Kovove Mater. 63 2025 147–156
DOI: 10.31577/km.2025.3.147

Flexural properties and failure modes of foam core sandwich beams reinforced by glass fiber laminates under quasi-static and dynamic loads

Sadegh Soltani[1], Hamed Deilami Azodi[2]*

[1] *Department of Mechanical Engineering, Arak University of Technology, Arak, Iran*
[2] *Faculty of Mechanical Engineering, Tarbiat Modares University, Tehran, Iran*

Received 19 February 2025, received in revised form 6 May 2025, accepted 9 May 2025

Abstract

Sandwich beams are widely utilized in numerous industries due to their substantial flexural strength-to-weight ratio and ability to absorb significant energy. This paper examines the deformation and failure of aluminum foam core sandwich beams subjected to quasi-static and dynamic bending loads. The sandwich beams are constructed with an exterior made of aluminum skin layers and an internal aluminum foam core, further strengthened by adding E-glass fiber laminates. The deformation behavior of foam core sandwich beams reinforced with E-glass fiber laminates has been experimentally compared to that of sandwich beams without E-glass fiber reinforcement. A uniaxial compression test determines the mechanical properties of aluminum foam used as a core. Flexural tests are performed on foam core sandwich specimens with three-point bending. Load-displacement behavior, failure modes, and energy absorption of two types of foam core sandwich beams are investigated, and the effect of reinforcing sandwich beams with glass fiber laminates is studied. Experiments show that adding glass fiber laminates significantly enhances the load-carrying capability of the foam core sandwich beams under both quasi-static and dynamic conditions. However, the sandwich beams reinforced with glass fibers exhibit earlier collapse than those without glass fiber. Glass fiber-reinforced foam core sandwich beams exhibit a substantial increase in energy absorption per unit mass compared to identical foam core sandwich beams without glass fiber reinforcement.

K e y w o r d s: foam core sandwich beam, aluminum foam, glass fiber, three-point bending, flexural properties, energy absorption capacity

1. Introduction

Sandwich panel structures are used extensively in various engineering applications due to their superior properties, such as high load resistance, stiffness, and significant energy absorption capacity [1–6]. Sandwich panel constructions are particularly popular in the aerospace [7, 8], shipbuilding [9, 10], and transportation [7, 8] industries. These constructions are held together by a thick, soft core that is sandwiched between two stiff, thin face sheets. The face sheets are fabricated from high-strength alloys or fiber-reinforced composite laminates. The center can be composed of lightweight components like foam [11]. In recent days, metal foams have proven to be a promising alternative for optimized sandwich cores. This is because metal foams can surpass some constraints that are common to ubiquitous core architectures and materials for industrial applications, such as honeycomb and polymer foams [12]. Because foam cores are very flexible in comparison to the face sheets, this might result in divergent behavior patterns in the top and bottom face sheets. This contrasts with the sandwich structure, which has a far more rigid core [13].

Extensive research has been conducted over the course of the last several decades on sandwich beams with foam core subjected to quasi-static bending, analyzing the deformation and failure behaviors. Experi-

*Corresponding author: e-mail address: hdazodi@arakut.ac.ir

ments with three-point and four-point bending have indicated that the primary initial failure modes of foam core sandwich beams are face yielding, face wrinkling, core shear, and indentation [14–16]. Sandwich beams may fail due to various causes based on the geometry of the beam and the relative strength of the face sheets and the core [14]. Either static stress or impact loading can cause the failure of sandwich beams.

As a result, initial failure loads for various failure types of foam core sandwich beams have been determined using analytical models. Failure modes are comparable to composite sandwich beams when subjected to quasi-static bending stress, and failure models related to those failure modes have been created for composite sandwich beams. Foam core sandwich beams used in industries are exposed to a variety of loads, including dynamic loads and quasi-static loads, in addition to static loads. Consequently, several researchers have investigated the dynamic bending characteristics of metal and composite sandwich beams. Qin et al. [17, 18] predicted the deformation, deflection, and impact load of metal sandwich beams composed of metal foam cores and corrugated plate cores theoretically.

Nowadays, researchers have focused more on different shapes and materials in the structure of sandwich beam cores to reduce defects. Dariushi et al. [19] experimentally examined a new class of sandwich beams with fiberglass sheet metal (FML) surfaces in three-point bending. They were evaluated alongside sandwich beams with features like those of fiber composite faces. Polyurethane (PU) foams and ethylene vinyl acetate (EVA) cores were utilized to evaluate the influence of core type on the flexural behavior of the material. The findings revealed that FMLs had a high durability to transverse local loads and decreased the stress concentration and local deformation of the skin and core below the loading tip. In addition, the results showed that FMLs exhibit a significant degree of resistance against local transverse stresses. Formisano et al. [20] stated that a research challenge in the field of foam structures is to improve the mechanical properties of these structures with a reinforced approach that does not compromise their lightness. So, in research, they made reinforced aluminum foam samples without significantly increasing their initial weight. They fabricated cylindrical specimens with a core of closed-cell aluminum foam and skin of fabrics and grids of different materials in a one-step process and investigated their mechanical behavior.

Another thing to mention about the research challenge is that it entails enhancing the mechanical characteristics of foam-based structures by using a reinforced technique that does not compromise the lightweight of the structures. Using aluminum foam can reduce weight and increase the compressive and flexural strength of production samples.

