments are shown in figure 4 below.

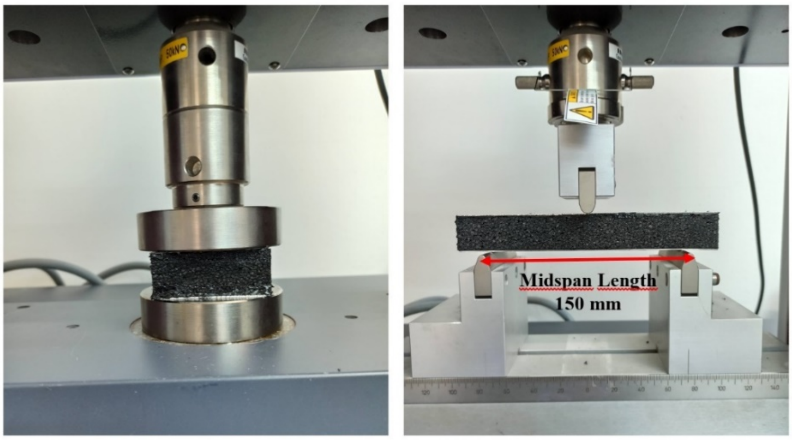


Figure 4. *Experimental Tests Setups for Quasi-Static Compression and 3-Point Bending Tests.*

2.2.2. Low- Velocity Compression and 3-Point Bending Tests

Material data, which are frequently encountered in the field of engineering, are generally obtained under quasi-static loading conditions. However, especially in the automotive industry, when examining the mechanical properties of structures with crash energy absorption potential, material behavior under dynamic loading conditions as well as quasi-static loading conditions is of great importance. Many engineering materials can exhibit different behaviors depending on the speed of the applied force; and this is called 'strain-rate dependency' (Türkoğlu, et al. 2022). In this study, both aluminum and EPP foam materials, which form the face plates and core structure of sandwich structures, are strain-rate dependency materials. For this reason, performing dynamic experiments of sandwich structures is an important factor in terms of their energy absorbing capabilities.

Dynamic tests were made with dynamic compression and bending test setups that obtained by using gas gun and incident bar of Split Hopkinson Compression Bar (SHCB) system in Applied Mechanics and Advanced Materials Research Group (AMAMRG) laboratory. Test setups are shown in figure 5 below. The gas pressure of the test device was 10 bar for each compression and bending test and this means ~250 kN force on the compression rod. According to the measurements made, the strain-rate of the experiments is 10^2 s^{-1}, which is included in the crash impact load class in the general classification table given in figure 6 below.

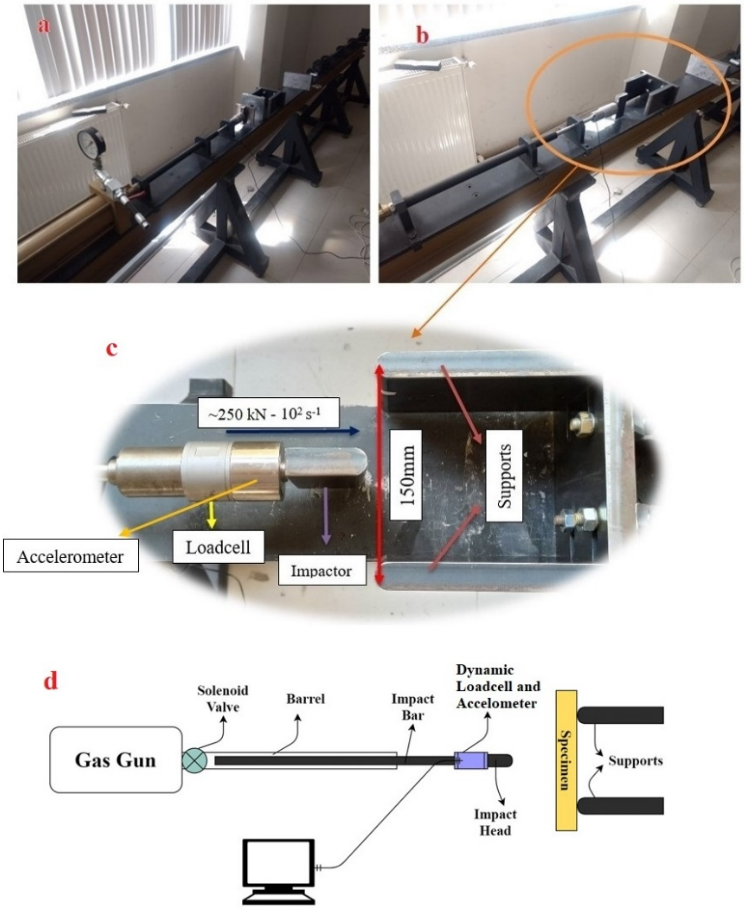


Figure 5: *Experimental Tests Setups for a-) Dynamic Compression and b-) 3-Point Bending Tests and c-) Details of Dynamic 3-Point Bending Test Setup, and d) Schematic of Modified Dynamic Bending Test System.*

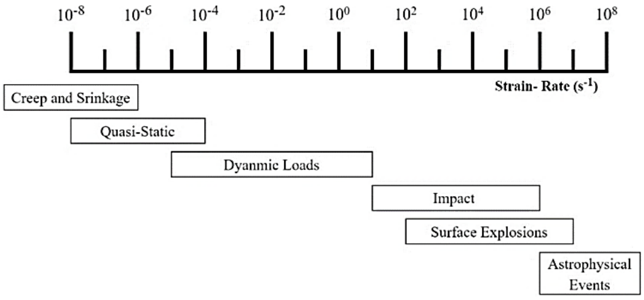


Figure 6: *Strain-Rate Range Classifications for Various Load Sources.*

The visuals of the experiments performed are shown in figure 7.

