Journal of
Composites Science

Review

Structural Performance of Polyurethane Foam-Filled Building Composite Panels: A State-Of-The-Art

Bijan Samali [1], Saeed Nemati [1,*], Pezhman Sharafi [1], Farzaneh Tahmoorian [2] and Farshad Sanati [3]

[1] Centre for Infrastructure Engineering, Western Sydney University, Kingswood 2747, Australia; B.Samali@uws.edu.au (B.S.); P.Sharafi@uws.edu.au (P.S.)
[2] School of Engineering and Technology, Central Queensland University, Mackay, QLD 4740, Australia; F.Tahmoorian@cqu.edu.au
[3] Mechanical Engineering Faculty, Mashhad University, Mashhad 9177948974, Iran; Sanati.farshad@yahoo.com
* Correspondence: Nematiuts@gmail.com; Tel.: +61-2-4736-0106

Received: 8 March 2019; Accepted: 26 March 2019; Published: 10 April 2019

Abstract: Composite panels with polyurethane (PU) foam-core and facing materials, such as gypsum, engineered wood or some composite materials, are being used as structural members in building construction. This paper reviews and summarises major research developments, and provides an updated review of references on the structural performance of foam-filled building composite panels from 1998 to 2017. The review revealed that previous studies on the structural performance of foam-filled building composite panels could be categorised into five themes; namely, energy absorption and dynamic behaviour; bending and shear behaviour, edgewise and flatwise compressive/tensile behaviour; delamination/deboning issues; and finally some miscellaneous issues. These categories comprise approximately 30%, 40%, 11%, 11% and 8% of related studies over the last two decades, respectively. Also, over the past five years, the number of relevant studies has increased by ~400% relative to the previous similar periods, indicating the attention and focus of researchers to the importance of the structural performance of foam-filled composite panels.

Keywords: composite panels; polyurethane (PU) foam; energy absorption; flexural behaviour; delamination

---

1. Introduction

Polyurethane (PUR or PU) could be a polymer composed of natural units joined by urethane joins with an assortment of applications in industry. The first urethane was made in 1849 by Wurtz. Afterward, in 1937, Otto Bayer provided PUs from the reaction between a polyester diol (polyols) and an isocyanate. Then, during World War II, polyurethanes were used as an aircraft coating. However, since 1954 ever more engineering applications have been proposed. PU foams cover a wide range of stiffness, hardness and densities. Highly resilient and flexible foam seating, rigid foam insulation panels, durable elastomeric wheels and tires, automotive suspension bushings, gaskets, seals and hard plastic parts are some examples of the application of PU in the industry [1]. Most of the global consumption of polyurethane products is in the form of foams [2]. PU products are strong and durable, yet lightweight and easy to install, hence making them an excellent choice for homes and buildings. Most amounts of the polyols that are used in the manufacturing of PU foams are derived from petroleum, but increasing concern over the environmental impact and paucity of petroleum in the future has incited the development of Polyurethane Foams (PUFs) from bio and renewable raw materials. The growing interest in the use of renewable materials has led to increasing use of renewable products, such as green and biobased polyols including vegetable oils, polysaccharides and biomass, represent a rich source of hydroxyl precursors, in the production of PUFs in the last decades. Herein a biobased precursor was used as a partial replacement of conventional polyol to manufacture PU foams. PU is a vital component in several kinds of insulation materials. Open cells foams are proper for sound insulation applications, while closed-cells foams are suitable for thermal insulation applications. Within this scenario, closed-cell rigid foams are a vital class of materials due to their excellent thermal insulation properties. For example, a brick wall would have to be 860-mm-thick to have a comparative level of insulation of 25 mm of PU foam. While PU foams have some of the highest insulating values, their mechanical strength is remarkable too. Therefore, high mechanical strength and easy processing make rigid PUFs an attractive choice in different industrial applications. With regard to the applications in structural members, foam-filled composite structures or Structural Insulated Panels (SIPs) are the most commonly used systems and have been utilised successfully for commercial buildings and houses worldwide for more than 50 years. As a history briefing, although foam-core panels gained attention in the 1970s, the idea of using stress-skinned panels for the building began in the 1930s. Then, in 1947, structural insulated panel development began when paperboard cores were tested with several facing materials of tempered hardboard, plywood and treated paperboard. Polystyrene core and paper overlaid with plywood facing panels were used in a construction in 1967, and the panels have been effective to the present day. These structures have many advantages such as lightweight, high strength, corrosion resistance, durability and speedy construction, together with their excellent thermal and acoustic properties. Foam-filled composite panels with polyurethane foam-core and facing materials such as gypsum, engineered wood or some composite materials, as efficient building elements, are becoming significant players in modular construction with several applications in residential and commercial buildings [3]. This paper reviews and summarises major research developments, and provides an updated review of references on the structural performance of foam-filled composite panels in the most common five different themes including energy absorption and dynamic behaviour, bending and shear behaviour, edgewise and flatwise compression/tension behaviour, delamination/deboning issues and some different themes.

2. Energy Absorption and Dynamic Behaviour

PU foams can be broadly classified as viscoelastic, making them suitable for repetitive use, and rigid, which is a preferred property for applications requiring impact energy absorption. Viscoelastic foams can compress under application of load and expand back to regain their original configuration. However, in rigid foams, cells are commonly of open types that allow higher deformation of foam under applied loading, and lead to higher energy absorption; but the damage is inflicted on cell walls causing the overall deformation to be permanent. More crushable foams termed 'semirigid', have higher energy absorption abilities compared to viscoelastic foams. The dynamic behaviour and energy absorption performance of PU foam-filled composite panels has been extensively studied in the literature. Wu et al. [4] investigated an innovative yet straightforward foam-filled lattice composite panel proposed to enhance peak load and energy absorption capacity (Figure 1). They conducted an experimental study to validate the effectiveness of the panel in increasing peak strength. Test results showed that by using lattice webs, an approximately 1600% increase in peak strength could be achieved. They also showed the energy absorption could be enhanced by increasing lattice web thickness and foam density, while by using lattice webs, the panel showed higher initial stiffness.

The effect of foam density variations in the composite structures under high-velocity impact loadings was investigated by Nasirzadeh et al. [5]. Their studied structures consisted of composite facing made from glass fibre woven roving reinforced unsaturated polyester resin and rigid polyurethane foam core with different densities. The results of analysis from Scanning Electron Microscopy (SEM) also revealed that low ballistic performance in low-density foam core (below 40 kg/m^3) in the composite structures could be associated with foam's low cell wall thickness and strut. They also showed that while foam cell wall thickness and strut play a vital role in crushing behaviour and consequently energy absorption, better ballistic performance was related to composite panels with foam core density below 70 kg/m^3.

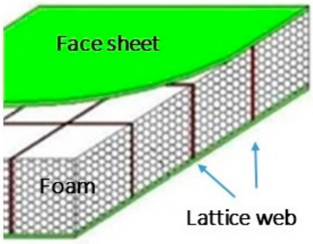

Figure 1. Foam-filled panel proposed by Wu et al. Adapted from [4].

The low-velocity impact behaviour of PU foam-core composite panels was studied by Wang et al. [6]. They conducted some experimental studies on composite panels with plain weave carbon fabric laminated face sheets. Results showed the impact parameters, such as peak load, absorbed energy/impact energy ratio and contact duration increase with impact energy, decrease with the impactor size. The absorbed energy/impact energy ratio and contact duration also decrease with the face sheet thickness, while the peak load increases. In addition, both the planar damage diameter and indentation depth increase with the impact energy, while decreasing with face sheet thickness. Also, they showed the impact response and damage state are independent of the foam core thickness. These researchers developed a progressive damage model to describe the nonlinear behaviour of plain weave carbon laminates during impact. The results from the numerical models agreed with experimental observations [7]. In another study by Zhang et al. [8], a polyurethane foam-filled pyramidal lattice core composite panel (Figure 2) was fabricated in order to improve the energy absorption and low-velocity impact resistance. Some compression tests revealed that the foam-filled composite panels have a higher load carrying capacity compared to the sum of the unfilled specimen and the polyurethane block. Also, it was found that for small compressive strains, the energy absorption of unfilled composite panels is more than that of foam-filled specimen with higher relative density lattice cores. On the other hand, the energy absorption of foam-filled composite panels, owing to lower relative density lattice cores, was inferior to that of the unfilled specimens.