Several studies focus on the special features, such as bending features, of a distinct class of sandwich panels known as hybrid sandwich beams, in which the upper and lower face sheet is fiber-reinforced composite, and the core is made of foam. The influence of core thickness on quasi-static three-point bending of sandwich panels with glass-fiber reinforced composite faces, and core made of aluminum foam, was studied by Styles et al. [21]. Reyes examined the static and low-velocity impact response of hybrid sandwich beams experimentally and theoretically [22]. These hybrid sandwich beams included glass-fiber reinforced composite faces and an aluminum foam core. Under quasi-static three-point bending, Sun et al. [23] investigated the influence of interfacial behavior of a special class of hybrid sandwich beams, with carbon-fiber/epoxy composite face sheets and an aluminum foam core.

In general, aluminum foam sandwich panels, due to their low density, high strength, and extraordinary hardness, have a coating of composite materials such as carbon fibers and are used in several engineering fields [24, 25]. But due to low surface roughness and cracking at low forces, it sometimes does not bring good results [26]. Lightweight metal alloys may also show problems with core-shell bonding methods, leading to premature damage and detachment of sandwich panel components [27, 28]. Factors affecting the main failure conditions of foam composite structures include the adhesive cured, the thickness of the panel, the presence of glass fibers, and the mass of the adhesive, which increase [29, 30]. Because the strength of the layer is sufficient for the composite structure (the amount of epoxy resin should not be excessive for the sample's weight reduction), the glass fiber types and epoxy resin amount do not affect the bending strength; the low porosity aluminum foam is preferred [29]. Guo and Zhang [31] developed a new energy-absorbing mode of a metal foam-filled sandwich circular tube (MFSC-Tube) that is expanded by a conical-cylindrical die to improve the load-carrying and energy-absorbing capacity of the energy-absorbing structure. They developed an analytical model of the MFSC-Tube expanding under axial compression, considering the effects of bending, stretching, and the hardening of the inner and outer tubes, as well as the compression of the metal foam core. Yan et al. [32] investigated the failure behavior of metal foam sandwich plates subjected to cutting loads applied by a wedge-shaped indenter using analytical, experimental, and numerical approaches. They concluded that the tip angle of the wedge-shaped indenter significantly impacts the cutting load and energy absorption of the sandwich plate. Wu et al. [33] proposed an efficient energy absorber comprising a biomimetic foam-filled diameter-gradient tube with internal and external gradient induction grooves (FD-

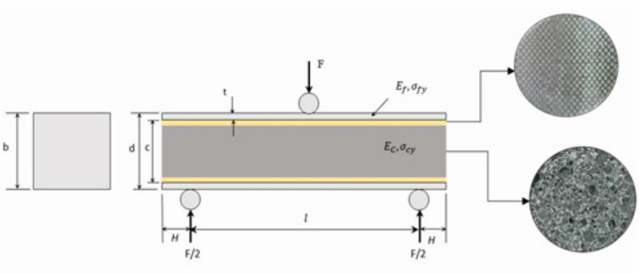

Fig. 1. Elements of the sandwich beam and schematic view of the beam under quasi-static and dynamic three-point bending test.

-GIG tube). Experiments involving axial compression were conducted on FD-GIG tubes filled with uniform-density foam. The analytical and numerical study was conducted on the axial crushing behavior of FD-GIG tubes filled with density gradient foam.

This study aims to examine the deformation and failure of foam core sandwich beams reinforced with glass fibers under quasi-static and dynamic loads. The uniaxial compression test is used to determine the mechanical characteristics of aluminum foam. Three-point quasi-static and dynamic bending tests are conducted on foam core sandwich beams reinforced with glass fiber and sandwich beams without glass fiber. Load-displacement behavior, failure modes, energy absorption capability, and specific energy absorption of two types of foam core sandwich beams are investigated. Previous studies in the literature review have mainly focused on foam cores or composite face plates independently, whereas this research uniquely provides a direct comparative analysis between reinforced and unreinforced sandwich beams fabricated under identical conditions. Furthermore, the study elucidates the effect of glass fiber reinforcement on altering the deformation and failure modes, specifically highlighting the emergence of face wrinkling and modified bond failure patterns, which were not extensively reported in the literature.

2. Experimental procedure

2.1. Materials

Sandwich beams consist of the upper and lower face sheets, the aluminum foam as the core, and glass fiber laminates as reinforcement layers (Fig. 1). Aluminum alloy AA3105 sheets with a thickness of 0.5 mm were used as skin layers in sandwich beams. Mechanical properties of the face sheets are listed in Table 1. The aluminum foam was produced using the Alporas method using aluminum alloy LM13. Calcium metal and $CaCO_3$ were used as stabilizing and foaming agents, respectively. LM13 aluminum alloy closed-cell foam was used as the core in the sandwich beams. The pore size distribution was measured on 250 pits with a standard deviation of 0.96 mm, as can be observed in Fig. 2. The average pore size in

Table 1. Mechanical properties of the face sheet and the foam core [34, 38]

Face sheet	
Young's modulus, E_f (GPa)	70
Yield strength, σ_{yf} (MPa)	152
Density (kg m^{-3})	2700
Poisson's ratio	0.33
Foam core	
Density (g cm^{-3})	0.64
Relative density	0.18
Young's modulus, E_c (GPa)	76
Compressive strength, σ_{cy} (MPa)	11
Shear strength, τ_{cy} (MPa)	4.7
Densification strain, ε_D	0.51
Average cell size (mm)	0.25