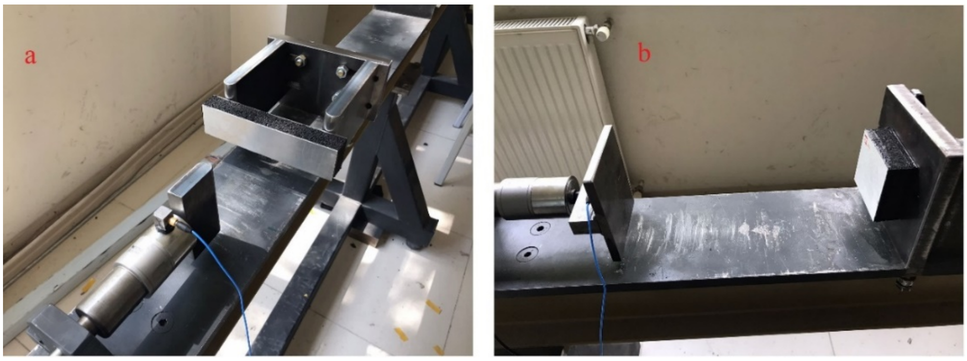


Figure 7: *Experiment Images Before the Test in Which the Samples are Placed a) Dynamic 3-Point Bending Test b) Dynamic Compression Test.*

3. RESULTS

3.1. Quasi-Static Compression Test Results

The test graph showing the mechanical behavior of EPP foam core sandwich structures with two different densities under quasi-static compression load is shown in figure 8. The force required for the sandwich structure with the denser (D_2) EPP foam to show the same amount of displacement is about two times that of the D_1 foam.

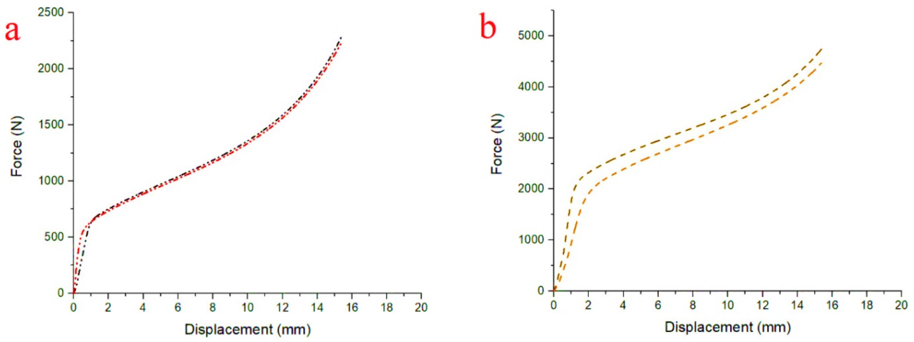
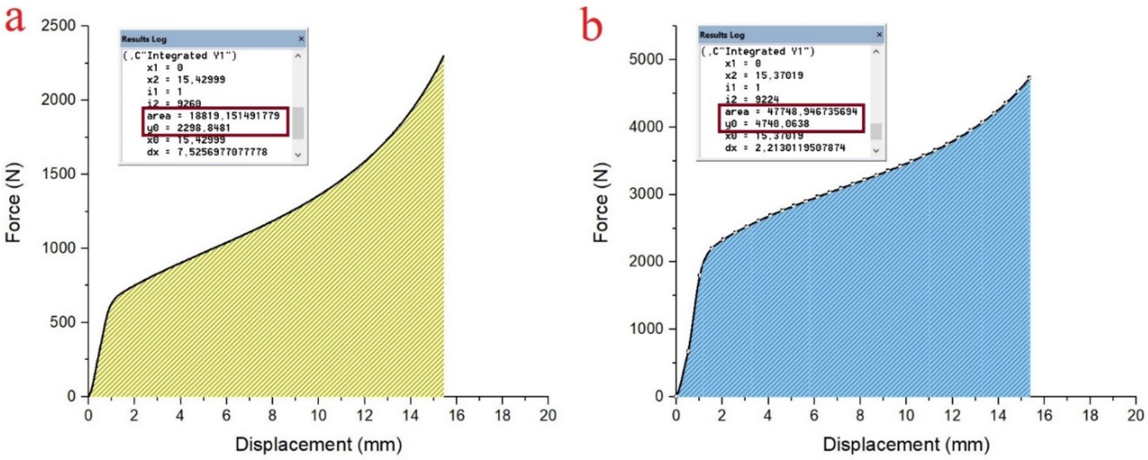


Figure 8: *Quasi-Static Compression Test Results of Sandwich Structures a) D_1 EPP Foam Core Sandwich Structures b) D_2 EPP Foam Core Sandwich Structures.*

As the displacement of the sandwich structures increases, the amount of force they carry increases as a result of the pores closing and condensing under the compression load of the foam structures. This ensures that the foam materials have a visco-elastic behavior. In this way, they can be good energy absorbing structures. Graph in figure 9 shows the max. force and absorbed energy values of sandwich structures under quasi-static compression load. While the D_1 EPP foam core sandwich structure absorbed a total of 18819.15 J energy, the D_2 EPP foam core sandwich structure absorbed 47748.95 J energy. In addition, the structures show the max. while the force values are 2298.85 N for D_1 EPP foam, it is 4740.06 N for D_2 EPP foam.