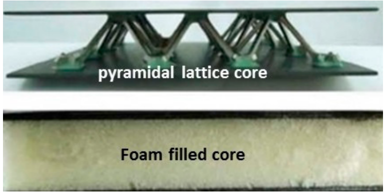

Figure 2. Studied composite panel by Zhang et al. Adapted from [8].

The dynamic response of foam-core composite panels subjected to low-velocity impact was also studied by He et al. [9]. Top facings of composite panels with a thick core were shown to be assailable to the low-velocity crashing under stepped levels of energy, while those with a thick core decreased deformation of the interior plates significantly. Their results also demonstrated that the sharper hemispherical samples were the most destructive with the lowest impact force peak. One of the main disadvantages of composite structures is the loss of bearing capacity due to indentation damage. Rizov et al. [10] evaluated the load–displacement response of foam core composite panels through experimental tests. The test specimens were made by using rigid foam with a thickness of 50 mm, and glass fibre-reinforced composite faces with a width of 2.4 mm. The load–displacement response for loading and unloading states was documented amide the testing. The diameter of the damaged area on the facings was investigated after the unloading. Also, numerical modelling of the indentation response was performed using finite element modelling as well. The primary objective of the investigation was to anticipate the residual stresses and strains, and particularly, the amount of the residual dent. A great coordinate between numerical modelling results and the corresponding experimental data was obtained. Their work ought to be considered as a step towards creating a more advanced numerical analysis capable of explaining indentation as well as postindentation mechanical behaviour of composite structures. The behaviour of nanoclay and polyurethane foam-filled composite panels and glass fibre-reinforced polyamide/polypropylenes face sheets was studied by Sachse et al. [11]. They conducted low energy impact tests under localised point and surface loads and studied the quasi-static compressive behaviour of the composite panels. The investigation showed usage of nanoclay in the polyurethane foam core promoted both energy absorbing and maximal deflection during impact. An increase in the compression modulus of 20–37% was also recorded for the composites with polyamide faces. Hua et al. [12] studied the structural response of carbon fibre composite panels subjected to blast loading through experimental and numerical approach. The measured strain histories illustrated inverse stages at the centre of the front and back face sheets. Both strains speared damped oscillation with a decreased oscillation frequency as well as increased facing deformations at the greater blast intensity. As the blast wave traversed across the panel, the observed flow separation and reattachment led to a pressure rise at the back side of the panel. The maximum deflection of the back face sheet also increased with higher blast intensity and decreased with larger face sheet and core thickness (Figure 3).

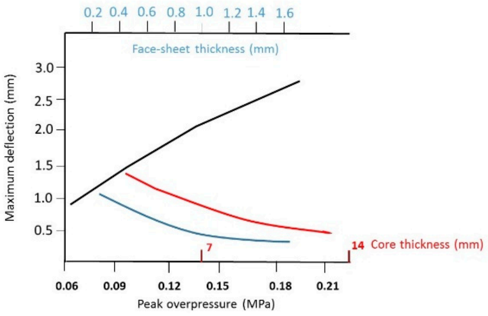

Figure 3. Deflection of panels depends on blast intensity, face thickness and core thickness. Adapted from [12].

In another study on the performance and effectiveness of fibre-reinforced polymer (FRP) composite panels under blast loading, Ahmed et al. [13] conducted a numerical model, verified by experiments (Figure 4). Their panel had an inner core made of woven and honeycomb shaped material, while the sand/PU was used as filling material. They studied the amount of energy absorbed by panels and their peak deformation. Finally, the analyses revealed that using the aforementioned core configuration noticeably enhances FRP panels' behaviour under blast loads.

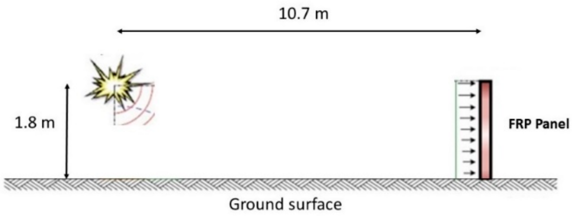

Figure 4. Schematic of experimental test. Adapted from [13].

Yang et al. [14] investigated the response of closed-cell PU foam core composite panels with woven carbon/epoxy laminate face sheets under low-velocity impacts. They introduced a numerical modelling for the composite panels, including continuum damage, cohesive layers and crushable foam model with isotropic hardening. Then, ultrasonic testing and high-speed cameras were used to determine the damage and delamination characteristics. The results showed that the higher exposure temperatures resulted in larger damage zones for both the low and high impact energies. In another study, Taraghi et al. [15] studied the effect of multiwalled carbon nanotubes on the internal and external damages of the core a fibre-reinforced epoxy face sheets subjected to a low-velocity impact. Results showed that this solution could improve the absorbed energy and penetration threshold of the foam-core composite panels. A comparative study between composite structures with and without foam core with regards to their impact behaviour was conducted by Kavianiboroujeni et al. [16] on three-layer composite structures made of high-density polyethylene (HDPE) and hemp. Low-speed falling weight and Charpy tests were used to study the role of hemp content, skin thickness and density of the core material. Based on the results, the structures with foam core had greater energy absorption capabilities. Also, based on the falling weight impact results, the energy dissipation properties of composite structures without foam core were better than the other one. This property was significantly affected by skin fibre content and thickness, and structure arrangement. In another study, Huang et al. [17] studied the static bursting and low-velocity impact behaviour of the flexible composite panels, which consisted of a 3D fabric filled flexible PU as core and two compound laminates as facings. The results revealed that the static bursting strength of the foam could increase to 324% by reinforcing with the filling-resistant 3D fabric. The fibre blending ratio of the filling resistant 3D fabric had a large effect on the static bursting strength, and the flexible composite panels with the filling resistant 3D fabric showed better elongation which is favourable to the low-velocity impact strength. In a numerical and experimental study on the low-velocity impact on composite panels with hybrid nanocomposite face sheets, Feli et al. [18] presented a three-dimensional solution based on Fourier series and the generalised differential quadrature method. The effects of impact energy and geometrical parameters including in-plane dimension ratio, core thickness and face sheet thickness on contact force and lateral deflection histories were also investigated [19]. Low-speed drop-weight tests of composite structures were also carried out by Jiang et al. [20], where a new lamellar orthogonal composite with auxetic effect was employed for impact resistance and energy absorption. Nonauxetic composite structure with the same components, but with other reinforcement structures, was also made for comparison to investigate the impact of reinforcing on the deformation mechanism and mechanical behaviour of the composite structures. It appeared that both auxetic and nonauxetic composite specimens exhibited different mechanical behaviour under distinct deformation and damage mechanism (Figure 5). Pull-out tests showed that strong interfacial bonding could warrant the desired deformation of structural reinforcements and auxetic impact of the composite. It was concluded that the auxetic composite had a higher energy absorption performance in medium strain range too.

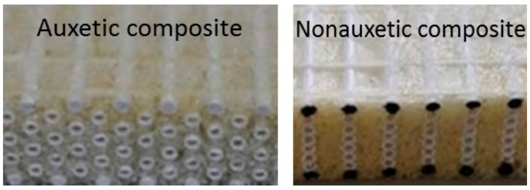

Figure 5. Studied composites by Jiang et al. Adapted from [20].

