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Investigation of the Effects of Polyurethane Foam Reinforcement Thickness on Modal Properties of Sandwich Beams

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ABSTRACT

In this study, the effects of polyurethane foam (PUF) reinforcement thickness on modal properties (natural frequency, mode shape and damping ratio) of sandwich beams were investigated. For this purpose, two types of PUF reinforced beams were used. The one of these was reinforced onto one surface of aluminum metal face sheet and the other was reinforced between two aluminum metal face sheets were produced. Each type was prepared in different PUF thicknesses from 10 mm to 50 mm. The modal properties were obtained by using experimental modal analysis (EMA) method for both types.

Keywords: Modal analysis, Polyurethane Foam, Sandwich Beam, Vibration

Poliüretan Köpük Takviye Kalınlığının Sandviç Kirişlerin Modal Özellikleri Üzerine Etkilerinin İncelenmesi

ÖZ

Bu çalışmada, poliüretan köpük (PUF) takviye kalınlığının sandviç kirişlerin modal özelliklerine (doğal frekans, mod şekli ve sönüm) etkileri araştırılmıştır. Bu amaçla, iki tip PUF takviyeli kiriş, biri alüminyum meta tabakasının bir yüzeyi üzerine ve diğeri iki alüminyum metal tabaka arasına takviye edilmiştir. Her tip 10 mm'den 50 mm'ye kadar farklı PUF kalınlıklarında hazırlanmıştır. Modal özellikler, her iki tip için deneysel modal analiz (EMA) yöntemi kullanılarak elde edilmiştir.

Anahtar Kelimeler: Doğal Frekans, Poliüretan Köpük, Sandviç Kiriş, Titreşim

INTRODUCTION

Sandwich structures have a very wide range of use from mechanical and structural engineering to aircraft, marine applications and automobile industry. By using different kinds of materials in sandwich structures, very useful new structures can be created. In general, a sandwich structure is made with a thick soft and low density viscoelastic core and two thin face sheets (generally metal). Nowadays there is a big demand on these structures for their advantages such as light weight, easy implementation to systems, vibration isolation, corrosion resistance and flexural strength [1, 2]. In vibration isolation applications PUF is widely used in sandwich structures as core material with good damping capability, light weight and low cost. It is used as soft-core material between two face sheets and can be used only onto one surface of a thin plate as well. There are numerous analytical models in literature developed to describe some properties of viscoelastic foams by using experimental studies made on viscoelastic materials like PUF using different methods. These methods have been developed with the help of mechanical models containing combinations of springs and damper components [3]. Wiechert [4], Maxwell [5] and Kelvin [6] are the examples of these modelling methods. There are also many studies on the investigation of dynamic properties of structures in which PUF is used. Havaldar and Sharma [7] studied on determining the dynamic characteristics of multilayer PUF sandwich structures. They determined the natural frequencies, mode shapes and damping ratio of rectangular sandwich panels with PUF material in different densities. Barbieri et al. [8] studied on PUF sandwich structures used in refrigerators and food freezers experimentally and numerically. They also estimated the Young's modulus of PUF and the high impact polystyrene by using genetic algorithm. Neves et al. [9] studied on determining dynamic characteristics of a composite sandwich structure in which 40 kg/m^3 PVC foam was used as core material of a hybrid bus. They used experimental modal analysis method and verified the results with that of numerical solutions. Sen and Cakar made an experimental study for investigating the effects of PUF reinforcement in sandwich plate structures for free boundary conditions [10]. Sen and Cakar studied on a commercial PUF corrugated sandwich panel for determining the dynamic properties [11]. In some

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vibration isolation applications, lightweight can be very important property, so the thickness of core material has to be in an optimum value that can also provide enough damping. In this study, the effects of PUF reinforcement thickness on modal properties (natural frequency, mode shape and damping) of beams are investigated.

MATERIAL and METHOD

In Figure 1, a beam in free-free boundary condition is illustrated.

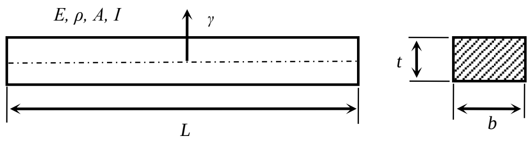


Figure 1. An Euler-Bernoulli beam in Free-Free boundary condition.