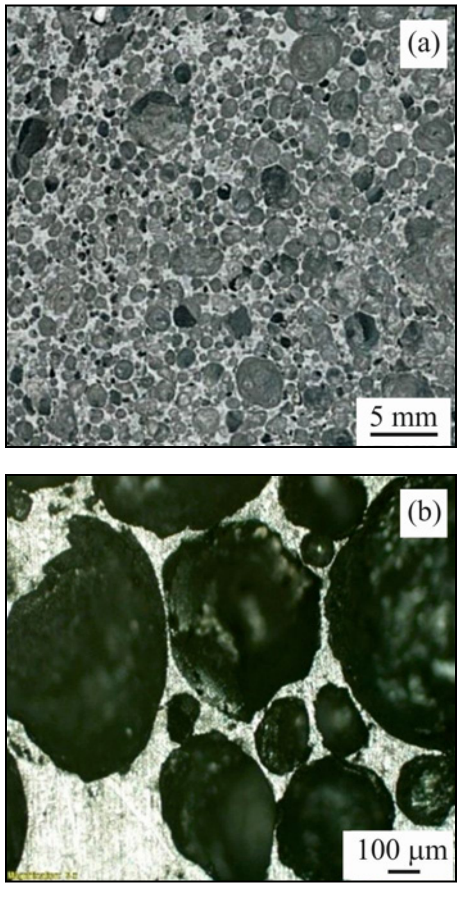

Fig. 2. Structure of LM13 aluminum foam with 1.5 wt.% $CaCO_3$.

Table 2. Properties of the E-glass fiber and epoxy resin at 23 ℃ [35, 37]

E-glass	
Elastic modulus, E (GPa)	72.3
Density, ρ (g cm^{-3})	2.58
Tensile strength (GPa)	3.445
Elongation (%)	4.8
Epoxy resin	
Yield strength, σ	55–130
Elastic modulus, E (GPa)	2.75–4.10
Density, ρ (g/cm^{-3})	1.2–1.3

LM13 foam specimens with 1.5 wt.% $CaCO_3$ foaming agent is 0.26 mm [34]. Mechanical properties of the aluminum foam are given in Table 1.

The selected material for the specimen is a Glass Fiber Roving/Epoxy Polymer (GFRP) composite. This material has been chosen for its cost-effectiveness in manufacturing and its ability to enhance impact resistance. Additionally, its transparency facilitates the visual inspection of any damage. E-glass fiber, a commonly utilized type of GFRP, is composed of aluminoborosilicate glass with less than 1 % alkali oxides. To investigate the effect of E-glass fiber reinforcement in foam core sandwich beams, two 0.2 mm-thick E-glass fibers were used as intermediate layers between aluminum skins and foam core [35, 36]. The properties of the E-glass fiber are presented in Table 2.

The layers of the beam were adhered with epoxy resin. The chemical composition of the epoxy prepolymer and the curing agent significantly influences the properties of the cured epoxy resin, allowing for substantial modifications. Epoxy systems outperform polyesters, particularly in adhesion properties with a wide range of fibers and in resistance to moisture and chemicals [37]. The properties of the cast epoxy resin at 23 ℃ are presented in Table 2.

Quasi-static compression tests were performed to find out the mechanical properties of aluminum foams using the STM-250 testing machine. Sandwich structures were also subjected to quasi-static and dynamic three-point bending tests. The specimens intended for the test are 100 mm in length and 50 mm in width. Foam cores with dimensions of 100 × 50 × 15 mm^3 were considered. The foam density can greatly affect the results, so foams with almost the same densities were used in test samples. There are two types of samples: (i) sandwich beams reinforced with E-glass fiber laminates (GF) and (ii) sandwich beams without E-glass fiber (F). Table 1 lists the mechanical parameters of the face sheet and core.

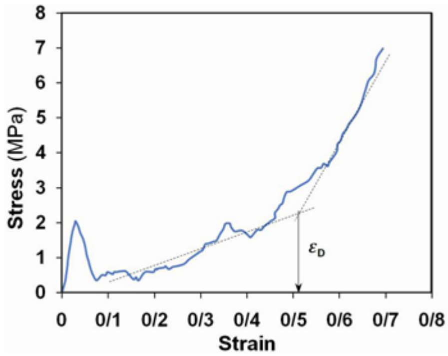

Fig. 3. Stress-strain curve of foamed aluminum under uniaxial compression.

Fig. 4. Foam core sandwich beam under three-point bending test.

2.2. Uniaxial compression test

The quasi-static uniaxial compression test was performed on a sample of cubic foams with dimensions of 25 × 25 × 25 mm^3 using an STM-250 test machine. The force was applied uniaxially at a rate of 0.5 mm min^{-1}.

Three samples of foam were tested for repeatability of results, and the average of the obtained results was reported. The compression test for each specimen was stopped when it reached 70 % strain. Figure 3 illustrates the compressive stress-strain curve of LM13 aluminum foam with 1.5 wt.% $CaCO_3$ foaming agent. Properties of the aluminum foam are given in Table 1.

2.3. Three-point bending test

The flexural test is accomplished using a bending technique involving three points of contact (Fig. 1). The specimen was placed on two roller supports. The load was applied at mid-span through a cylindrical applicator (Fig. 4). The span of the supports was determined to be 80 mm. Diameters of the cylindrical applicator and the supporting rollers were 10 mm. For quasi-static tests, the displacement rate was set at

0.5 mm min^{-1}, ensuring that the structural response primarily reflected static behavior with minimal influence from inertia and strain-rate sensitivity. Conversely, for dynamic tests, a higher displacement rate of 10 mm min^{-1} was applied to capture the material's response under conditions where inertia effects and strain-rate sensitivity become significant. These loading rates were chosen based on standard practices and prior studies in the field to effectively evaluate the mechanical properties of panels across different loading scenarios.

