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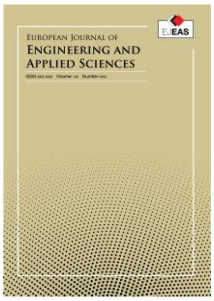

Research Article

Experimental Study on the Energy Absorption Behavior of Syntactic Foam-Filled Thin-Walled Tubes

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Abstract: Thin-walled profiles with different core structures have been utilized to obtain lightweight energy absorbers. In this paper, syntactic foams introduced aluminum tubes. Syntactic foams are composed of epoxy resin and expanded glass granules. The energy absorption behavior of empty tubes and syntactic foam-filled tubes are studied through quasi-static axial compression tests. The effects of the interaction between the tube and the foam on the deformation mode are analyzed in the aspect of several parameters such as specific energy absorption, energy absorption effectiveness, initial peak load, and average load. It is found that the addition of syntactic foam to the aluminum tube increases the specific absorbed energy by 42 %.

Keywords: *Aluminum tube, Crashworthiness, Expanded glass, Syntactic foam*

Boşluklu Köpük Dolgulu Ince Duvarlı Tüplerin Enerji Absorpsiyon Davranışı Üzerine Deneysel Çalışma

Öz: Hafif enerji emiciler elde etmek için farklı çekirdek yapılarına sahip ince cidarlı profiller değerlendirilmektedir. Bu çalışmada, boşluklu köpükler alüminyum tüplere doldurulmuştur. Boşluklu köpükler, epoksi reçine ve genleştirilmiş camdan oluşturulmuştur. Boş tüplerin ve boşluklu köpük dolgulu tüplerin enerji absorpsiyon davranışı, statik eksenel sıkıştırma testi ile araştırılmıştır. Tüp ve köpük arasındaki etkileşim ve bunun deformasyon modu üzerindeki etkisi araştırılmıştır. Spesifik enerji absorpsiyonu, enerji absorpsiyon etkinliği, ilk tepe yük, ortalama yük gibi çeşitli parametreler karşılaştırılmıştır. Geliştirilen boşluklu köpüğün aluminyum boruya ilavesi spesifik enerji absorpsiyonunda %42 iyileştirme sağlamıştır.

Anahtar Kelimeler::*Alüminyum boru, Boşluklu köpük, Çarpışmaya Dayanıklılık, Genleştirilmiş cam*

1. Introduction

Energy absorption is a significant phenomenon for saving the life of passengers during crashes. Kinetic energy during a crash should be dissipated via plastic deformation, fracture, friction, etc. In this regard, thin-walled structures like tubes are commonly used to absorb energy [1].

To improve the energy absorption capacity of thin-walled structures, different kinds of foam such as metallic foams [2-12], polymeric foams [13-17], syntactic foams [18-22], and aluminum honeycombs [23, 24] are introduced to the thin-walled structures without meaningful increase in total weight. In addition to foam filling, the interaction between the foam and the tube wall has a positive effect to improve the energy absorption capacity. Total energy absorption capacity is greater than the sum of the energy absorption capacities of the tube and the foam alone due to the interaction effect [13, 17]. Yalcin and Genel [13] considered two polymeric foam-filled Aluminum tube specimen configurations including uniform and radially-graded density foam to show the interaction effect. The axial crushing test results revealed that radially-graded foam filling improves the energy absorption capacity

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due to the squeezed foam between inward parts of the folds. Toksoy and Guden [17] noted the same phenomenon and pointed out that the deformation of the filler between folds exceeds the plateau stress of the foam.

To dissipate more kinetic energy by expanding the plastic deformation zone without losing weight efficiency, tubes filled with honeycomb structures [23, 24]. Zhang et al. [24] used six different honeycomb structures between two circular tubes. It was shown that the kagome core gave the best energy absorption. Zarei and Kröger [23] used a multi-design optimization technique to maximize the energy absorption capacity with less weight for the honeycomb core tubes. It was found that the same energy as that of the empty tube has been absorbed by the filled tube with a 14% reduction in weight.