For a simple uniform Euler-Bernoulli beam, the equation of motion for bending vibrations can be expressed by Eq. (1).

$$EIv^{IV} + \rho A\ddot{v} = 0 \qquad (1)$$

Where, *E*, *I*, *p*, *A* and *v* represent modulus of elastisity, moment of inertia, density, cross-section area and displacement respectively. For free-free boundary condition natural frequencies of the beam can be obtained in Hz as in Eq. (2).

$$f_n = \frac{\lambda^2}{2\pi L^2}\sqrt{\frac{EI}{\rho A}} \qquad (n = 1, 2, 3...n) \qquad (2)$$

Were *L* is the length of the beam, *n* is the natural frequency for the nth mode and λ is the dimensionless frequency parameter. The values of λ for the first 3 modes for free-free boundary condition are calculated as: 4.73, 7.853 and 10.996.

For uniform beams these mathematical formulations can be used easily, but for non-uniform beams it is very difficult to calculate the dynamic properties mathematically. For this respect some equivalent or experimental approaches can be used. In this study, the EMA method is used to obtain the dynamic characteristics of PUF sandwich beams.

In EMA method, the system is excited with a known force and the response of the system to this force is measured. The excitation force can be applied to the system by using a modal hammer or a modal shaker and it can be measured by using a force meter. The response of the system can be measured by using accelerometer(s). By using these measurements, the response/impulse ratios called frequency response functions (FRF) of the system are obtained. These FRFs describe the relationship between the input and output of the system. By using these FRFs the dynamic characteristics of the system (natural frequency, mode shape and damping ratio) can be determined.

In Figure 2, a simple modal test setup is illustrated schematically.

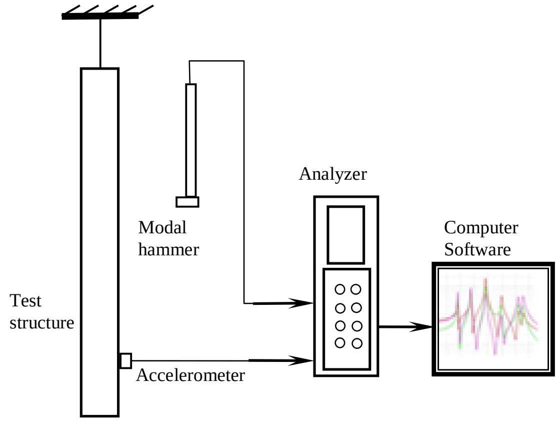


Figure 2. A basic modal test setup.

The experimental studies of this research were carried out at Firat University, Machine Theory and Dynamics Laboratory. Before the measurements, some calibration tests like reciprocity and repeatability to be sure of experimental results were performed. After the calibration tests firstly, a uniform AISI 1040 steel beam in free-free boundary condition was tested to obtain the dynamic properties. The experimental results were verified with the results obtained analytically and numerically. The mechanical and the physical properties of test structure are given in Table I.

Table 1. The mechanical and the physical properties of the AISI 1040 steel beam

Young's modulus (GPa)	200
Poisson's ratio	0.3
Shear modulus (GPa)	80
Density (kg/m^3)	7850
Length (m)	0.850
Width (m)	0.025
Thickness (m)	0.012

The test structure was partitioned with 40 mm intervals and 22 measurement points on the test sample were defined. Then, the beam was hung on a stand from the one end by using fiber thread to provide free boundary condition as shown in Figure 3.

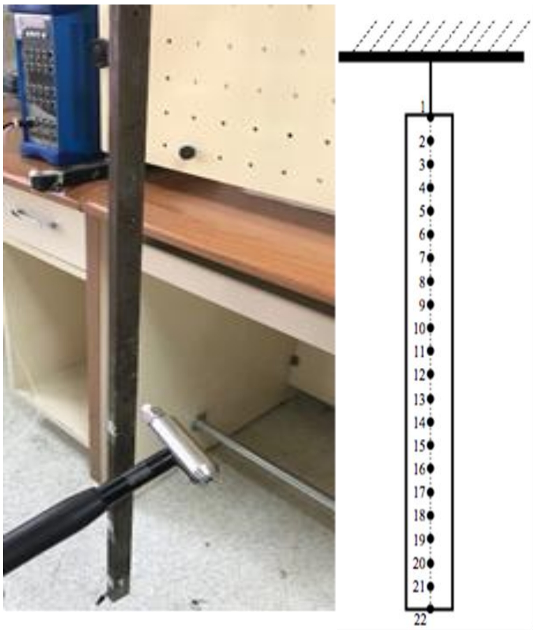


Figure 3. Suspended test structure and measurement points.