3. Results and discussion

3.1. Compressive strength of aluminum foam

Figure 3 shows the compressive stress-strain curve of LM13 foam with a density of 0.64 g cm^{-3}. As illustrated in this figure, the stress-strain curve for a cellular material such as metal foam exhibits three distinct regions: the elastic deformation region (initial linear behavior at low strains), the plastic deformation region (nearly constant stress despite increasing strain, characterized by progressive pore collapse) and the densification region (marked by a sharp, non-linear increase in stress as pores are fully collapsed and solid material starts to carry the load). The density, relative density, and average cell size of LM13 aluminum foam can be seen in Table 1.

The elastic region at low stresses and strains is followed by a prolonged stress-strain in which the stress in the sample under pressure reaches a steady state, and plastic deformation occurs. The plastic region begins with the first peak, which is accompanied by the collapse of the wall of the pores, where the stress changes are relatively small, and the strain increases. With the collapse of the walls and the destruction of the pores, the densification region begins, accompanied by a sudden increase in stress and relatively low strain changes [34]. Decomposition in the foam gradually spreads to all walls. The energy absorption of metal foam is almost efficient until the strain of compaction and crushing of aluminum foam begins when the strain increases more than the strain of densification. In this study, the strain at the onset of the densification (ε_D) was determined at the transition point where the stress starts to rise steeply after the plateau region, corresponding to the closure of most pores. The average density, relative density, and porosity of all samples were calculated using Eqs. (1)–(3):

$$P\rho = M/V, \tag{1}$$

$$\rho_{rel} = \rho^*/\rho_s, \tag{2}$$

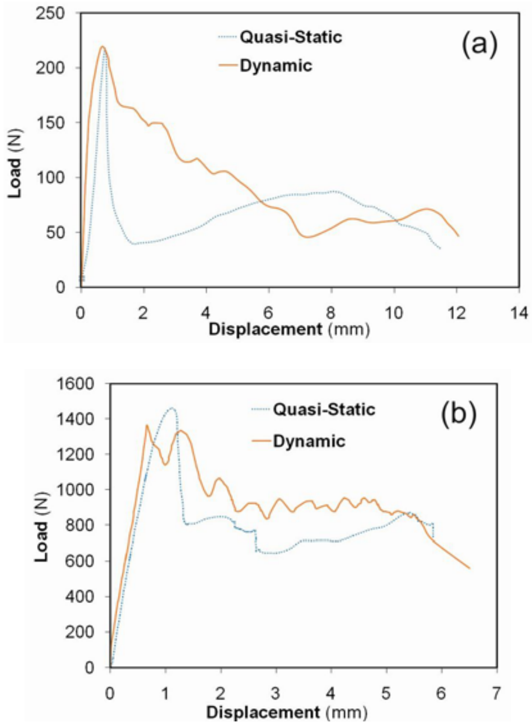

Fig. 5. Force-displacement curves of (a) non-glass fiber sandwich beams (F) and (b) E-glass fiber-reinforced sandwich beams (GF).

$$\phi = \frac{(\rho_s - \rho)}{\rho_s} \times 100, \tag{3}$$

where V is the volume of the sample (mm^3), M is the weight of the specimen (g), ρ is the sample density (g cm^{-3}), ρ_s is the density of the base material, and ρ_{rel} is the relative density.

3.2. Load-displacement curves

Figure 5 depicts a load-displacement curve that is common for dynamic and quasi-static three-point bending tests of sandwich beams. As shown in this figure, the load-carrying capacity curves of sandwich beam structures subjected to dynamic and quasi-static three-point bending are typically the same. However, the differences observed between the dynamic and quasi-static force-displacement curves in Fig. 5 can be attributed to several reasons, including strain rate sensitivity, inertia effect, energy absorption mechanism, and crack propagation behavior affected by loading rate. The results shown in Fig. 5 indicate that the load-carrying capability of the sandwich beam construction is greatly improved by the addition of glass fiber. The load-carrying capacity of foam core sandwich beams without glass fiber is the lowest. In contrast, the load-carrying capacity of sam-