To improve the energy absorption capacity and specific energy absorption (SEA) different aluminum foam cores were considered [2, 3, 10, 11, 20, 21]. Song et al. [2] used bio-inspired foam cores in aluminum and carbon-reinforced polymer tubes. Holes were introduced to the foams inspired by cornstalk. Dynamic and quasi-static tests were conducted. According to test results, specimens with holes improved the SEA values as compared to filled tubes. A similar study was performed by Li et al. [21]. They also used double circular and square tubes including aluminum foam. Dimensions of the inner tube were found to have a significant effect on the structural crashworthiness. The ex-situ ordered aluminum cellular structure is used as a foam material in the study of Wang et al. [10]. Altin et al. [3] investigated the effect of foam fill ratio on the energy absorption performance of the aluminum foam-filled circular tubes. Alumina hollow spheres were dispersed inside the aluminum to obtain syntactic foam, and thin-walled aluminum tubes were prepared by inserting these foams into empty tubes [20]. During axial compression, foam-filled tubes were deformed by concertina mode, which was different from the diamond mode of tubes and the brittle deformation characteristic of the foam. Interaction between foam and the tube increased with deformation, and syntactic foam-filled one gave higher SEA values.

Axially [8, 12, 15] and radially [13] graded foams were also evaluated to explore interaction effect and thus energy absorption capacity. It was found that functionally graded foam-filled tubes enhance the SEA more than the uniform-filled tubes [8, 12, 15]. This effect can be explained by the rising in the plateau stress of the functionally graded foams, which comes from the higher plastic energy damping in layers of graded structures [12]. Cui et al. [15] proposed a functionally graded foam model, including density gradient functions such as logarithmic, square root, linear, quadratic, and cubic through-thickness direction. It was shown that convex gradients perform better than concave gradients in terms of SEA, the performance of these foams can be enhanced by increasing the density difference.

To develop lightweight energy-absorbing structures, aluminum tubes were filled with syntactic epoxy foams [22]. Higuchi et al. [22] used acrylonitrile copolymer micro-balloons with epoxy resin to fill the aluminum tubes. According to the static and dynamic test results, the structure developed led to higher energy absorption capacity. Zhang et al. [18] developed low-cost syntactic foams using fly ash cenospheres in the rigid polyurethane foams. It is found that when the relative density is below 0.29 the cenosphere size marginally affects the compression response.

In the light of previous studies such as [23], circular tubes outperformed as compared to the square and rectangular tubes concerning energy absorption capacity. Thus, circular aluminum tubes were considered in the study. The expanded glasses were introduced to the epoxy matrix as a core material. Aluminum tubes were filled with the developed syntactic foam.

2. Materials and Manufacturing

Syntactic epoxy foams are composed of expanded glass particles and an epoxy binder. Expanded glasses are a white inorganic material made from recycled glass, in the form of small porous spheres [25]. Thanks to its porous structure, it can be used to manufacture lightweight syntactic foam cores. Epoxy resin system MGS R285/H285 was preferred as the matrix material for binding expanded glasses. The properties and the sizes of the expanded glasses and epoxy resin are given in Table 1. Syntactic foam samples were manufactured through mechanical mixing. Firstly, resin and its hardener are mixed at a ratio of 100/40 by weight for five minutes. The expanded glasses were added to the mixture of resin system and mixed gently until ensuring homogeneity. A conventional turning machine was used to prepare samples to their final dimensions after demolding. The samples included expanded glasses with a mass fraction of 56%. The foam material had an 18 mm outer diameter and 25 mm height. The aluminum tube had a 20 mm outer diameter, 1 mm thickness, and 25 mm height. The mechanical properties of the aluminum material (6060-T6) are given in Table 2. Three samples were produced for each configuration. Samples manufactured are shown in Figure 1 with their designations. SF, BT, and FFT correspond to syntactic foam, base tube, and foam-filled tube, respectively.