Hybrid laminated composites, fabricated based on high-density flexible polyurethane foam and reinforced with inter/intra-ply hybrid laminates was proposed by Yan et al. [21]. Their experimental results revealed that foam cell collapse and hybrid laminates rupture were dominant mechanisms of energy absorption under quasi-static and dynamic loadings. Also, interlaminar stress and composite tensile strength determined the compressive potential energy and double-peak behaviour. Quasi-static bursting and puncture resistances exhibited entirely different relationships to various construction and expansion factors. According to their results, energy dissipation capacity was influenced most significantly by the constant rate of transverse (CRT) puncture compared to the dynamic puncture process. In a comprehensive study, Ghalami et al. [22] investigated the effect of parameters of projectile velocity, core density, core thickness, face sheet thickness and orientation of fibres on ballistic limit and energy absorption of composite structures with polyurethane foam core and aluminium and composite face sheets. Their results showed that the face sheets have a significant contribution to the energy absorption of composite panels. Also, increasing core density did not significantly change absorbing energy in comparison with the effects of other parameters. Velecela et al. [23] explained the utilisation of finite element analysis for the simulation of the crushing response of glass reinforced plastic (GRP) composite panels gained to absorb clash energy. Finite element analysis was used to predict the collapse mode associated with the configuration of a triggering mechanism that was presented in the foam-cored composite panels and for analyses of the affection of the samples' aspect ratio on the specific energy absorption of these panels. The numerical analysis predicted a trigger geometry that indicates the transition from buckling failure to oncoming crushing, and showed that there is no apparent trend between the aspect ratio of specimens and their specific energy absorption. Mamalis et al. [24] studied the edgewise compressive behaviour, failure modes and crushing characteristics of different types of composite panels. The investigated panels consisted of four kinds of polymer foam core and two types of FRP facing laminates. The effect of some critical parameters of the facings and foam core and the composite configuration on the compressive response and the crushing characteristics of the panels, such as collapse modes, crash energy absorption and the peak load, are investigated. George et al. [25] studied the composite panels fabricated using a fixed carbon fibre-reinforced polymer (CFRP) truss and a variety of closed-cell polymer and syntactic foams (Figure 6). Results showed the thickness and in-plane shear modulus and strength of the cores increase with rising foam density. The usage of semirigid foams as the core material was found to result in a serious decrease in the compressive contributed by the CFRP trusses. X-ray tomography showed that the trusses develop an elliptical cross-section during pressure-assisted resin transfer. Micromechanical modelling was employed to study the interaction between the mechanical properties and volume fractions of the core materials and truss topology.

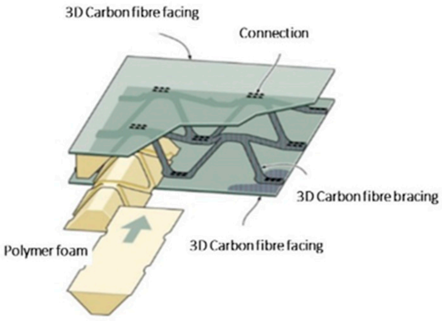

Figure 6. Hybrid composite core of a composite panel with 3D woven carbon fibre composite faces. Adapted from [25].

In a similar work, the effect of the polyurethane foam-filled lattice core composite panel on the energy absorption and the compression strength was studied by Rostamiyan et al. [26]. Results of the compression tests showed that the foam-filled composite panels have a better bearing capacity compared to the sum of the unfilled specimens and PU block. Abdi et al. [27] compared the indentation and the compression behaviour of PRFCS composite panels with the common traditional composite panels. Their results showed that by using cylindrical polymer pins, the indentation strength, energy absorption and compression strength of the composite panels were increased. In addition, the diameter of pins had a significant role in the indentation and compression behaviour of polymer pin-reinforced FCS panels. Also, the influence of polymer pins on indentation behaviour is similar to the effect of increasing the thickness of the face sheet. On the other hand, they found that by increasing the strain rate, the indentation and energy absorption properties of composite panels are improved. Table 1 shows a summary of the critical literature in the area of energy absorption and dynamic behaviour of PU foam-filled composite panels.

Table 1. Summary of the critical literature of energy absorption and dynamic behaviour.

Ref.	Goal	Investigated Parameters	Variables
[4]	Increasing the peak load and energy absorption capacity of composite panels	• initial stiffness • deformability • energy absorbing capacity	• lattice web thickness • lattice web spacing • foam density
[5]	Determination of effects of foam density on composite panels energy absorption	• ballistic limit velocity • energy absorption capacity	• foam density
[6,7]	Determination of low-velocity impact behaviour of foam-core composite panels	• impact response • damage states • absorbed energy/impact energy ratio • contact duration and peak load	• impactor diameter • impact energy • face sheet thickness • foam core thickness
[8]	Study on the response of foam core composite panels to indentation	• load–displacement response • the diameter of the damaged zone on the face sheet • geometrical nonlinearity	• No variation
[9]	Determination of the dynamic response of foam-core composite plates subjected to low-velocity impact	• impact force time history • dynamic displacement time history • the residual plastic deformation • the energy absorption capacity • backplate deflection	• impact energy • foam-core thickness • punch-head shape • punch-head size
[10]	Improvement the energy absorption	• contact duration • load capacity • energy absorption capacity	• density
[11]	Determination of effects of nanoclay on polyurethane foam-filled composite panels energy absorption	• energy absorption capacity • deflection • quasi-static compression modulus	• foam components • face sheet materials
[12]	Study on the structural response of carbon fibre composite panels subjected to blast loading	• the maximum deflection of the face sheets • damage/delamination characteristics • penetration rate	• peak overpressure • face sheet thickness • core thickness
[13]	Conduction a numerical model to study the effectiveness of fibre-reinforced polymer (FRP) composite panels under blast effect	• amount of energy absorbed by panels • panels peak deformation	• core configurations • core material
[14]	Study on the response of foam core composite panels under low-velocity impacts.	• damage and delamination characteristics	• temperature • level of impact energy

Table 1. *Cont.*

Ref.	Goal	Investigated Parameters	Variables
[15]	Improvement of absorbed energy and penetration threshold of the foam-core composite panels	• Energy profile diagrams (EPDs) • damage size	• level of impact energy
[16]	Experimental investigation of the impact behaviour of three-layer composite structures made of high-density polyethylene (HDPE) and hemp, with and without a foam core	• strength • load • absorbed energy • deflection • failure patterns	• skin thickness • core density • skin fibre content • structure configuration
[17]	Investigation of the static bursting and low-velocity impact property of the composite flexible composites	• static bursting strength • elongation	• fibre blending ratio
[18,19]	Modelling of low-velocity impact on the composite panels with hybrid nanocomposite face sheets	• contact force • lateral displacement of the contact point	• No variation
[20]	Study on the low-velocity drop-weight impact tests of composites	• deformation mechanism • mechanical responses • strain rate • pull-out test • energy absorbing capacity	• reinforcement structure • auxetic/nonauxetic • composites
[21]	Study on hybrid laminated composites energy absorption	• mechanisms of energy absorption • such as foam cell collapse and hybrid • laminates rupture • interlaminar stress • composite tensile strength • quasi-static bursting resistances • quasi-static puncture resistances • energy dissipation capacity	• type of loading • thicknesses • expansion factors • constant rate of transverse (CRT) puncture/dynamic puncture
[22]	Investigation of high-velocity impact on composite panels	• ballistic limit and energy absorption	• projectile velocity • core density/thickness • face sheet thickness • orientation of fibres