For experimental studies of the research, to excite the structures, a modal hammer, to measure the response of the structure an ICP accelerometer and for data acquisition and signal processing a vibration analyzer with modal software were used. The properties of the test equipment are given in Table 2.

Table 2. The properties of testing equipment

Vibration Analyzer	
Production	OROS
Type	OR36
Number of Channels	8 Channels
Frequency Bandwidth	40 kHz
Modal Hammer	
Production	KISTLER
Type	9724A2000
Frequency Range	6600 Hz
Accelerometer	
Production	DYTRAN
Type	3097A2
Sensitivity	100 mV/g

The free end point is more suitable for determining the dynamic properties of the beam over a wide frequency bandwidth for free boundary condition. Because this point does not match with a node point (the point does not move in that mode). So, the accelerometer was attached to the first measurement point on the end of the test structure by using wax. The test structure was excited from all measurement points 1 to 22 by using the modal hammer and 22 FRFs were measured. Measurement and analysis parameters used for the tests are given in Table 3. The testing process is shown in Figure 4.

Table 3. The measurement analysis parameters

Frequency Bandwidth	0-800 Hz
Frequency Resolution	0.5 Hz
Sampling Number	1600
Measurement Time	2 s
Windowing (response/impulse)	(uniform/uniform)

Figure 4. The testing process setup.

In EMA, it is important the amplitude of the measurements in time domain have to be almost zero in the measurement period of time. If not, some windowing functions have to be used. In the experimental studies of this research the amplitudes of the measurements were observed almost zero in the measurement time so, additional damping can be caused due to exponential window was eliminated. The time signal of force and response is given in Figure 5.

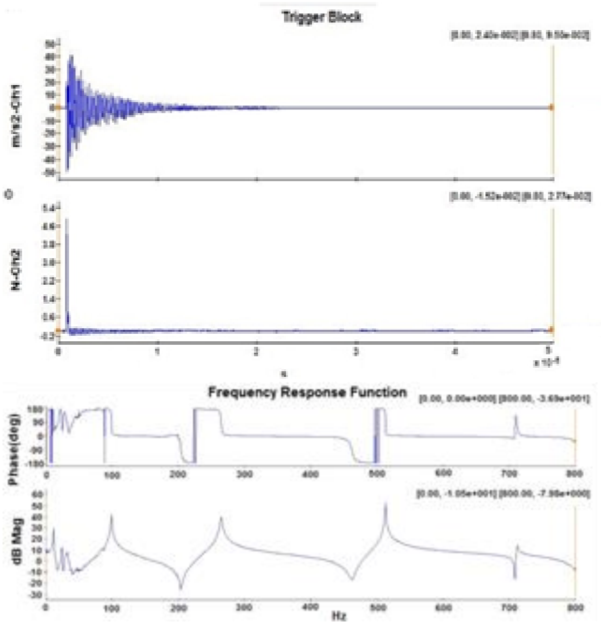


Figure 5. Time signals obtained from force and accelerometer transducers and a simple FRF.

The first three bending modes of the test beam are given in figures (6-8). The first three natural frequencies of the test beam obtained by EMA, calculated by using the analytical method and the ANSYS finite element software are given in Table 4 comparatively with the percentage errors. According to this comparison, it can be considered that the experiment system is reliable enough.

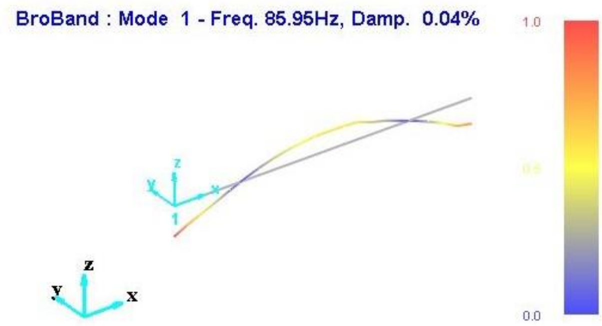


Figure 6. First bending mode shape

Figure 7. Second bending mode shape

Figure 8. Third bending mode shape

Table 4. Verification of the Test Setup by Using the Natural Frequencies of the AISI 1040 Test Beam

Mode	Exp. (Hz)	Num. (Hz)	Diff. (%)	Analy. (Hz)	Diff. (%)
1	85.95	86.16	-0.24	86.17	-0.26
2	236.19	237.2	-0.42	237.5	-0.55
3	463.29	464.11	-0.18	465.7	-0.52

After confirming the experimental, numerical and analytical results of the test sample, EMA of PUF sandwich beams with different thicknesses were performed. The PUF sandwich beams were partitioned with 50 mm intervals and 11 measurement points on the structure were determined. The sandwich beams are illustrated in Figure 9 and the mechanical and the physical properties are given in Table 5 and 6.