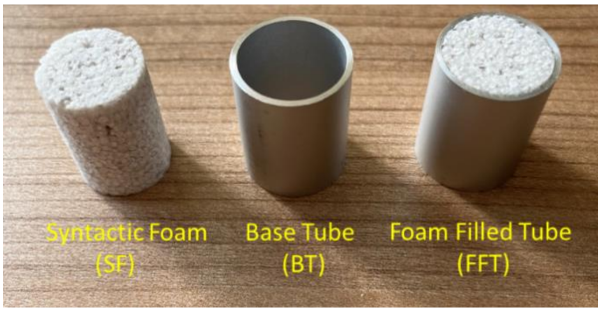


Figure 1. *Samples manufactured*

3. Results and Discussions

Figure 2 shows the load-displacement curves and crushing behavior of the base tube, the syntactic foam, and the foam-filled tube under the quasi-static compression test. The total compression displacement was 20 mm but the values considered were up to the compaction region. There are three stages in the curves for all samples; linear region, plateau region, and densification (compaction) region. The images were captured at the beginning of the initial failure (a, d, g), at the plateau region (b, e, h), and around 16 mm (c, f, l). Buckling of the tube wall initiated the deformation of the base tube (d). The collapse mode of the base tube was diamond mode (non-symmetrical deformation), which related to diameter over thickness ratio.

Table 1 Mechanical and physical properties of the resin system and the expanded glass.

Cured resin (MGS R285/H285) [26]	
Properties	Values
Tensile strength, (MPa)	70-80
Compressive strength (MPa)	120–140
Elastic modulus, (GPa)	3.2
Poisson's ratio	0.36
Shear modulus (GPa)	1.18
Density (g/cm3)	1.20
Expanded glass [25]	
Density (kg/m^3)	230
Crush strength (MPa)	1.5-2.5
Particle size (mm)	1-2

Table 2 Mechanical and physical properties of the aluminum tube material.

Properties	Values
Yield strength, (MPa)	195
Tensile strength, (MPa)	230
Elastic modulus, (GPa)	69
Poisson's ratio	0.33
Percent elongation at break%	12