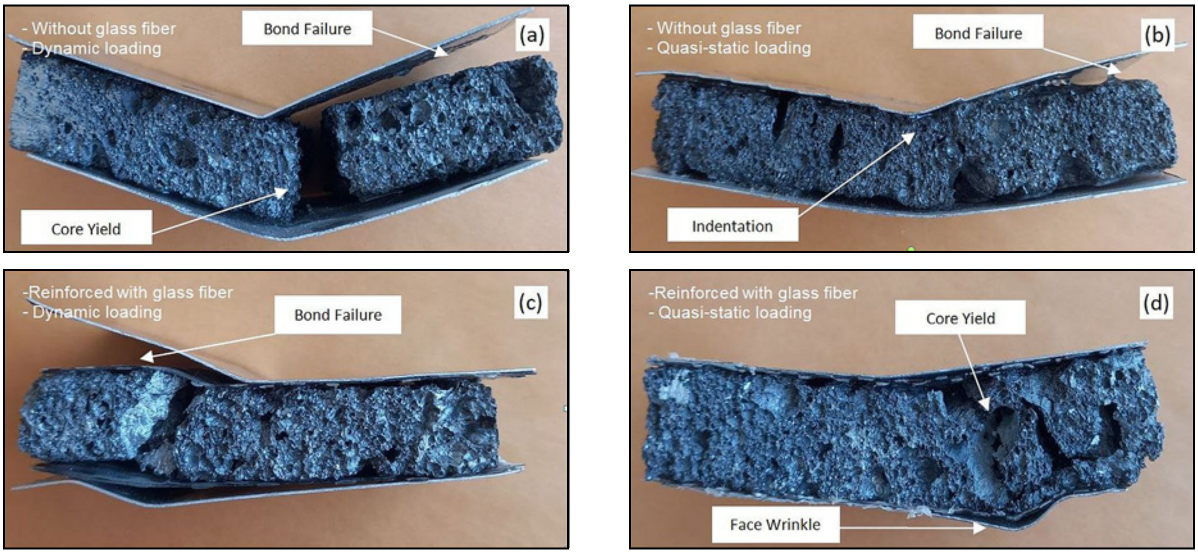

Fig. 6. Failure mode observed in foam core sandwich beams without glass fiber (a), (b) and reinforced with glass fiber (c), (d) under dynamic (a), (c) and quasi-static (b), (d) loading.

ples reinforced with glass fiber is greater, and this holds true for both quasi-static and dynamic tests. This demonstrates that the flexural strength of foams reinforced with glass fibers rises, and this is due to the important role of aluminum foam in enhancing the local indentation resistance. In addition, glass fibers play a very effective role in strengthening the ability to resist force. However, foam-core beams, especially beams without glass fibers as reinforcement, are damaged more quickly despite their relatively high load-carrying capacity. The load-carrying capacity of the beams reinforced with glass fibers (GF) is approximately seven times higher than that of the beams without glass fibers (F), which indicates the high energy absorption efficiency of these beams. Therefore, glass fiber reinforced beams perform much better than foam core beams without glass fibers in terms of load carrying capacity. As shown in the figure, in the curve obtained in the quasi-static loading mode, an area with a severe load drop and then a plateau can be seen, which respectively indicates the damage of the beam in the core and then the resistance of the beam and load control. Load carrying continues until the top surface sheet is completely damaged. Although this is accompanied by a gradual drop in the load in the dynamic test, it becomes almost uniform in the following, like the curve of the quasi-static state of the load. The force-displacement curves show linear behavior up to a force of 220 N for the F samples and 1400 N for the GF samples. However, after reaching the maximum load capacity and passing these limit values, the behavior of the curves changes to a non-linear phase. This transition is attributed to the initiation and propagation of shear cracks in the foam core that originate perpendicular to the loading points. Understanding the nature and mechanism of these shear cracks is crucial for the development of advanced materials with high strength and reliability, paving the way for innovations in various engineering applications that require superior structural integrity and performance.

Compared to sandwich beams without glass fibers (F), the maximum displacement in quasi-static and dynamic bending tests for sandwich beams reinforced with glass fibers (GF) was significantly reduced. The maximum displacement at which the collapse occurs is almost the same in both quasi-static and dynamic tests for each type of sandwich beam (reinforced with glass fiber and without glass fiber).

3.3. Deformation and failure modes

Four different failure modes, such as core indentation, face wrinkle, core yield, and bond failures, were identified in the three-point bending test process (Fig. 6). Bond failure mode was observed in both samples with and without glass fibers. Core indentation failure mode occurred in the samples without glass fibers, and face wrinkling was seen in specimens reinforced with glass fibers. The face wrinkle failure phenomenon, characterized by the development of wrinkles, mainly appears in the bottom face sheet of the sandwich beam and in the vicinity of the supports. This was attributed to a complex interplay of factors, including the resistance exerted by the glass fibers and the simultaneous failure of the foam core, which ultimately led to the wrinkling of the aluminum bottom sheet.

Figure 5 also illustrates the complete collapse of sandwich beams without glass fibers along a specific section below the punch axis, elucidating the inherent vulnerability of such structures. The incorporation of aluminum foam serves to extend lateral support

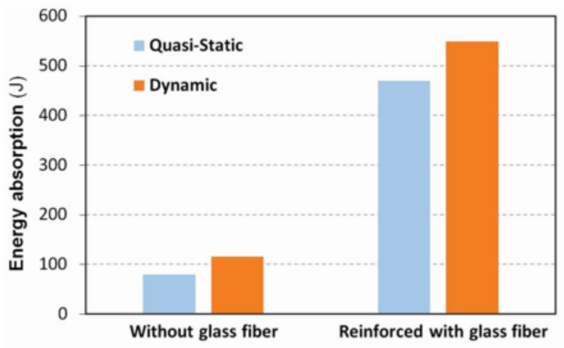

Fig. 7. Energy absorption in sandwich beams.

to the aluminum shell, thus effectively delaying shell degradation and mitigating sectional collapse of the structure, resulting in a significant increase in flexural strength. In glass fiber reinforced sandwich beams, foam collapse is confined to the region between the punch axis and the support, a phenomenon that is not observed in sandwich beams without glass fibers. Notably, the reinforcement of aluminum foam and skins by glass fibers provides a significant improvement in the flexural strength of the sandwich beam, thereby delaying damage to both beam components, especially the foam core.

Sandwich beams reinforced with glass fibers (GF) exhibit an earlier collapse compared to those without glass fiber (F). Additionally, the presence of diagonal cracks in sandwich beams reinforced with glass fiber (GF) is indicative of distinct deformation and failure modes compared to beams without glass fiber (F).

This observation underscores the notion that local buckling in glass-fiber reinforced foam sandwich beams propagates to neighboring sections, thereby influencing the structural behavior without diminishing the cross-sectional area of the beam. Consequently, sandwich beams reinforced with glass fiber are compelled to form more plastic hinge lines, thereby augmenting bending strength while maintaining the integrity of the original structure.