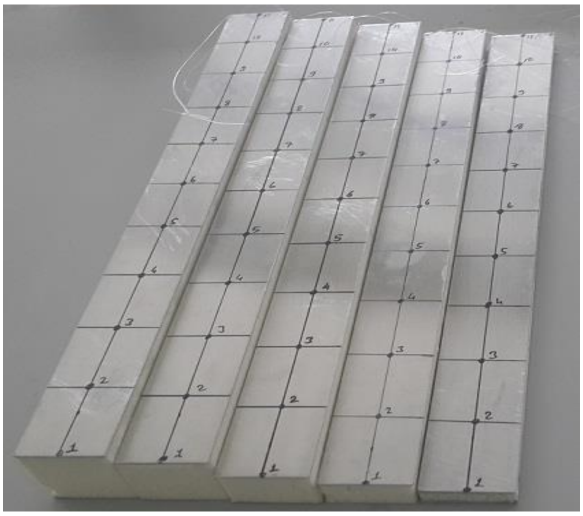


Figure 9. Different thicknesses PUF sandwich beams

Table 5. The mechanical and the physical properties of the aluminum face sheet

Young's modulus (GPa)	69
Poisson's ratio	0.33
Shear modulus (GPa)	25.94
Density (kg/m^3)	2700
Length (m)	0.5
Width (m)	0.05

Table 6. The mechanical and the physical properties of the PUF core material

Young's modulus (GPa)	0.006
Poisson's ratio	0.35
Shear modulus (GPa)	0.0036
Density (kg/m^3)	38
Length (m)	0.5
Width (m)	0.05

The first three natural frequencies with the damping ratios of the three bending modes of the sandwich beams Aluminum-PUF-Aluminum (Al-PUF-Al) obtained by EMA are given in Table 7 and illustrated in Figures 10 and 11.

Table 7. Natural frequencies and damping ratios of PUF reinforcement sandwich beam (Al-PUF-Al)

PUF Thickness (mm)	Modes 1		Modes 2		Modes 3	
	f_1 (Hz)	ζ_1 (%)	f_2 (Hz)	ζ_2 (%)	f_3 (Hz)	ζ_3 (%)
10	157.1	1.68	254.52	1.53	358.93	1.95
20	210.53	1.42	312.45	2.43	435.26	2.92
30	260.53	1.58	379.51	0.66	582.56	4.10
40	295.82	1.44	423.76	2.03	656.48	2.99
50	279.09	1.20	381.35	10.5	592.63	2.42

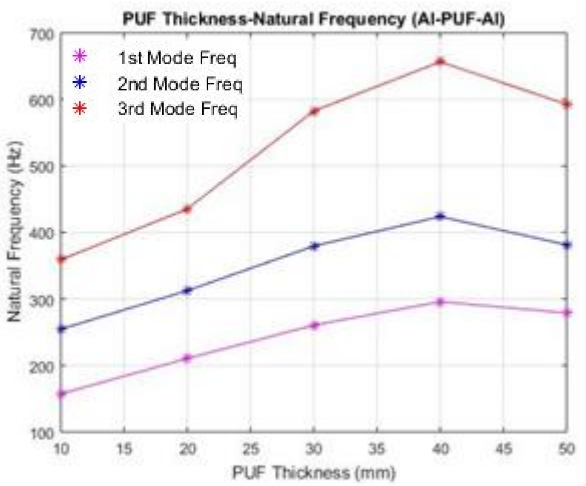


Figure 10. Natural frequencies of PUF sandwich beams for different reinforcement thicknesses.