Table 1. *Cont.*

Ref.	Goal	Investigated Parameters	Variables
[23]	Use of FE analysis for the simulation of the crushing response of composite panels aimed to absorb collision energy	• failure mode • crush zone morphology • specific energy absorption	• width • height • the angle of the top surface of the panel
[24]	Study on compressive properties, collapse modes and crushing characteristics of various types of composite panels in edgewise compression tests.	• compressive properties • collapse modes • peak load • crash energy absorption	• type of foam core • types of faceplate • composite construction geometry
[25]	Study on composite panels fabricated using a fixed carbon fibre-reinforced polymer (CFRP) truss and a variety of closed-cell polymer and syntactic foams	• core in-plane shear modulus • core in-plane shear strength • compressive strength • the ellipticity of the truss cross sections • volumetric energy absorptions • gravimetric energy absorptions	• core foam density • the compressive strength of the foam
[26]	Investigation of the effect of the polyurethane foam-filled lattice core composite panel on the energy absorption and the compression strength	• energy absorption efficiency • the compression strength	• relative density lattice cores • foam-filled and unfilled core
[27]	Comparison between the indentation and compression behaviour of PRFCS and common traditional composite panels	• indentation strength • energy absorption • compression strength	• the diameter of polymer pins • the thickness of the face sheet • type of foam core reinforcement • strain rate

3. Bending and Shear Behaviour

With respect to strength, in addition to global buckling, there are at least five major modes of failure of the composite panels when loaded in bending and shear (Figure 7).

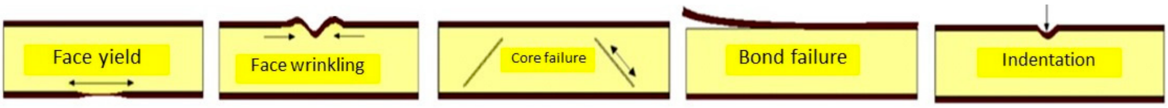

Figure 7. Major failures modes under bending and shear. Adapted from [28].

Considering the possible failures, in research by Mirzapour et al. [28], an experimental study was carried out to investigate and optimise the processing conditions in the fabrication of the composite structures designed for flexural load bearing applications. Outputs showed that the core bearing capacity reduces and the debonding strength rises with the enhancement of temperature during the preparation of the rigid PU foam core. Flexural behaviour of composite panels, fabricated by laminating two glass fibre-reinforced polymer skins and polyurethane foam core, was also studied by Sharaf et al. [29]. Soft and hard foams were tested in three-point and four-point bending as well as under uniform load. They showed that stiffness and bending strength improved by 165% and 113%, respectively, as the core density was doubled. In addition, the contributions of shear deformation of the soft and hard cores to deflection on mid-span were 75% and 50%, respectively. In another study, Manalo [30] presented the structural behaviour of a new preconstructed wall system made of glass fibre-reinforced rigid PU foam and a magnesium oxide board. The results of tests demonstrate that the strength of the board manages the behaviour of the composite walls. Dawood et al. [31] evaluated the static and fatigue characteristics of an innovative 3-D glass-fibre-reinforced polymer (GFRP) composite panel by analytical modelling verified by experimental results. The results indicated that the shear behaviour and degree of composite interaction of the panels are sensitive to the arrangement of the panel core. They showed the panels with stiffer cores generally exhibited a higher degree of degradation than panels with more flexible cores. Wang et al. [32] experimentally focused on the bending behaviour of novel composite panels with GFRP facing and foam-web core panels. They investigated the influence of web thickness, web height and web spacing on failure mode, initial bending stiffness and mid-span deflection. Test results showed that the bending strength and stiffness are increased by the web thickness and height increasing. A composite panel composed of glass fibre-reinforced polymer skin with polyvinyl chloride and polyurethane foam core with epoxy resin was proposed by Mostafa et al. [33]. The flexural response of the composite panel with and without shear keys was evaluated under four-point bending test. They observed a significant improvement in the flexural stiffness and strength of the panel incorporated with shear keys. In another work of same researchers, lightweight foam-filled composite panels were tested through four-point bending tests to characterise their flexural behaviour, and the results were compared with the predictions of the classical composite theory [34]. Tuwar et al. [35] evaluated three different polyurethane foam configurations for GFRP foam-core composite panels. The facings of the three core configurations are shown in Figure 8. The results showed that the type-1 and -2 cores were very weak and flexible, but the third one showed a more strength and stiffness than the others.

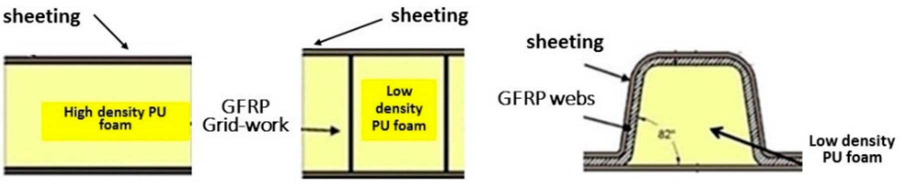

Figure 8. Composite panel configurations for type 1, type 2, and type 3. (left to right) Adapted from [35].

The effect of fully reversed bending loading on high cycle fatigue performance of composite panels was studied by Mathieson et al. [36] by comparing them to similar panels tested under fully unloaded conditions. Their panels failed in shear of the foam core when the fatigue life reduced significantly at fully reversed loading to ~10% of that at fully unloaded conditions. They showed in order to achieve at least 2 million cycles—the commonly acceptable fatigue life in structural engineering—the maximum service loads should be limited to 30% and 45% of ultimate monotonic strength, respectively. They estimated that the threshold loading levels at infinite fatigue life were 23% and 37% of ultimate monotonic strength for the cases of fully reversed loading and fully unloaded conditions, respectively. Kumar et al. [37] also studied the effect of change of thickness of fibre-reinforced polymer (FRP) facing sheets and inserts on the composite panels bending behaviour. They kept the total thickness of composite panels constant, while the span length was varying to find which combination of the panel, containing varied thickness of face sheets and inserts, could provide the best static flexural values. Composite panels with reinforcement ribs or webs are prone to creep when subjected to significant permanent loads. The effects of this phenomenon were studied by Garrido et al. [38]. They presented an experimental assessment and the analytical modelling of the viscoelastic response of two types of composite panels, with and without reinforcement ribs by considering panels comprising GFRP faces, cores of PU foam and longitudinal GFRP ribs. The results showed that ribs increased the flexural strength and stiffness of the panels by a factor of two while providing a threefold reduction in their creep compliance. Junes et al. [39] provided a nonlinear calculation procedure for textile reinforced concrete (TRC) facing composite panels with some main properties including the use of materials "real" behaviour law, the use of numerical methods, the application of arbitrary combination loads and allowing the study of both global and local behaviour. This procedure is based on the cross-section and length of the panel meshing and the noncoupling of bending, shear and local bending effects of the mechanical behaviour of the panel. A sensitivity study is carried out to investigate the evolution of the error depending on the mesh size, too. The effects of soy-based rigid PU foam cores and composite foams, containing wood fibre, on the performance of small-scale wooden wall panels was studied by Kakroodi et al. [40]. They investigated the strengthening of the core under monotonic and static cyclic shear loads. Adding wood fibre resulted in a reduction in the density (23%) and compressive strength (63%) of the foam, while specific tensile modulus, i.e., the ratio of tensile modulus to the density of the foam, increased by ~39%. Mostafa [41] studied the mechanical properties of composite structures, focusing on the behaviour of semicircular shear keys (Figure 9). Their composite panel was composed of GFRP skin with polyvinyl chloride (PVC) and PU foam core, while the shear keys were made of chopped strand glass fibre impregnated with epoxy resin. They investigated different pitches to determine the most sustainable form.