3.4. Energy absorption capacity

The total energy absorption, denoted by the symbol E_t, is equal to the region of the load-displacement curves that is below the failure point. This region may be characterized as:

$$E_t = \int_0^{\delta_{max}} F d\delta, \quad (4)$$

where F, δ, and δ_{max} stand for bending load, punch displacement, and the maximum displacement, respectively.

Figure 7 illustrates the total energy absorption of two different sandwich beams, which are subjected to two different loading conditions: dynamic loading and quasi-static loading. The energy absorbed by beams subjected to bending differs from 80 to roughly 550 J. It can be seen that when it is subjected to three-point bending, the sample (F) under the quasi-static test and the sample (GF) under the dynamic test have the lowest and highest amount of energy, respectively, compared to other tests for each sample. However, the aluminum foam core sandwich beam (F) shows a good energy absorption capacity, possibly due to the increased maximum displacement in this type of sandwich beams. The foam core sandwich beam reinforced with glass fibers showed a lower maximum displacement than the sandwich beam without glass fibers. Still, it showed a high bending strength, which is the main reason for increasing the energy absorption capacity in this beam. Therefore, prior to reinforcing the foam core for applications involving energy absorption, it is vital to keep in mind that any change in the failure behavior caused by the aluminum foam reinforcement can change the crushing performance of the structure. This is something that should be considered before reinforcing the sandwich beam. The foam core sandwich beam reinforced with glass fibers showed an excellent performance in energy absorption. Therefore, the high bending strength is maintained, and the retard in collapse increases the energy absorption capacity.

3.5. Specific energy absorption

In the design of structures like automobiles, aircraft, and motorcycles, where weight minimization is one of the main objectives, specific energy absorption (SEA) is one of the most important considerations during the design process. In previous research, the SEA has often been used as the design criterion for lightweight needs when referring to foam materials or foam-core constructions. The SEA is the energy absorption per unit of the crushed specimen mass and is defined as:

$$\text{SEA} = \frac{E_t}{M} = \frac{\int_0^{\delta_{max}} F d\delta}{M}, \quad (5)$$

where M is the entire structure mass.

As seen in Table 3, the total masses of the sandwich beams are almost the same. The SEAs of the two types of structures are compared in Fig. 8. Foam cores sandwich beams reinforced with glass fibers (GF) absorb the most energy through flexural failure per unit mass. In contrast, sandwich beams without glass fibers absorb less energy through failure at lower forces. The amount of energy absorbed per unit mass is different

T a b l e 3. Summary of the experimental results of quasi-static and dynamic tests

Sample	m (g)	F_{max} (kN)	δ (mm)	E (J)	SEA (J g^{-1})	Failure mode
F-Q	45	0.21	11.48	78.79	2.62	CS, BF
F-D	37	0.25	12.05	115.35	3.29	IN, BF
GF-Q	52	1.45	5.82	469.27	10.42	CS, BF
GF-D	49	1.38	6.53	549.06	43.72	CS, FW

NOTE: CS is Core shear mode, BF is Bond face, IN is Indentation mode, and FW is Face wrinkle

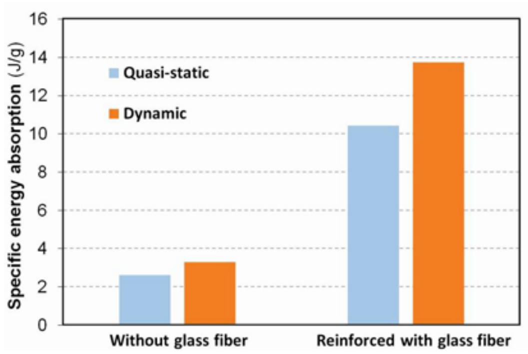

Fig. 8. Specific energy absorption in sandwich beams.

for each of the quasi-static and dynamic tests, which is evident in the structure of the foam core reinforced with glass fibers. This may be due to the increase in the surface resistance of the sample. In comparison, the energy absorption per unit mass of the beams without glass fibers is relatively the same in both quasi-static and dynamic tests. Based on the experiments, energy absorption efficiency is higher in the reinforced beam with glass fibers despite the same mass between the samples. Also, in the case of using foam reinforced with glass fibers, when it is compressed by local forces, its pores are prevented from being compressed, and the impact efficiency is reduced.

4. Conclusions

In this paper, the deformation and failure of aluminum foam core sandwich beams have been studied experimentally. The deformation behavior of foam core sandwich beams reinforced with E-glass fiber laminates and sandwich beams without E-glass fiber has been examined and compared under quasi-static and dynamic bending loads. A uniaxial compression test was conducted to determine the mechanical properties of aluminum foam used as a core. Load-displacement behavior, failure modes, energy absorption capability, and specific energy absorption of two types of foam core sandwich beams were investigated, and the effect of reinforcing sandwich beams with glass fiber was studied. The main conclusions are as follows:

– Foam core sandwich beams that have been reinforced with glass fiber laminates are able to support greater bending loads compared to those that do not include any glass fibers. The load-carrying capacity of reinforced sandwich beams increased approximately seven times compared to non-reinforced beams. However, the maximum displacement at which the collapse occurs is less in these beams, and they exhibit an earlier collapse compared to unreinforced beams. This holds true for both quasi-static and dynamic loadings.

– The maximum displacement at which the collapse occurs is almost the same in both quasi-static and dynamic loading for each type of foam core sandwich beam (reinforced with glass fiber and without glass fiber).