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     i2 = 9260
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     x0 = 15,42999
     dx = 7,5256977077778
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     i2 = 9224
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     x0 = 15,37019
     dx = 2,2130119507874
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Figure 9: *Absorbed Energy and Max. Force Values of Sandwich Structures under Quasi-Static Compression Load a) D_1 EPP Foam Core Sandwich Structures b) D_2 EPP Foam Core Sandwich Structures.*

3.2. Dynamic Compression Test Results

The test graph showing the mechanical behavior of EPP foam core sandwich structures with two different densities under dynamic compression load. Both dynamic compression force and acceleration values were measured in dynamic experiments. As a result of the measurements, acceleration-time and force-time graphs were obtained. The graphs of the experiments are given in figure 10 below.

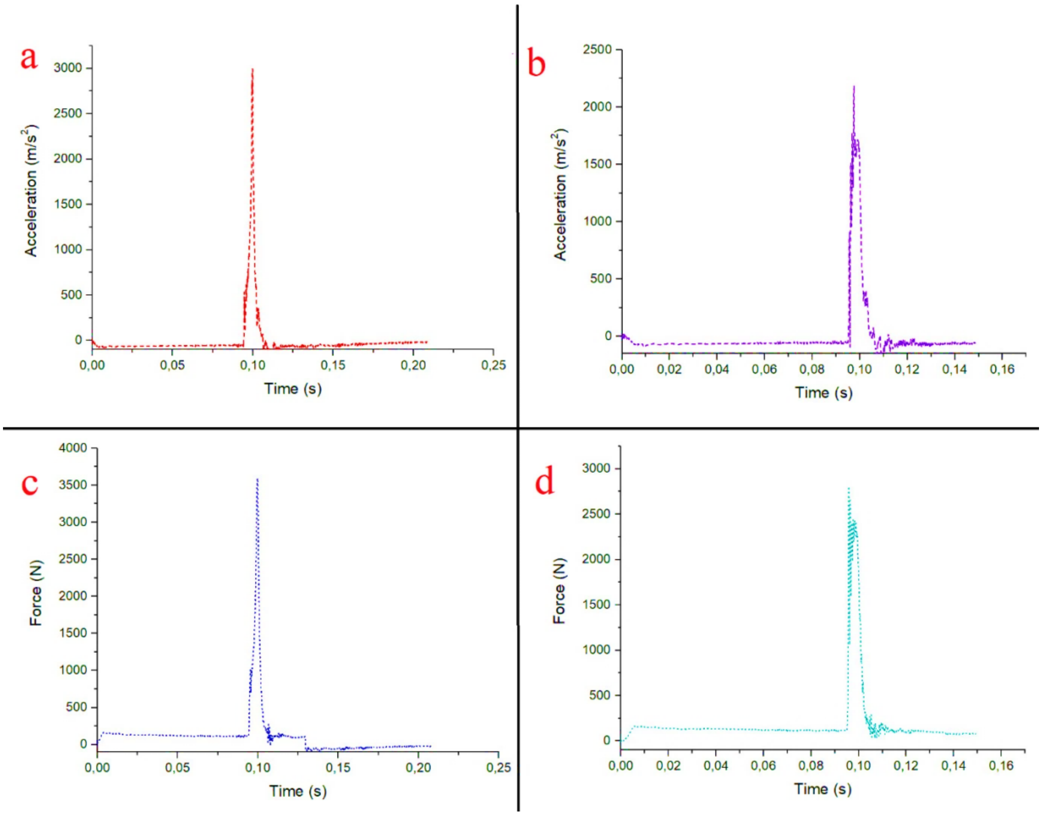
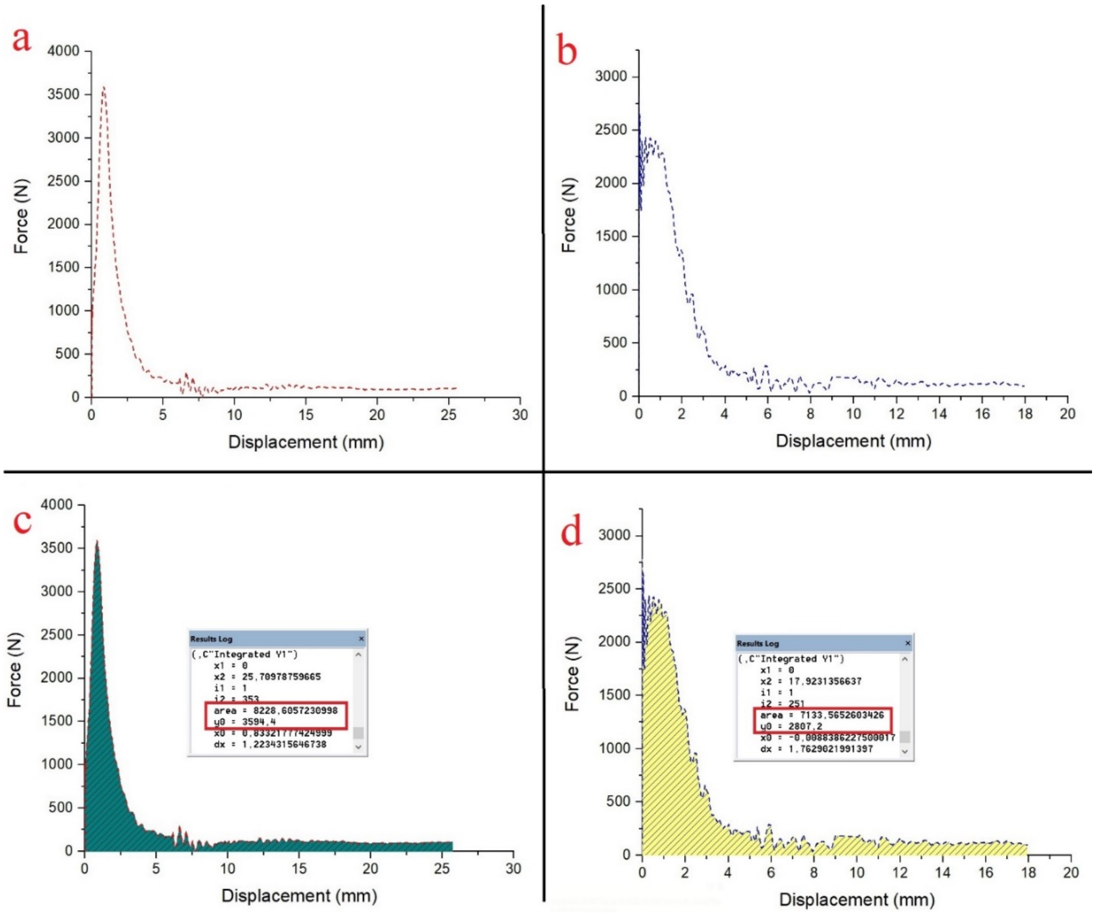