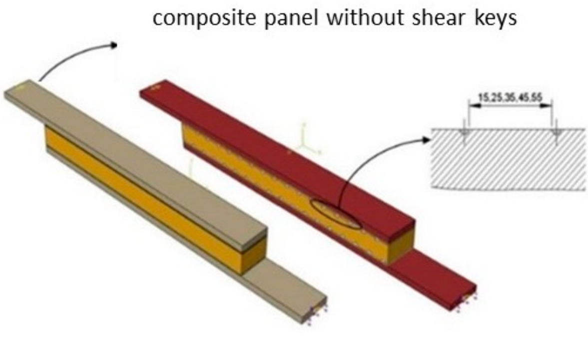

Figure 9. Investigated composite panel with and without shear keys by Mostafa. Adapted from [41].

Sharaf studied the flexural performance of composite panels composed of a PU foam core and GFRP skins and with and without GFRP ribs [42,43]. The study comprises experimental, numerical, and analytical investigations that showed flexural strength and stiffness could increase by 50% to 150%, depending on the rib configuration, compared to a panel without ribs. He proposed an analytical model to predict the possible failure modes as well. His results also demonstrated that as the core density increased, flexural strength and stiffness increased and shear deformation reduced. Besides, increasing skin thickness became more effective as the core density increased. In another effort, Sharaf et al. [44] studied finite element modelling of the bending performance of composite panels consisted of GFRP facings and PU core, considering different patterns of glass FRP ribs and different densities for cores. The model covers both material and stability failure. It was shown that ribs allow compression skin to reach its full material strength. Skin wrinkling was the failure mode of panels without ribs, while those under distributed loads failed either by excessive shear deformation or diagonal fracture of the core, depending on the core density. Also, tensile failure of GFRP skin never occurred in their study. These researchers, in a similar work, also addressed the numerical modelling of lightweight composite panels intended for the cladding of buildings. The panels are designed to resist wind loading. A robust 3D FE model was developed for the large-scale panels (9145 mm × 2440 mm × 78 mm) tested under transverse loading. It was then successfully validated using experimental results. The results again showed that failure of tensioned skin never occurs in this type of panels as compression skin wrinkling and crushing consistently govern [45]. Mastali et al. [46–48] focused on a novel composite panel made of deflection hardening cementitious composites on the top and GFRP on the bottom layer and some shear connectors in the GFRP ribs. They used two types of shear connectors, which include perforated and indented shapes, as shown in Figure 10. The tests showed that the shear connection mechanical behaviour strongly influences the deflection at peak load, the peak load, the postpeak load bearing capacity and the degree of composite action.

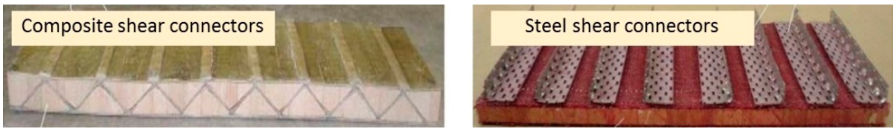

Figure 10. Used connectors by Mastali et al. Adapted from [46–48].

Dawood et al. studied the two-way flexural performance of 3-D GFRP composite panels. The panels included GFRP facings and through-thickness fibre insertions foam core. An experimental test was carried out to evaluate the influence of the fibre insertion pattern and the core thickness on the flexural performance under a single load. The experimental results were used to verify a static finite element model which was used to predict the behaviour. Both results indicate that at smaller deflections the panel behaviour is dominated by plate bending action, while for larger deflections membrane action dominates. In addition, the parametric study indicates that increasing the relative flexural or shear rigidities of the panel alters the behaviour towards the plate bending mechanism, thereby reducing the percentage of load carried by membrane action [49]. Fam et al. explored the feasibility of fabrication and flexural performance of panels composed of a low-density PU core composited between two GFRP facings. Large-scale panels with dimensions of 2500 mm by 660 mm by 80 mm were tested in one-way bending under a simulated uniform load. Various arrangements of GFRP ribs connecting the two facings were compared to a panel without ribs. The investigation showed that by integrating the ribs both strength and stiffness of the panels improved. The maximum growth in strength was regarded doubling the core density in a panel without ribs. Also, in the panel without rib, the shear deformation of the core contributed to over 50% of deflections at the mid-span. By adding the ribs, bending behaviour became more dominant, and shear behaviour contributed only 15% to 20% of the maximum deflection. Simple analytical investigations indicated that the ultimate strengths of the studied panels were the same with similar size reinforced concrete panels while concrete panels were 9 to 14 times heavier in weight [50]. Garrido et al. [51] studied the shear response of polyethylene terephthalate (PET) and PU foams in composite panels under elevated temperature through experimental and numerical investigations. Their results showed that with increasing temperature, the shear responses of PET and PU foams became more nonlinear. In a similar study, Garrido et al. [52] presented an experimental and numerical analysis of the influence of temperature on the shear creep reaction of a rigid PU foam in composite panels. The results revealed that the foam's creep reaction increases with both stress level and temperature.

Shams et al. [53] presented possible applications, the production method and the major results of experimental investigations on the shear load-bearing behaviour of composite sections with textile-reinforced concrete (TRC) and ultrahigh performance fibre-reinforced concrete (UHPFRC), as well as varying types of connectors and foam cores. Kim et al. [54] investigated the static and fatigue characteristics of PU foam-cored composite structures. Three types of specimens: nonstitched, stitched and stiffened composite specimens, with glass fabric faces and a PU foam core, were used (Figure 11). Results showed that after fatigue loading of 106 cycles, the static bending strengths of all specimens decrease compared with those of the static tests. Also, from the results of scanning images, no failure is found to have occurred under fatigue loading. Results indicate that the degradation of stiffness causes the decrease in bending strength of foam-cored composite structures due to the aging of the polyurethane foam core during fatigue cycles. In addition, the strength of stitched specimen is improved by increasing the stitching thread diameter and decreasing its distance. However, fatigue characteristics are not predominantly affected by the variation of stitching thread diameter and distance.

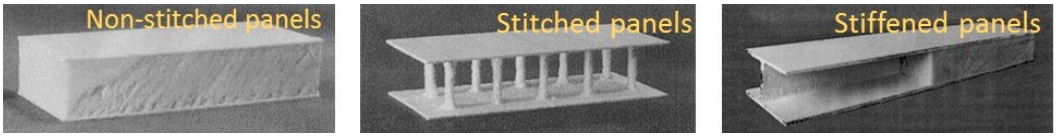

Figure 11. Configurations of 3 types of specimens. Adapted from [54].

In addition, a series of experimental tests have been done on three types of creative composite panels of lightweight mobile housing by Labans et al. [55] (Figure 12). Their mechanical behaviour was investigated in a four-point bending test comparing the data to the plywood panel. Also, numerical simulations were used to evaluate stress distribution and global behaviour. Results identified that studied panels are suitable for floor and wall units.

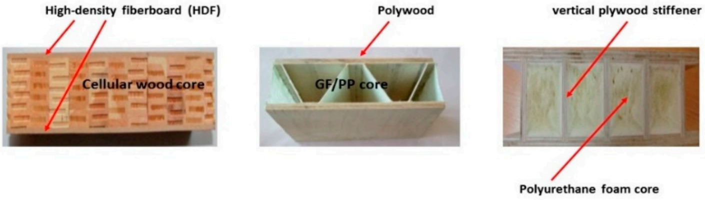

Figure 12. Studied composite panels by Labans et al. Adapted from [55].

Abdolpour et al. [56] performed a series of experimental tests on a composite specimen to be used as a floor slab module of an emergency housing system. The specimen comprises a frame made of GFRP pultruded profiles, and two composite panels formed by GFRP skins and a PU core (Figure 13). They investigated the feasibility of the assemblage process of the prototype and performance to support load conditions typical of residential houses. Furthermore, composite panels were tested, analysing their flexural response, failure mechanisms and creep behaviour. Results showed the great behaviour of the specimen to be used as a structural floor module of emergency housing. Also, numeric simulations were carried out to evaluate the stress distributions in the specimen components as well as bearing mechanism of the connections.