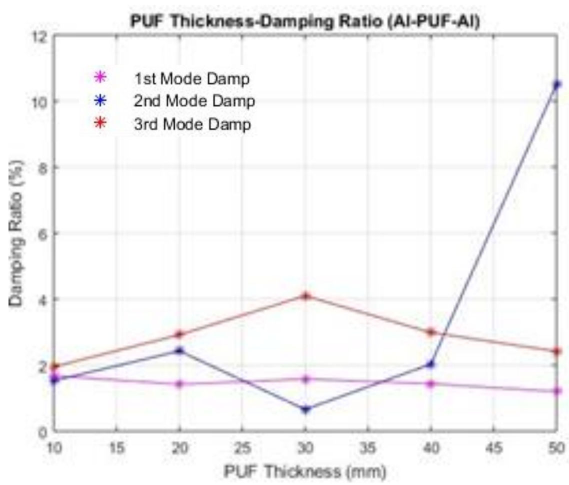


Figure 11. Damping ratios of PUF sandwich beams for different reinforcement thicknesses.

The first three natural frequencies with the damping ratios of the three bending modes of the layered beams Aluminum-PUF-Aluminum (Al-PUF) obtained by EMA are given in Table 8 and illustrated in Figures 12 and 13.

Table 8. Natural frequencies and damping ratios of PUF reinforcement layered beam (Al-PUF)

PUF Thickness mm	Modes 1		Modes 2		Modes 3	
	f_1 Hz	ζ_1 %	f_2 Hz	ζ_2 %	f_3 Hz	ζ_3 %
10	15.62	3.35	80.88	1.94	158.43	1.47
20	53.11	2.17	140.64	1.62	260.92	1.76
30	90.19	1.95	223.83	1.58	381.54	2.32
40	126.07	1.90	294.54	2.41	458.49	4.92
50	158.66	1.62	348.98	2.03	520.91	3.31

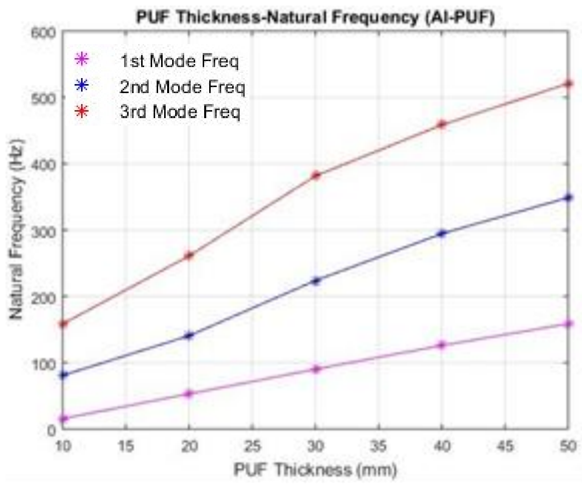


Figure 12. Natural frequencies of PUF layered beams for different reinforcement thicknesses.

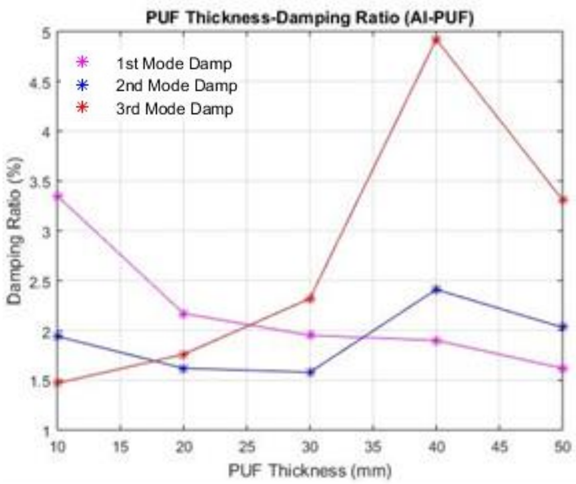
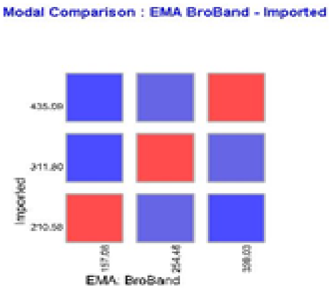


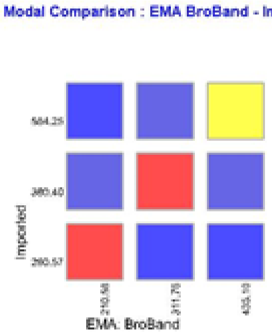
Figure 13. Natural frequencies of PUF layered beams for different reinforcement thicknesses.