– Four failure modes, core indentation, face wrinkle, core yield, and bond failure, are identified in the three-point bending tests of foam core sandwich beams. Bond failure is observed in both sandwich beams with and without glass fibers, whereas face wrinkle core indentation occurs in the beams reinforced with glass fiber and beams without glass fibers, respectively.

– The foam core sandwich beams reinforced with glass fibers showed an excellent performance in energy absorption. The energy absorption capacity and the specific energy absorption of sandwich beams with glass fiber-reinforced foam core are significantly greater than those of foam core sandwich beams without glass fibers. The energy absorption of foam core sandwich beams reinforced with glass fiber laminates rose by approximately 4.8 times in dynamic loading and by around 6 times in quasi-static conditions, in comparison to sandwich beams without glass fiber reinforcement.

Acknowledgements

The authors received no financial support for the research, authorship, and/or publication of this article.

References

[1] J. R. Vinson, The Behavior of Sandwich Structures of Isotropic and Composite Materials, first ed., Routledge, New York, 1999.
https://doi.org/10.1201/9780203737101

[2] I. M. Daniel, J. L. Abot, Fabrication, testing and analysis of composite sandwich beams, Compos. Sci. Technol. 60 (2000) 2455–2463. https://doi.org/10.1016/S0266-3538(00)00039-7
[3] J. Xiong, Y. Du, D. Mousanezhad, M. Eydani Asl, J. Norato, A. Vaziri, Sandwich structures with prismatic and foam cores: A review, Adv. Eng. Mater. 21 (2019) 1800036. https://doi.org/10.1002/adem.201800036
[4] E. Rizze, E. Papa, A. Corigliano, Mechanical behavior of a syntactic foam: experiments and modeling, Int. J. Solids and Struct. 37 (2000) 5773–5794. https://doi.org/10.1016/S0020-7683(99)00264-4
[5] A. M. Harte, N. A. Fleck, M. F. Ashby, Sandwich panel design using aluminum alloy foam, Adv. Eng. Mater. 2 (2000) 219–222. https://doi.org/10.1002/(SICI)1527-2648(200004)2:4<219::AID-ADEM219>3.0.CO;2-%23
[6] H. Guo, H. Yuan, J. Zhang, D. Ruan, Review of sandwich structures under impact loadings: Experimental, numerical and theoretical analysis, Thin-Walled Struct. 196 (2024) 111541. https://doi.org/10.1016/j.tws.2023.111541
[7] P. Hung, K. Lau, L. Cheng, J. Leng, D. Hui, Impact response of hybrid carbon/glass fiber reinforced polymer composites designed for engineering applications, Compos. B: Eng. 133 (2018) 86–90. https://doi.org/10.1016/j.tws.2023.111541
[8] F. Sarasini, J. Tirillo, L. Ferrante, M. Valente, T. Valente, L. Lampani, P. Gaudenzi, S. Cioffi, S. Iannace, L. Sorrentino, Drop-weight impact behaviour of woven hybrid basalt-carbon/epoxy composites, Compos. B: Eng. 59 (2014) 204–220. https://doi.org/10.1016/j.compositesb.2013.12.006
[9] H. Adam, Carbon fiber in automotive applications, Mater. Des. 18 (1997) 349–355. https://doi.org/10.1016/S0261-3069(97)00076-9
[10] S. N. A. Safri, M. T. H. Sultan, M. Jawaid, K. Jayakrishna, Impact behaviour of hybrid composites for structural applications: A review, Compos. B: Eng. 133 (2018) 112–121. https://doi.org/10.1016/j.compositesb.2017.09.008
[11] G. Sun, X. Huo, D. Chen, Q. Li, Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression, Mater. Des. 133 (2017) 154–168. https://doi.org/10.1016/j.matdes.2017.07.057
[12] J. K. Paik, A. K. Thayamballi, G. S. Kim, The strength characteristics of aluminum honeycomb sandwich panels, Thin-Walled Struct. 35 (1999) 205–231. https://doi.org/10.1016/S0263-8231(99)00026-9
[13] M. A. Khan, A. K. Syed, H. Ijaz, R. Shah, Experimental and numerical analysis of flexural and impact behaviour of glass/pp sandwich panel for automotive structural applications, Adv. Compos. Mater. 27 (2018) 367–386. https://doi.org/10.1080/09243046.2017.1396199
[14] T. M. McCormack, R. Miller, O. Kesler, L. J. Gibson, Failure of sandwich beams with metallic foam cores, Int. J. Solids Struct. 38 (2001) 4901–20. https://doi.org/10.1016/S0020-7683(00)00327-9
[15] H. Bart-Smith, J. W. Hutchinson, A. G. Evans, Measurement and analysis of the structural performance of cellular metal sandwich construction, Int. J. Mech. Sci. 43 (2001) 1945–63. https://doi.org/10.1016/S0020-7403(00)00070-9
[16] T. Besant, G. A. O. Davies, D. Hitchings, Finite element modelling of low velocity impact of composite sandwich panels, Compos. A: Appl. Sci. Manuf. 32 (2001) 1189–1196. https://doi.org/10.1016/S1359-835X(01)00084-7
[17] Q. Qin, C. Xiang, J. Zhang, M. Wang, T. J. Wang, L. H. Poh, On low-velocity impact response of metal foam core sandwich beam: A dual beam model, Compos. Struct. 176 (2017) 1039–1049. https://doi.org/10.1016/j.compstruct.2017.06.038
[18] Q. Qin, W. Zhang, S. Liu, J. Li, J. Zhang, L. H. Poh, On dynamic response of corrugated sandwich beams with metal foam-filled folded plate core subjected to low velocity impact, Compos. A: Appl. Sci. Manuf. 114 (2018) 107–116. https://doi.org/10.1016/j.compositesa.2018.08.015
[19] S. Dariushi, M. Sadighi, A study on flexural properties of sandwich structures with fiber/metal laminate face sheets, Appl. Compos. Mater. 20 (2013) 839–855. https://doi.org/10.1007/s10443-012-9307-2
[20] A. Formisano, A. Barone, L. Carrino, D. De Fazio, A. Langella, A. Viscusi, M. Durante, Improvement of the mechanical properties of reinforced aluminum foam samples, 21st International ESAFORM Conference on Material Forming, Palermo, AIP Conference Proceedings, 1960 (2018) id. 100007. https://doi.org/10.1063/1.5034947
[21] M. Styles, P. Compston, S. Kalyanasundaram, The effect of core thickness on the flexural behaviour of aluminium foam sandwich structures, Compos. Struct. 80 (2007) 532–538. https://doi.org/10.1016/j.compstruct.2006.07.002
[22] G. Reyes, Static and low velocity impact behavior of composite sandwich panels with an aluminum foam core, J. Compos. Mater. 42 (2008)1659–1670. https://doi.org/10.1177/0021998308092216
[23] Z. Sun, X. Hu, S. Sun, H. Chen, Energy absorption enhancement in carbon-fiber aluminum-foam sandwich structures from short aramid-fiber interfacial reinforcement, Compos. Sci. Technol. 77 (2013) 14–21. https://doi.org/10.1016/j.compscitech.2013.01.016
[24] J. Banhart, H. W. Seeliger, Recent trends in aluminum foam sandwich technology, Adv. Eng. Mater. 14 (2012) 1082–1087. https://doi.org/10.1002/adem.201100333
[25] U. K. Vaidya, S. Pillay, S. Bartus, C. A. Ulven, D. T. Grow, B. Mathew, Impact and post-impact vibration response of protective metal foam composite sandwich plates, Mater. Sci. Eng. A 428 (2006) 59–66. https://doi.org/10.1016/j.msea.2006.04.114
[26] V. Crupi, R. Montanini, Aluminum foam sandwiches collapse modes under static and dynamic three-point bending, Int. J. Impact Eng. 34 (2007) 509–521. https://doi.org/10.1016/j.ijimpeng.2005.10.001
[27] H. Xi, L. Tang, J. Yu, X. Zhang, B. Xie, Y. Liu, Z. Jiang, Z. Liu, Low velocity penetration mechanical behaviors of aluminum foam sandwich plates at elevated temperature, Int. J. Struct. Stab. Dyn. 15 (2015) 1450063. https://doi.org/10.1142/S0219455414500631
[28] T. M. McCormack, R. Miller, O. Kesler, L. J. Gibson, Failure of sandwich beams with metallic foam cores, Int. J. Solids Struct. 38 (2001) 4901–4920. https://doi.org/10.1016/S0020-7683(00)00327-9