In addition, Jayaram et al. [57] studied incorporating polyester pins in a polyurethane foam-filled honeycomb core composite panel to increase the interfacial strength between the faces and core (Figure 14). The effect of strain rates on bending performance of composite panels was also evaluated. Results show that increasing the pin diameter has a larger effect, whereas the strain rate had a moderate influence on the failure load of all of the composite panels.

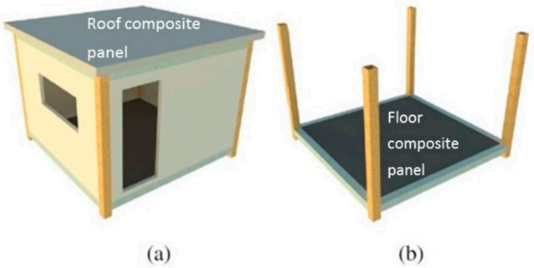

Figure 13. Schematic of the modular prototype: (**a**) full prototype; (**b**) prototype without walls and roof. Adapted from [56].

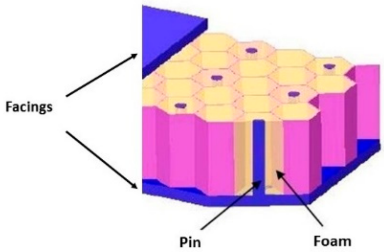

Figure 14. Schematic representation of PU foam-filled honeycomb core composite panel. Adapted from [57].

On the other hand, Reis et al. [58] proposed a novel composite panel. The top and bottom faces, consisting of GFRP plates, are connected with through-thickness fibres to achieve the composite action with a polyurethane foam core (Figure 15). They discussed the influence of the panel thickness, through-thickness fibre configuration and density, and other parameters on the tension, compression, flexure and shear behaviour, deeply.

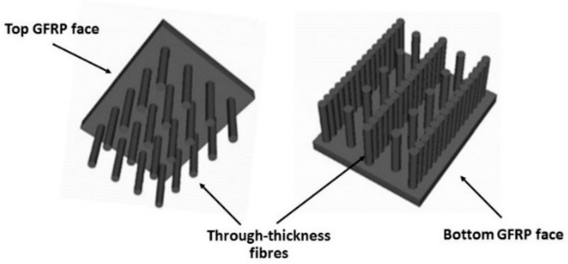

Figure 15. Different arrangements of through-thickness fibres. Adapted from [58].

Table 2 shows a summary of the critical literature in the area of bending and shear behaviour of PU foam-filled composite panels.

Table 2. Summary of the critical literature of bending and shear behaviour of PU foam-filled composite panels.

Ref.	Goal	Investigated Parameters	Variables
[28]	Optimisation of processing conditions in the fabrication of the composite structures designed for flexural applications	• specific flexural strength • core strength • debonding strength	• construction processing conditions
[29]	Study on the flexural behaviour of a new composite panel proposed for cladding of buildings	• flexural strength • flexural stiffness • shear deformation at the mid-span	• core density • loading arrangement
[30]	Identification of the behaviour of an emerging prefabricated wall system	• shear stiffness and strength • bending moment capacity • effective flexural stiffness • mid-span deflection	• No variation
[31]	Study on static and fatigue bending behaviour of composite panels	• effective elastic modulus • shear modulus • the degree of composite interaction • the degree of degradation	• pattern and density of fibre • thickness of panels • number of skins FRP plies • core stiffness
[32]	Study on the bending behaviour of an innovative composite panel	• ultimate bending strength/ stiffness • failure mode such as local wrinkling • mid-span deflection	• web thickness • web height • web spacing
[33]	Analysis of flexural behaviour of the composite composite panels	• flexural stiffness and strength • stress-strain curve	• with and without shear keys • foam type
[34]	Study of composite panel flexural behaviour	• linear/nonlinear flexural response	• No variation
[35]	Evaluation of three core alternatives for GFRP foam-core composite panels	• bending strength • bending stiffness	• core foam material
[36]	Study of composite panel fatigue behaviour	• flexural stiffness/fatigue life curve	• loading condition
[37]	Study on the effect of facing thickness on composite panels flexural behaviour	• flexural stiffness	• facing thickness • span length
[38]	Presentation of an experimental assessment and analytical modelling of the viscoelastic response of composite panels	• flexural strength • flexural stiffness • creep curve	• types of composite panels, with and without reinforcement ribs
[39]	providing a nonlinear calculation procedure of textile reinforced concrete (TRC) facings composite panels	• load-deflection behaviour • failure mode • strain development	• cross-section of the panel • length of the panel

Table 2. *Cont.*

Ref.	Goal	Investigated Parameters	Variables
[40]	Study on the strengthening of soy-based PU foam cores, neat and composite foams containing wood fibre on the performance of small-scale wooden wall panels under monotonic and static cyclic shear loads	• foam density/compressive strength • the specific tensile modulus of foam • the ratio of tensile modulus to the density of the foam • shear strength of panel	• loading • foam components
[41]	Study on effects of semicircular shear keys on composite panels shear strength	• shear strength	• kind of core foam • space between shear keys
[42,43]	Experimental, numerical and analytical investigations on the flexural performance of composite panels composed of a polyurethane foam core and GFRP skins	• comprehensive material testing • flexural strength and stiffness • deflection • possible failure modes	• Panels with and without GFRP ribs connecting • skin thickness/rib spacing • core density
[44]	Numerical modelling of the flexural behaviour of composite panels composed of woven glass fibre-reinforced polymer skins and polyurethane foam core	• material/geometrical nonlinearity • shear deformation/flexural strength • material/stability failure • tensile failure and skin wrinkling • longitudinal rib spacing	• patterns of glass fibre-reinforced polymer ribs • density of core • panel thickness
[45]	Numerical modelling and large-scale testing of lightweight composite panels intended for cladding of buildings in order to satisfy design code requirements in terms of strength and stiffness	• load-strain response • load-deflection response • failure modes • stiffness	• No variation
[46–48]	Evaluation of the flexural performance of hybrid composite panels	• peak load-mid-span deflection • postpeak load carrying capacity • the degree of composite action	• shear connectors' geometry
[49]	Evaluation of the two-way bending behaviour of 3-D GFRP composite panels	• two-way bending behaviour • bearing capacity	• fibre insertion pattern • panel thickness • flexural/shear rigidities
[50]	Feasibility study of fabrication and flexural performance of composite panels of low-density PU foam and GFRP skins	• strength and stiffness of the panels • shear deformation • mid-span deflection	• configurations of internal and exterior GFRP ribs • core density
[51]	Study on the effects of elevated temperature on the shear response of PET and PUR foams used in composite panels	• shear modulus of composite panels	• kind of core foam • temperature

Table 2. *Cont.*

Ref.	Goal	Investigated Parameters	Variables
[52]	Experimental/analytical study on the effect of temperature on the shear creep response of a rigid PUR foam at composite panels	• shear creep/shear strength • creep coefficient • shear modulus reduction factor	• shear stress level • temperature
[53]	Presenting the possible applications, the production method, and the major results of experimental investigations on the load-bearing behaviour of composite panels with textile-reinforced concrete (TRC) and ultrahigh performance fibre reinforced concrete	• mid-span deflection • axial load capacity • shear load capacity • possible applications • possible production methods	• types of connectors • types of foam cores
[54]	Investigation of the static and fatigue characteristics of nonstitched, stitched and stiffened PU filled composite panels	• bending strength • ultrasonic C-scanning crack controlling • bending stiffness	• static and fatigue loading • nonstitched, stitched and stiffened configuration • the distance of stitching thread • the diameter of stitching thread
[55]	Mechanical evaluation of novel composite panels for application in lightweight mobile housing	• global behaviour • stress distribution • specific stiffness • strength characteristics	• core material • facing material • panel configuration
[56]	Performing a series of experimental tests on a composite prototype to be used as a floor module of an emergency house	• flexural response • failure mechanisms • creep behaviour • stress distribution • load transfer mechanism	• No variation
[57]	Increase the interfacial strength between the faces and core	• flexural stiffness • flexural stress • flexural strength • damping properties • failure load • deflection at failure load • natural frequency • damping ratio	• strain rates • pin diameter
[58]	Introducing a new 3D fibre-reinforced polymer (FRP) panels designed to overcome delamination	• tensile strength of the composite panel • the compressive strength of the composite panel • flexural strength of composite panel • shear strength of composite panel • facing elastic modulus • the shear modulus of the composite panel	• panel thickness • through-thickness • fibre configuration • fibre density • Fibre insertion (per cm^2)