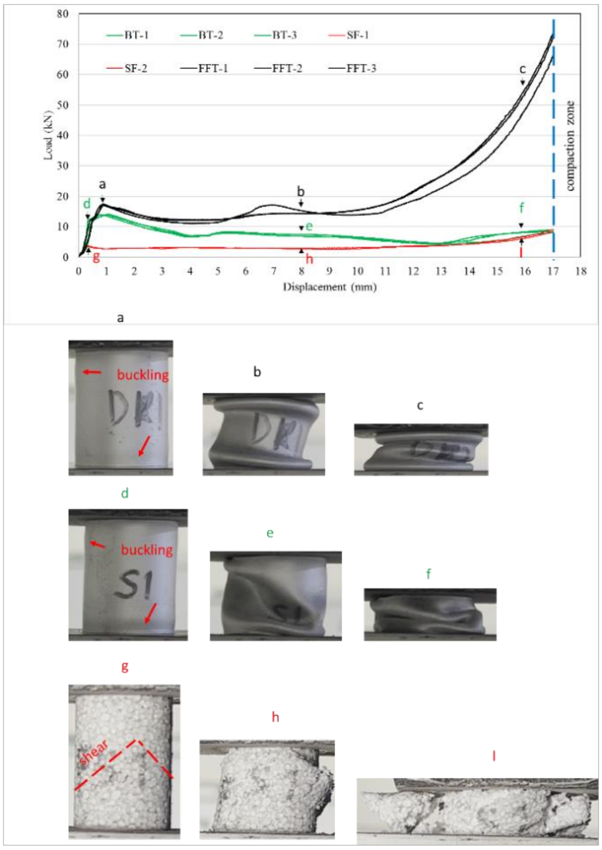


Figure 2. Load-displacement curves under a compression test

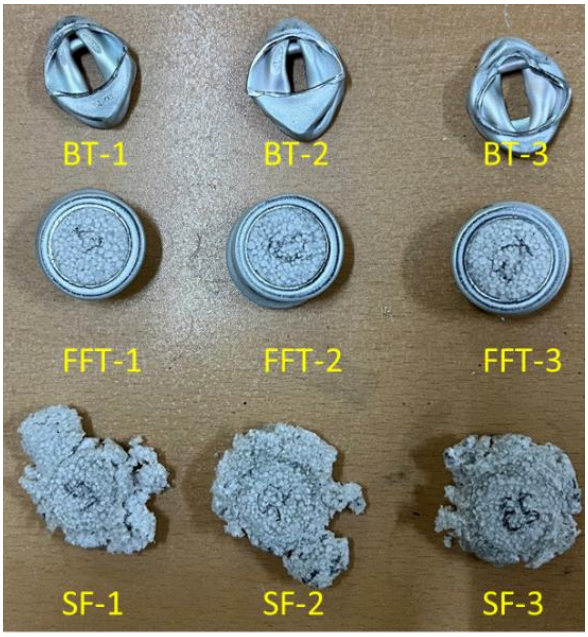


Figure 3. The top view of the samples after the tests

The collapse mode of the diamond changed to ring/concertina mode (b, c) as the syntactic foam was introduced to the base tube as shown in Figure 2. Shear deformation is the failure initiation in the syntactic foams (g). Then the collapse continues with the separation of material from the sample (h, l). The collapse modes can be seen in Figure 3, which is captured after tests from the top view. Diamond mode for base tube, ring mode for foam-filled tube, and material separation can be also seen in Figure 3. Tube confined the foam material to prevent separation in foam-filled tube configuration. The initial peak load value of FFT samples was higher than the base tube but the difference between the initial peak load value and the average plateau load is lower than the base tube, which is preferable.

To show the interaction effect between the foam and the base material, the sum of load values of the base tube and the syntactic foam was compared to the foam-filled tube. There was a difference in the energy absorption capacity between the foam-filled tube, and the sum of the base tube and syntactic foam, which is shown in Figure 4 in yellow color.

The foam-filled tube had a higher energy absorption capacity (EAC) than the sum of the base tube and the syntactic foam, which is an indication of the interaction effect between the tube wall and the foam. The yellow region starts from compression of 3 mm. Up to 3 mm, the crushing of expanded glasses occurs, after that point expansion of the foam constraint by the tube wall and absorbed energy increases. It should be noted that the load value exceeds the initial peak value for FFT samples after 11 mm. Most of the absorbed energy occurred after this compression value.

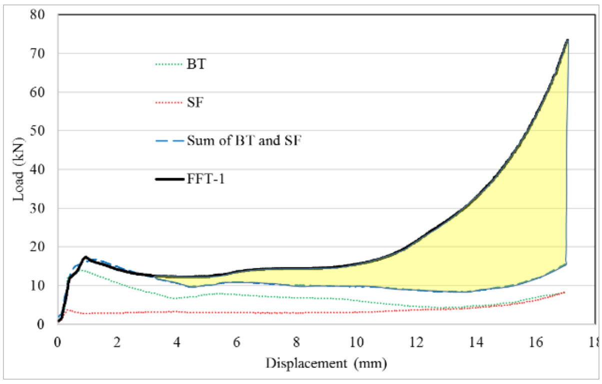
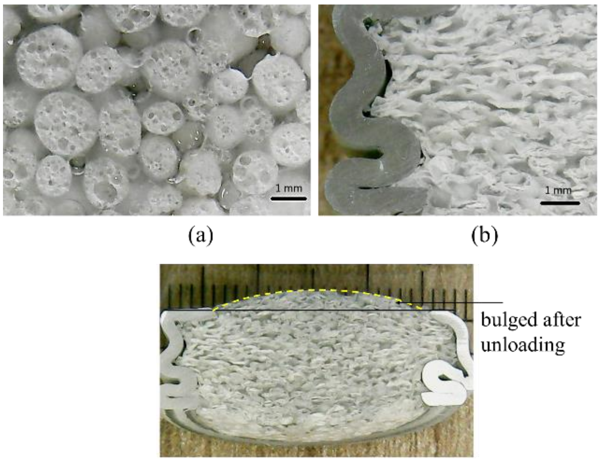