Figure10: *Dynamic Compression Test Results of Sandwich Structures a) D_1 EPP Foam Core Sandwich Structure's a-t Graph b) D_2 EPP Foam Core Sandwich Structure's a-t Graph c) D_1 EPP Foam Core Sandwich Structure's F-t Graph d) D_2 EPP Foam Core Sandwich Structure's F-t Graph.*

These data from experiments are raw data. These data have been carefully arranged and made more useful. With these processed data, other necessary graphics were drawn and calculated. In order to determine the amount of energy absorbed by sandwich structures, especially under dynamic compression load, a Force-Time graph is needed. In order to obtain this graph, the displacement-time (x-t) graph was obtained by integrating the processed a-t graph twice. This obtained x-t graph is combined with the existing F-t graph to produce the required F-x graph. The F-x graphs of sandwich structures and the amount of energy absorbed by the structures under dynamic compression load are given in figure 11 below.



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    y0 = 3594,4
    x0 = 0,83321777424999
    dx = 1,2234315646738
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    x2 = 17,9231356637
    i1 = 1
    i2 = 251
    area = 7133,5652603426
    y0 = 2807,2
    x0 = -0,008838622750001 7
    dx = 1,7629021991397
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Figure 11: *Dynamic Compression Test Results of Sandwich Structures a) D_1 EPP Foam Core Sandwich Structure's F-x Graph b) D_2 EPP Foam Core Sandwich Structure's F-x Graph c) D_1 EPP Foam Core Sandwich Structure's Absorbed Energy and Max. Force Value d) D_2 EPP Foam Core Sandwich Structure's Absorbed Energy and Max. Force Value.*

The data obtained from the materials as a result of both quasi-static and dynamic compression tests are shown in table 1 below. In order to make the necessary comparisons, the weights of the sandwich specimens were also measured and added to the table 1, and it was aimed to find the specific values by proportioning the obtained data to the weight of the structures. In this way, more valid comparisons can be made regardless of the weight of sandwich structures with two different foam densities.

Table 1. Mechanical Behavior of Foam Structures Tested Under Quasi-Static and Dynamic Compression Loads.

Loading Condition	Sandwich Specimen	Max. Force (N)	Max. Displacement (mm)	Absorbed Energy (J)	Weight of Sandwich Structure (gr)	Specific Absorbed Energy (J/gr)
Quasi - Static	*D_1 EPP Foam*	*2298,85*	*15,42*	*18819,15*	*45,36*	*414,88*

	D_2 EPP Foam	*4740,06*	*15,32*	*47748,95*	*61,02*	*782,51*
Dynamic	*D_1 EPP Foam*	*3594,4*	*25,71*	*8228,61*	*44,24*	*186*
	D_2 EPP Foam	*2807,2*	*17,92*	*7133,57*	*59,56*	*119,78*

Foam materials show some elastic and some plastic deformation after the applied load. When the load is removed, they first give back most of their elastic deformation. However, the deformation remaining on it decreases a little more after a certain period of time. This is a factor that affects the post-load usage of the material. The amount of recovery of dimensional properties is a matter to be considered in foam structures. In order to compare the values, the compression test samples were measured from four side after the experiment and the values were noted. After waiting 72 hours, the samples were re-measured and the measured values were noted again. By taking the average of the data obtained from both measurements, the differences of the materials in two different measurement ranges were determined. The measurement values and change amounts of the samples are given in the table 2 below.

Table 2. Springback Behavior of Visco-Elastic EPP Foam Structure After Deformation.

Loading Condition	Sandwich Specimen	Measurement After Experiment (mm)	Measurement After 72 Hours (mm)	Dimensional Change (mm)	Dimensional Change (%)
Quasi-Static	*D_1 Foam S_1*	*27,3345*	*28,355*	*1,025*	*3,75*
	D_1 Foam S_2	*27,8125*	*28,6325*	*0,82*	*2,95*
	D_2 Foam S_1	*26,4475*	*28,025*	*1,5775*	*5,97*
	D_2 Foam S_2	*26,5675*	*28,1975*	*1,63*	*6,14*
Dynamic	*D_1 Foam S_1*	*28,66*	*28,8*	*0,14*	*0,49*
	D_1 Foam S_2	*28,5*	*28,6*	*0,1*	*0,35*
	D_2 Foam S_1	*28,22*	*28,37*	*0,15*	*0,53*
	D_2 Foam S_2	*28,26*	*28,39*	*0,13*	*0,46*

3.3. Quasi-Static 3-Point Bending Test Results

The produced samples were first subjected to quasi-static 3-point bending tests. Force-Displacement graphs were drawn with the raw data obtained from the test device. F-x graphs of sandwich structures are given in figure 12 below. As in the compression test, it is seen in the graphs that the maximum force carried by the sandwich structure with a denser foam core (D_2) is almost twice as much as the other.