[29] N. Wang, X. Chen, A. Li, Y. Li, H. Zhang, Y. Liu, Three-point bending performance of a new aluminum foam composite structure, Trans. Nonferrous Met. Soc. China 26 (2016) 359–368. https://doi.org/10.1016/S1003-6326(16)64088-8

[30] Z. Li, Z. Zheng, J. Yu, C. Qian, F. Lu, Deformation and failure mechanisms of sandwich beams under three-point bending at elevated temperatures, Compos. Struct. 111 (2014) 285–290. https://doi.org/10.1016/j.compstruct.2014.01.005

[31] H. Gou, J. Zhang, Expansion of sandwich tubes with metal foam core under axial compression, J. Appl. Mech. 90 (2023) 051008. https://doi.org/10.1115/1.4056686

[32] H. Yuan, X. Wu, J. Zhang, Cutting failure behavior of foam core sandwich plates, Int. J. Solids Struct. 303 (2024) 113009. https://doi.org/10.1016/j.ijsolstr.2024.113009

[33] X. Wu, H. Gou, J. Zhang, Bi-surface induction in biomimetic multi-gradient foam-filled tubes with enhanced energy absorption: Theory, experiment, and simulation, J. Appl. Mech. 92 (2025) 051010. https://doi.org/10.1115/1.4068061

[34] S. Soltani, H. Deilami Azodi, S. H. Elahi, The influence of the amount of $CaCO_3$ foaming agent on the physical structure and mechanical properties of LM13 aluminum foam, Iranian Journal of Manufacturing Engineering 9 (2022) 33–39. https://doi.org/10.22034/ijme.2022.160057

[35] S. Prashanth, K. M. Subbaya, K. Nithin, S. Sachhidananda, Fiber reinforced composites – A review, J. Material Sci. Eng. 6 (2017) 2–6. https://doi.org/10.4172/2169-0022.1000341

[36] M. Zhang, J. P. Matinlinna, E-glass fiber reinforced composites in dental applications, Silicon 4 (2012) 73–78. https://doi.org/10.1007/s12633-011-9075-x

[37] G. Singh, V. Kumar, Analysis of ultimate strength of defective glass fiber reinforced composite subjected to bending, Materials, Mechanics & Modeling (NCMMM 2020), AIP Conference Proceedings, 2341 (2020) id. 020044. https://doi.org/10.1063/5.0049940

[38] H. Deilami Azodi, R. Darabi, A comparative study on the formability prediction of two-layer metallic sheets, Iranian Journal of Materials Forming 4 (2017) 39–51. https://doi.org/10.22099/ijmf.2017.3998