Figure 4. *Interaction effect between foam material and the tube wall*

To observe the shape of the deformation, samples were cut and polished. Micrographs were captured from the cross-section of the samples, as shown in Figure 5. The microvoids inside the expanded glasses and macro voids between the expanded glasses can be seen in Figure 1a, which was captured before testing. Micrographs captured after testing show that spheres were crushed and elongated. It is also observed that foam material is confined in fold clearance (Figure 5b). There was bulging at the top of the samples after unloading due to elastic recovery of the epoxy material.



(a) (b)

(c)

Figure 5. *Micrograph views of the samples (a) before the compression test, (b) after the compression test, and (c) elastic recovery*

Figure 6 shows specific absorbed energy and absorbed energy values. The addition of syntactic foam in the aluminium tube enhanced the specific absorbed energy (SAE) by 42 % and absorbed energy (AE) by 188 %.

4. Conclusion

To improve the energy absorption capacity and specific energy absorption a syntactic foam was developed using an epoxy resin system and expanded glasses. The samples produced included expanded glasses of 56% mass fraction. There was a difference in the energy absorption capacity between the foam-filled tube and the sum of the base tube and the syntactic foam.

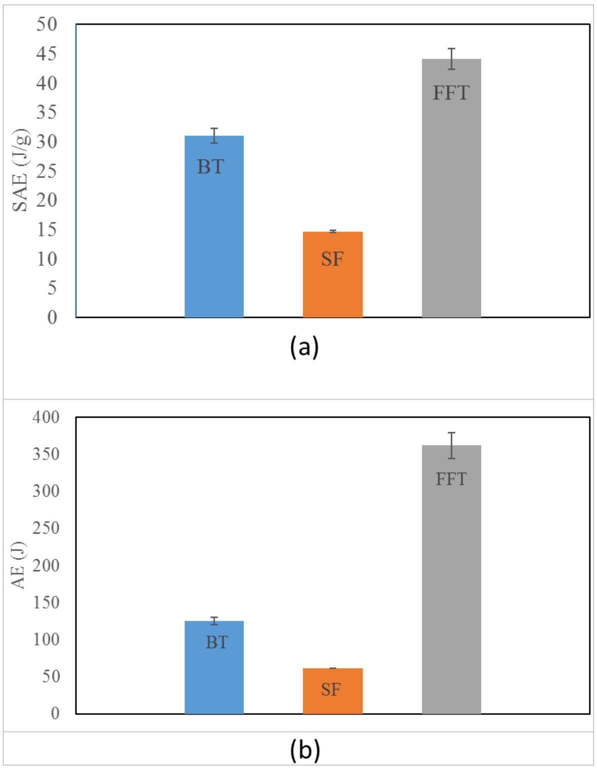


Figure 6. *Comparison of (a) specific absorbed energy and (b) absorbed energy*

The foam-filled tube had a higher energy absorption capacity (EAC) than the sum of the base tube and the syntactic foam, which is an indication of the interaction effect between the tube wall and the foam. Tube confined the foam material to prevent separation in foam-filled tube configuration. As a result, the addition of the syntactic foam to the aluminum tube enhanced the specific absorbed energy by 42 %.

Author Contrubition

Data curation – Kenan Çınar (KÇ); Formal analysis - KÇ; investigation - KÇ; Experimental Performance - KÇ; Data Collection - KÇ;, Processing - KÇ; Literature review - KÇ; Writing - KÇ; review and editing - KÇ.

Declaration of Competing Interest

The authors declared no conflicts of interest with respect to the research, authorship, and/or publication of this article.

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