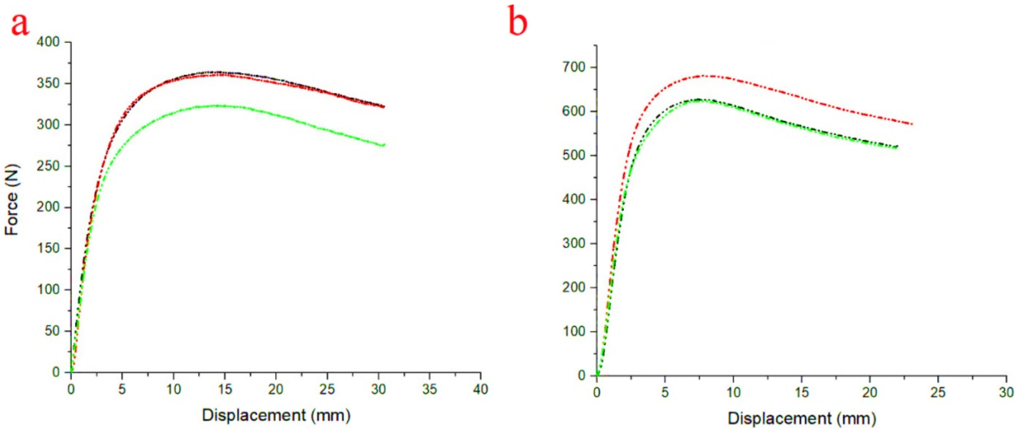


Figure 12: *Quasi-Static 3-Point Bending Test Results of Sandwich Structures a) D_1 EPP Foam Core Sandwich Structures b) D_2 EPP Foam Core Sandwich Structures.*

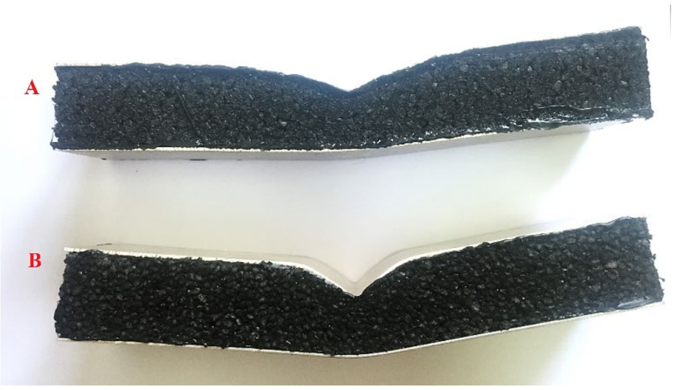
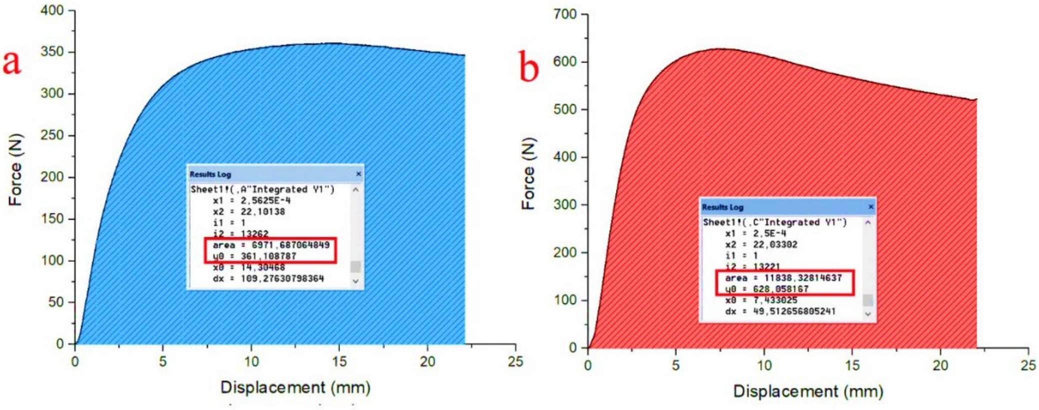


Figure 13: *Damage Appearance of Samples After Quasi-Static 3-Point Bending Experiment A-) D_1 EPP Foam Core Sandwich Structure B-) D_2 EPP Foam Core Sandwich Structure*

Figure 13 shows damaged specimens after quasi-static 3-point bending tests. When the samples are examined, it is seen that the core and face plate crush damage has occurred in both sandwich structures. However, the back face damage of the sandwich structure with D_2 EPP foam core is higher than the other. The main reason for this is that D_2 foam is denser and more material condensation occurs when crushed due to the lesser space inside.

Unlike compression test, the facesheets of the sandwich plates also undergo deformation in the 3-point bending test. In this way, both the face plates and the core structure are deformed and absorb the energy coming on them. Due to the loading conditions, especially for the automotive industry, the amount of energy absorbed by the structures in the 3-point bending test is more important than in the compression test. The max. force and absorbed energy values of sandwich structures under quasi-static bending load are shown in figure 14. The amount of energy they absorb is calculated for equal displacement amount.