4. Edgewise and Flatwise Compressive/Tensile Behaviour

Mathieson et al. [59] presented experimental and analytical investigations of axially loaded large-scale slender composite panels with and without ribs (Figure 16). The model showed reasonable agreement with test results for strength and stiffness and was used in a parametric study. It was shown that the addition of a longitudinal rib connecting the skins at mid-width resulted in a 180% increase in axial strength by changing the failure mode from skin wrinkling to global buckling. Adding longitudinal external ribs to the internal one changed the failure mode to skin crushing and increased stiffness by 40%, but did not enhance strength. Axial stiffness and strength also increased as skins or ribs became thicker, or their Young's modulus increased or as core shear modulus increased, however, the failure mode varied depending on length.

Mohamed et al. [60] studied three designs of glass reinforced composite structures, namely boxes, trapezoid and rigid polyurethane foam (Figure 17). The mechanical response of three designs of composite structures under flexural loading was analysed using the finite element method. The simulation results of flexural behaviour were validated by experimental findings.

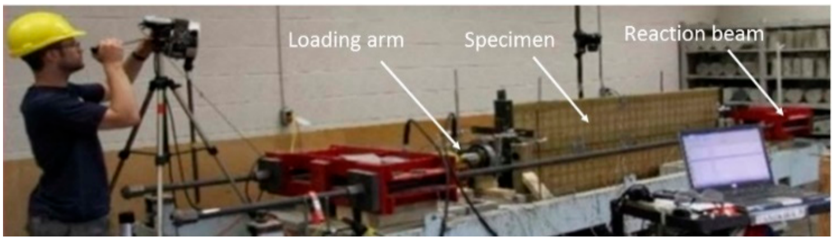

Figure 16. Test setup. Adapted from [59].

Figure 17. Investigated Composite panels. Adapted from [60].

The behaviour of foam core composite (FCS) and polymer pin-reinforced foam core composite (PRFCS) panels was experimentally investigated for flatwise compression and flexural tests by Abdi et al. [61]. The FCS and PRFCS specimens were made of chopped strand mat glass/polyester as facings and PU foam as the core material (Figure 18). Their goal was to explore the influence of the polyester pin reinforcement in the foam core under mentioned loadings. Also, the influence of several loading rates on the bending behaviour of glass/polyester laminate in both types of panels was explained. It was found that by using cylindrical polymer pins, the flatwise strength and bending properties of the panels were raised. Furthermore, it was found that the diameter of pins had a significant influence while the loading rate had a moderate influence on the flexural stiffness of both types of composite panels.

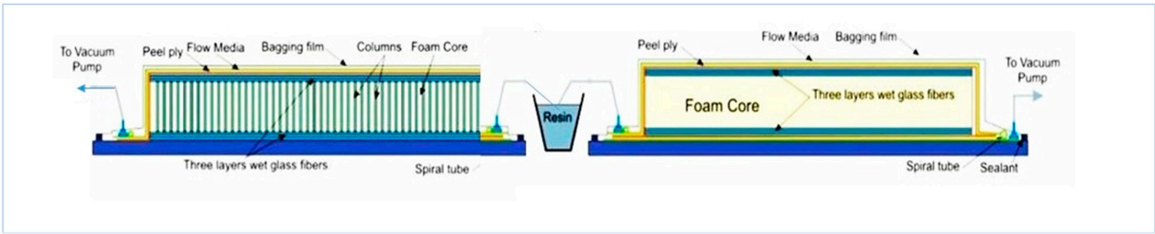

Figure 18. The schematic of the fabrication process of FCS and PRFCS composite panels. Adapted from [61].

Nemati et al. [62] proposed a creative composite panel, which has been made for rapid assembled postdisaster buildings and prefabricated modular construction. The panel is made with two high-density polyethylene (HDPE) sheets as the skins and a high-density PU foam as the core (Figure 19). HDPE sheets, manufactured with a studded surface, considerably enhance the pull-out and delamination strength, as well as the stress distribution and buckling of the panel. Flatwise and edgewise compression tests were carried out following ASTM codes to study the compressive strength and the bearing performance of the composite panels. Numerical analysis was also conducted to simulate the compressive behaviour of composite structures. They found that the innovated composite panel improves the compressive performance of foam panels.

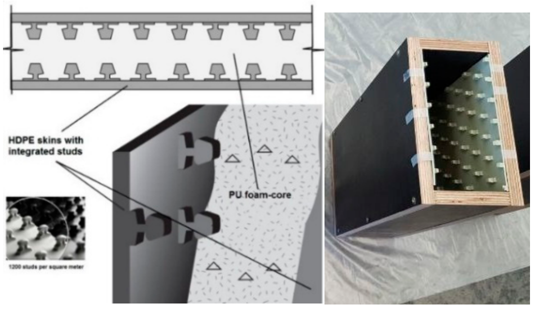

Figure 19. Illustration of the 3-D composite panel with HDPE skins and PU core (**left**) and used formwork (**right**). Adapted from [62].

Koissin et al. [63] addressed the behaviour of composite panels subjected to edgewise compression. They conducted a local low-velocity impact test and investigated the residual strength of the foam core. Results showed that such damage can alter the edgewise compressive strength. Table 3 shows a summary of the critical literature in the area of edgewise and flatwise compressive/tensile behaviour of PU foam-filled composite panels.

Table 3. Summary of the critical literature of edgewise and flatwise compressive/tensile behaviour of PU foam-filled composite panels.

Ref.	Goal	Investigated Parameters	Variables
[24]	Study on compressive properties, collapse modes and crushing characteristics of various types of composite panels in edgewise compression tests.	• compressive properties • collapse modes • peak load • crash energy absorption	• type of foam core • types of faceplate • composite construction geometry
[25]	Study on composite panels fabricated using a fixed carbon fibre-reinforced polymer (CFRP) truss and a variety of closed-cell polymer and syntactic foams	• core in-plane shear modulus • core in-plane shear strength • compressive strength • the ellipticity of the truss cross sections • volumetric energy absorptions • gravimetric energy absorptions	• core foam density • compressive strength of foam
[26]	Investigation of the effect of the polyurethane foam-filled lattice core composite panel on the energy absorption and the compression strength	• energy absorption efficiency • compression strength	• relative density lattice cores • foam-filled and unfilled core
[27]	Comparison between the indentation and compression behaviour of PRFCS and common traditional composite panels	• indentation strength • energy absorption • compression strength	• diameter of polymer pins • thickness of face sheet • type of foam core reinforcement • strain rate
[59]	Experimental and analytical investigations of axially loaded composite panels	• axial strength • axial stiffness • failure mode (global buckling or skin wrinkling) • failure load	• with and without ribs • slenderness ratio • thickness of skin • thickness of rib • Young's modulus of skin • Young's modulus of rib • core shear modulus • length of panel
[60]	Core shear, flatwise and edgewise compression studies of three designs of glass reinforced composite composite panels	• flexural stiffness • flatwise compressive strength • edgewise compressive strength • core shear strength	• composite construction geometry
[61]	Study on the effect of composite panels' foam core pin reinforcement under flexural and flatwise compression loadings	• flexural stiffness • deflection • failure load	• loading rates • type of foam core reinforcement • diameter of polymer pins
[62]	Study on edgewise and flatwise compression behaviour of an innovative composite panel	• edgewise compression strength • flatwise compression strength • failure mode	• No variation
[63]	Study on the effect of a local quasi-static indentation or a low-velocity impact on the residual strength of foam core composite panels subjected to edgewise compression	• edgewise compression strength	• with face-core debonding • without face-core debonding