Modal Assurance Criterion (MAC) is very useful approach for comparing mode shapes to verify. It is a mathematical approach used for comparing two vectors obtained from different sources [6]. The mode shapes of the first three modes obtained for 5 different PUF reinforcement thicknesses from 10 mm to 50 mm reinforcement thickness were compared to each other according to MAC. The results are given in Figures 14-17. It can be said that the mode shapes are in good agreement for five different PUF reinforcement thicknesses.



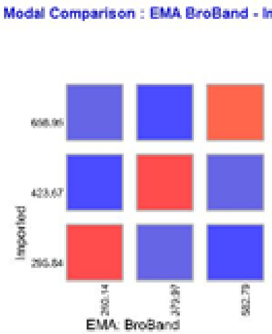
No.	1-210.58	2-311.80	3-435.09
1-157.08	98.8	1.6	1.3
2-254.48	3.7	97.5	4.8
3-359.03	0.0	4.6	97.5

Figure 14. Determination of MAC for 10 mm-20 mm PUF reinforced sandwich beam



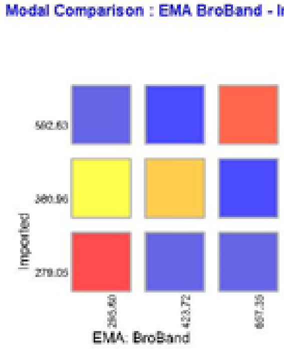
No.	1-260.57	2-380.40	3-584.25
1-210.58	99.6	3.7	2.8
2-311.76	2.9	97.0	4.7
3-435.10	0.7	6.2	[illegible]

Figure 15. Determination of MAC for 20 mm-30 mm PUF reinforced sandwich beam



No.	1-295.84	2-423.67	3-656.95
1-260.14	99.6	3.4	6.7
2-379.97	6.4	99.1	2.3
3-582.79	1.0	4.2	95.7

Figure 16. Determination of MAC for 30 mm-40 mm PUF reinforced sandwich beam



No.	1-279.05	2-380.96	3-592.63
1-295.80	99.6	[illegible]	6.5
2-423.72	3.8	65.7	0.6
3-657.35	5.3	0.4	93.2

Figure 17. Determination of MAC for 40 mm-50 mm PUF reinforced sandwich beam

DISCUSSION

The polyurethane foam material, with its continuous coating ability, becomes a porous structure with a swelling of 30-40 times its own volume within a few seconds. Due to its porous property there can be some inhomogeneous in the structure. The PUF in the test beams was glued to the face sheets. This glue can also become inhomogeneous when solidification. This inhomogeneity can affect the experiment results. In vibration measurement applications, the weight of transducers is very important and can also affect the measurement quality. The transducer weight may have affected the results of low weight sandwich materials in the experimental study of this research.

CONCLUSION

Sandwich structures have very wide range of use in engineering applications from automotive industry, civil engineering, aerospace to watercrafts etc. [11]. These structures can be exposed to different dynamic loads in working conditions so performing detailed dynamic analysis for working conditions is very important for taking necessary precautions for system performance. In this study, firstly, free vibration analysis of a uniform steel beam with 12 mm thickness, 25 mm width and 850 mm length was performed. The experimental modal analysis results have been verified with the results calculated by using analytical and numerical approaches. It has been observed that the natural frequencies of the uniform AISI 1040 steel beam obtained by using experimental, numerical and analytical methods are quite close together. Then different thicknesses PUF reinforced beams were produced by gluing the PUF to the aluminum face sheet materials as one type Al-PUF-Al sandwich beam and the other type Al-PUF layered beam and the dynamic analyzes were performed for each thicknesses for both types. According to the results, for Al-PUF-Al sandwich beams for all three modes, the natural frequencies are inclined to decrease from the 40 mm PUF reinforcement thickness when increasing from 10 mm to 40 mm reinforcement thickness. For this sandwich type, the maximum damping ratio is detected for the first mode at 10 mm reinforcement thickness, for the second and third modes at 50 mm. For Al-PUF layered beams for all three modes, the natural frequencies are inclined to increase for the PUF reinforcement thickness from 10 mm to 50 mm. Also, for this layered type, the maximum damping ratio is detected for the first mode at 10 mm reinforcement thickness, for the second and third modes at 40 mm. The study of the authors is continuing on the subject.

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