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     dx = 49,512656805241
```

***Figure 14:** Absorbed Energy and Max. Force Values of Sandwich Structures under Quasi-Static 3-Point Bending Load a) D_1 EPP Foam Core Sandwich Structures b) D_2 EPP Foam Core Sandwich Structures.*

3.4. Dynamic 3-Point Bending Test Results

As in the compression test, the dynamic force and acceleration values were obtained in a time-dependent manner. According to the obtained data, a-t and F-t graphs of the dynamic bending test are given in figure 15.

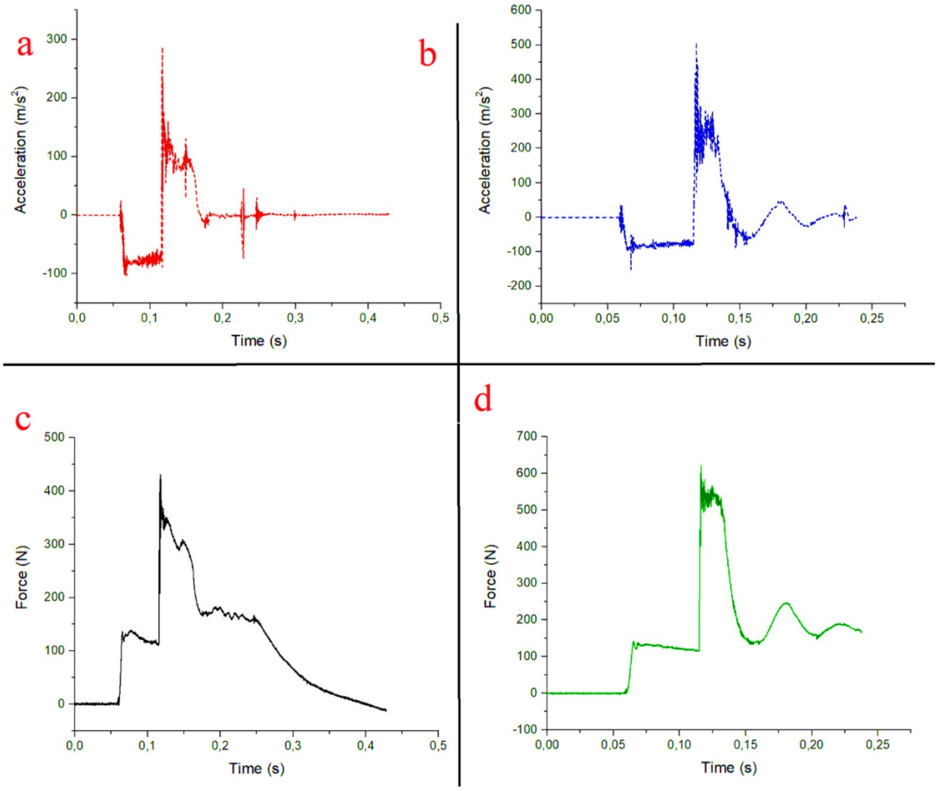


***Figure 15:** Dynamic 3-Point Bending Test Results of Sandwich Structures a) D_1 EPP Foam Core Sandwich Structure's a-t Graph b) D_2 EPP Foam Core Sandwich Structure's a-t Graph c) D_1 EPP Foam Core Sandwich Structure's F-t Graph d) D_2 EPP Foam Core Sandwich Structure's F-t Graph.*

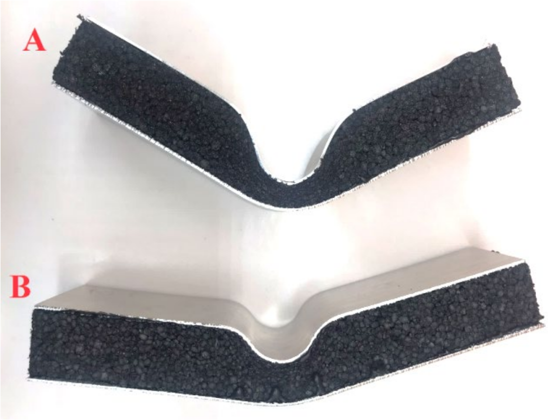
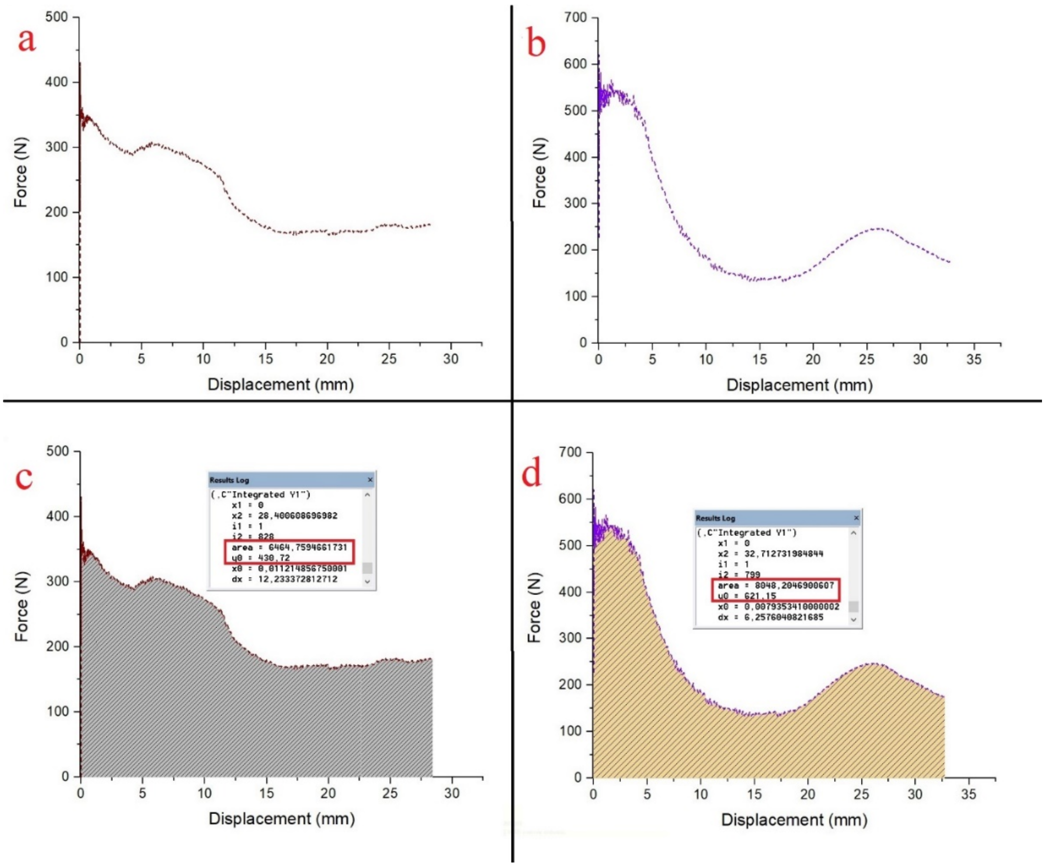


Figure 16: *Damage Appearance of Samples after Dynamic 3-Point Bending Experiment A-) D_1 EPP Foam Core Sandwich Structure B-) D_2 EPP Foam Core Sandwich Structure*

Damaged samples of dynamic 3-point bending tests were given in figure 16. Again, it is observed that core and face crush damage occurred in both sandwich structures. It is seen that the D2 EPP foam structure, which is denser, behaves more rigidly and keeps the damage transmitted to the back surface at a lower level under dynamic load. It is seen that the structure shows more bending damage in the less dense D1 EPP foamed sandwich structure.

As a result of the necessary mathematical operations of these obtained data, the F-x graphs, which is needed for comparisons were created. Both the F-x graphs and the graphs showing the maximum force values that the structures show and the amount of energy they absorb are given in figure 17 below.



```
(,C"Integrated Y1")
     x1 : 0
     x2 : 28,400608696982
     i1 : 1
     i2 : 828
     area : 6464,7594661731
     y0 : 430,72
     x0 : 0,011214856750001
     dx : 12,233372812712
```

```
(,C"Integrated Y1")
     x1 : 0
     x2 : 32,712731984844
     i1 : 1
     i2 : 799
     area : 8048,2046900607
     y0 : 621,15
     x0 : 0,0079353410000002
     dx : 6,2576040821685
```

Figure 17: *Dynamic 3-Point Bending Test Results of Sandwich Structures a) D_1 EPP Foam Core Sandwich Structure's F-x Graph b) D_2 EPP Foam Core Sandwich Structure's F-x Graph c) D_1 EPP Foam Core Sandwich Structure's Absorbed Energy and Max. Force Value d) D_2 EPP Foam Core Sandwich Structure's Absorbed Energy and Max. Force Value.*

Especially in possible crash and accident scenarios, this is accepted as the loading conditions to which energy absorber structures are exposed are more similar to the conditions in the 3-point bending test. For this reason, the criterion that interests us as a result of these tests is the amount of energy that the structures absorb. But making comparisons with this value alone will not be enough. There are other criteria that must be considered in automotive crash energy absorber elements (Türkoğlu, et al. 2022). These criteria can be briefly summarized as follows;

Mean Crush Force (F_{mean})

The mean crush force is obtained by dividing the amount of total energy absorbed by the structure by the maximum amount of deformation made by the structure. The higher F_{mean} value means the higher crash energy absorption capability of the structure. This value is calculated as follows;

$$F_{mean} = \frac{\int_0^{\delta_{max}} F.d\delta}{\delta_{max}} \qquad (1)$$

Peak Crush Force (F_{peak})

Peak crush force (F_{peak}) indicates the maximum amount of force the structure showed during the test. The higher this value, the more the structure transmits the incoming load to other vehicle elements to which it is connected. Therefore, this value is desired to be low as possible.

Crush Force Efficiency (CFE)

The Crush Force Efficiency (CFE) parameter is ratio of the mean crush force value to the peak crush force value. The higher the CFE value, the more effective the energy absorption of the structure is occurred.

$$CFE = \frac{F_{mean}}{F_{peak}} \tag{2}$$

Crushing Strain (CS)

This parameters is the ratio of the crushing displacement to the initial sandwich structure thickness, and calculated as;

$$CS = \frac{\delta_{max}}{L} \tag{3}$$

Along with these values, the main criteria Absorbed Energy (EA) and the Specific Absorbed Energy (SEA) values obtained by the ratio of this value to the weight of the sandwich structures. These values are calculated as follows;

$$EA = \int_0^{\delta_{max}} F.d\delta \tag{4}$$

$$SEA = \frac{EA}{m} \tag{5}$$

These values will be calculated for both quasi-static and dynamic bending tests and will be given in table 3. In this way, comparisons can be made according to both foam density and loading speed.

Table 3. Mechanical and Energy Absorption Data Obtained as a Result of Quasi-Static and Dynamic 3-Point Bending Tests of Sandwich Structures.

Loading Condition	Sandwich Specimen	Absorbed Energy (J)	Weight (gr)	Specific Absorbed Energy (J/gr)	F_{mean} (N)	F_{peak} (N)	CFE	CS
Quasi-Static	*D_1 Foam S_1*	*6971,69*	*81,05*	*86,02*	*451,82*	*2298,85*	*0,197*	*0,514*
	D_2 Foam S_2	*11838,33*	*88,35*	*133,99*	*770,22*	*4740,06*	*0,165*	*0,512*

Dynamic	*D_1 Foam S_1*	*6464,76*	*80,28*	*80,53*	*230,55*	*430,72*	*0,535*	*0,94*
	D_2 Foam S_2	*8048,24*	*87,07*	*92,43*	*246,05*	*621,15*	*0,396*	*0,92*

4. CONCLUSION

In this study, it is focused on the examination of the mechanical properties and energy absorption capacities of sandwich structures with two different densities of foam core placed between the Al panels under quasi-static and dynamic loads. In order to examine the properties desired to be investigated, the produced sandwich structures were subjected to quasi-static and dynamic compression and 3-point bending tests. From the tests performed, the force-displacement graphs of the sandwich structures were obtained, and data suitable for comparison were obtained about both the strengths and the energy absorption capacities of the structures. Specific values were found by proportioning these obtained data to the weights of the structures, and the comparison was made much more clearly. It has been investigated whether the produced sandwich structures are suitable for use in the body sheet panels of especially new generation hybrid electric commercial vehicles. Although the structures used in these parts of the vehicles are not expected to carry as much load as the main skeleton structure; It is expected that it will show sufficient strength, in particular, it will have good energy absorbing properties. In addition to these expected mechanical properties, in order to increase the range of electric vehicles, the materials to be used in new generation electric vehicles are expected to lightweight. For this reason, sandwich structures have been produced with very low density EPP foams placed between thin aluminum plates. EVA-based hot melt adhesive material was used for combining Al plates and EPP foam material. As a result of the quasi-static and dynamic tests carried out, the following conclusions were deduced;

- Both foam structures exhibited superior energy absorption behaviors under quasi-static compression loads. However, when the foam structure with D_2 density contains less voids in the structure, the amount of reaction force shown under the incoming loading was higher. This value exhibited by the D_2 density foam structure is 2.06 times that of the D_1 density foam. Due to the equal amount of displacement in both sandwich structures during the compression test, the D_2 density foam structure with a greater maximum force absorbed 2.5 times more energy. Even when compared to the total weight of the structures, the sandwich structure with D_2 density foam showed a much superior ability to absorb compression energy. In addition, the post-damage behavior of the structures was also examined as a criterion. According to this review, most of the deformation shown during the test was exhibited as elastic deformation due to the visco-elastic property of the foam structures. The measurements revealed that after the test, the amount of crushing of the structures decreased after 72 hours, that is, some of the remaining deformation was returned after a certain time. When the deformation recovery mechanisms are examined, it has been shown that the denser D_2 foam recovers the remaining deformation much more, that is, it approaches its initial dimensions much more. This revealed that D_2 foam is a much better energy absorbing structure under quasi-static compression loads and is a much more ideal material for use after deformation.

- Similarly, when structures under dynamic compression load are examined, it is seen that foam structures exhibit much higher strength values under dynamic loads due to their strain-rate sensitivity. However, unlike in quasi-static loading, these high force values are instantaneous and are not seen during deformation. For this reason, while structures show much higher reaction forces under dynamic loads, the amount of energy they absorb is not higher. There was a difference in the behavior of the structures under dynamic load compared to the quasi-static situation. In these tests, the D_1 density foam showed much higher strength values. In addition, the total amount of deformation was also higher for the D_1 foam. An equal amount of deformation was achieved in quasi-static loading, but both structures were allowed to exhibit natural deformation behavior in dynamic tests and the comparison was made accordingly. According to these values, D_1 foam, which has a lower density under dynamic compression load, showed both higher strength and higher energy absorption ability. In addition, when the deformation-restoring behavior of the structures was examined, it was calculated by measuring that the D_2 density foam structure, similar to the quasi-static loading situation, again returned more deformation and approached its original size more.
- As the structures are examined under quasi-static bending load; again, it is seen that the D_2 density foam reaches higher strength values thanks to its greater densification. It was observed that the F_{mean} values of the structures were 1.7 times higher than that of the D_2 density foam. When the amount of energy they absorb under equal deformation values is examined, it was measured that the D_2 density foam absorbs 1.7 times more energy. On the other hand, it is seen that the F_{peak} value, which shows how much load is transmitted to other structures with which they are connected, is 2.06 times higher in D_2 density foam, that is, it will transmit the incoming load to other parts of the vehicle under load. However, this situation becomes more advantageous when it is aimed to use these structures in the outer panels rather than the chassis system. In this way, it means that the transmission of the load on them to the vehicle chassis system in the main load carrier position will be higher.
- When the sandwich structures under dynamic bending load are examined; contrary to expectations, it was observed that the strength values of the foam structures in quasi-static loading exhibited similar values. The reason for this can be shown that the deformation value in dynamic loading is shorter and the deformation intensification is less. Although instantaneous dynamic load is applied, it is thought that the reaction force values are lower than expected due to the lower deformation concentration. Apart from this, it has been seen as a result of the tests that the D_2 density foam absorbs more energy. In addition, it is seen that both structures exhibit similar F_{mean} values in the dynamic loading condition, but the D_2 density foam is slightly higher. Additionally, it has been revealed as a result of the calculations that the F_{peak} value, which is a desired feature from these structures, is 1.44 times higher in the D_2 density foam.

As a result of the tests and calculations, it is seen that both foams are very ideal structures for the use of body outer panels, floor, ceiling panels and baggage cabin lower panels of new generation electric commercial vehicles. EPP foam core sandwich structures have been shown to be materials that should be taken into account, thanks to their ultra-lightweight structures, in addition to their strength and high energy absorption capacity. Among the foam cores of two different densities, which are the subject of this study, when compared in overall, it is seen that the D_2 density foam is much superior in terms of some desired properties for use in electrical vehicles body. Although the density is higher, the obtained values are superior even when the specific values are obtained by proportioning the weight of the structure. For this reason, it has been shown that their use is somewhat more advantageous in applications where both strength and energy absorption expectations are the main criteria.

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CONFLICT OF INTEREST

Author(s) approve that to the best of their knowledge, there is not any conflict of interest or common interest with an institution/organization or a person that may affect the review process of the paper.

AUTHOR CONTRIBUTION

All of the manufacturing, material tests, test interpretations and article writing processes carried out in the study were carried out by İ.Kürşad Türkoğlu.

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