5. Delamination and Debonding

Due to the layered composition of composite panels, core–face junction delamination is a commonly occurred failure mode, often referred to as a lamellar or peeling failure. Jakobsen et al. [64] presented a novel delamination stopper concept for composite panels. Their goal was rerouting the peeling and confining it to the first conditions. They carried out some three-point bending tests on different material compositions of composite structures. Their results showed that for all the tested configurations the suggested peel stopper was able to stop face core delamination. Looped fabric reinforced foam composite (U-core) is a new type of composites that has been studied by Chen et al. [65]. The loop can be effectively embedded in the foam core so that the interface mechanical properties can be improved. In this study, a simulation of damage evaluation and strength analysis was carried out on a micromechanical model of foam. In addition, some flatwise tension and shear loadings test were conducted. Test results showed that the drawback of traditional composite panels under flatwise tension and shear loadings is overcome (Figure 20).

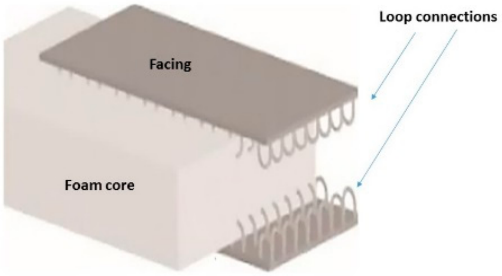

Figure 20. Structure concept of looped fabric reinforced foam composite (U-core). Adapted from [65].

Miron et al. [66] used the digital image correlation method (DIC) for a study on interface damage characterisation and interlaminar failure of composite specimens. Virtual strain gauges are used at the interface in the PU core to measure the opening strains. Peel tests showed interesting particularities on damage arrangement and strain variation is completed. Also, the critical strain at damage initiation and the critical displacement when damage is finalised is established in the cohesive zone. Then, after the calibration, the use of the coherent elements together with a linear softening law provided in the core a pattern of strain variation similar to the one obtained experimentally. Sharma et al. [67] studied all vibration modes of composite panels to ensure that debonding between facings and core in the through-thickness vibration mode does not occur during service. They conducted an experimental modal analysis on composite panels of different densities and core thicknesses under different boundary conditions and evaluated the corresponding mode shapes and modal damping. In their study, a nondimensional parameter representing the ratio of core density and core thickness to face density and face thickness was established, which correlates with the measured fundamental natural frequency. Besides, Sharma et al. [68] investigated the influence of drilling velocity, feed rate and flank length on the peeling of PU foam composite panels (Figure 21). A scanning electron microscopy system was used to show the damage from drilling. The drilling process was evaluated based on a factor called the delamination factor, which is defined as the ratio of the maximum diameter of the damage zone to drill diameter. Results showed that drilling speed was the most important controllable parameter during drilling of composite panels followed by feed rate and flank length.

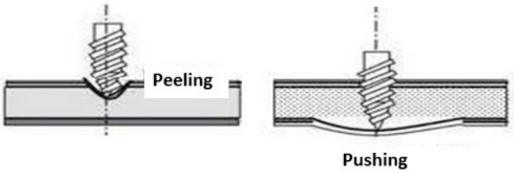

Figure 21. Delamination damage mechanisms of drilling. Adapted from [68].

Mostafa et al. [69] presented semicircular shear keys to improving the shear performance and skin–core peeling resistance for foam-filled composite panels with the core. Polyvinylchloride (PVC) and PU foam core are chosen for the study and composited between glass fibre-reinforced polymer facings, while the chopped strand (CS) glass fibre is used for the shear key. A parametric study on the influence of the shear key diameter on the in-plane shear performance has been performed numerically. Also, a comprehensive experimental testing program was conducted on the constituents to obtain the basic parameters used in the finite element modelling. Results showed for all studied configurations the considered shear keys were able to stop interface peeling and to redirect it to diagonal orientation with a great improvement in the shear behaviour. Lameiras et al. [70] proposed an innovative and thermally efficient composite panel for the structural walls of a prefabricated modular housing system. Their composite panel consists of glass fibre-reinforced polymer (GFRP) connectors and two thin facings of steel-fibre-reinforced self-compacting concrete (SFRSCC) (Figure 22). The feasibility of using the connectors and SFRSCC on the outer layers is studied through a series of pull-out tests where failure modes and load capacity of the connections are analysed. Table 4 shows a summary of references [57,58,64–70].

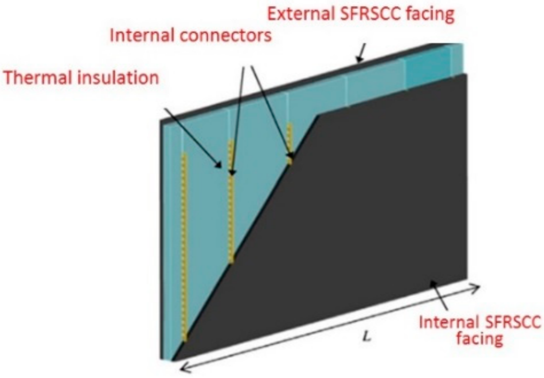

Figure 22. Components of the proposed devised load-bearing composite panel. Adapted from [70].

Table 4. Summary of references [57,58,64–70].

Ref.	Goal	Investigated Parameters	Variables
[57]	Increase the interfacial strength between the faces and core	• flexural stiffness • flexural stress • flexural strength • damping properties • failure load • deflection at failure load • natural frequency • damping ratio	• strain rates • pin diameter
[58]	Introducing a new 3D fibre-reinforced polymer (FRP) panels designed to overcome delamination	• tensile strength of the composite panel • the compressive strength of the composite panel • flexural strength of composite panel • shear strength of composite panel • facing elastic modulus • the shear modulus of the composite panel	• panel thickness • through-thickness • fibre configuration • fibre density • Fibber insertion (per cm^2)
[64]	presenting a new peel stopper concept for composite structures	• debonding/delamination	• No variation
[65]	Study on interface mechanical properties of Looped fabric reinforced foam composite (U-core) panels	• flatwise tension strength • shear strength • pull strength • failure mode • pressure–displacement curves under the flatwise tension • The pressure–displacement curves under the shear load	• foam density • type of foam fabric reinforcement (U-core and traditional 2D)
[66]	Numerical and experimental study on interface damage characterisation and interlaminar failure of composite panels	• interface damage characterisation of composite panels including opening strain at the interface • interlaminar failure of composite panels including critical strain at the damage and critical displacement when damage is finalised • the pattern of strain variation • crack opening	• width of specimens • thickness of specimens • length of initial delamination • the Position of the monitored points
[67]	Study on dynamic characteristics of composite panels	• first fundamental frequency • corresponding mode shapes • modal damping	• core density/thickness • boundary conditions • rigid inserts
[68]	Study on the influence of drilling on the delamination of PU composite panels	• delamination factor (the ratio of the maximum diameter of damage zone to drill diameter) • surface roughness	• cutting/ drilling velocity • feed rate • flank length • flute length
[69]	Improvement of debonding failure between skin and core is highly important composite panels	• shear strength	• kind of foam material • shear keys diameter
[70]	Introducing an innovative and thermally efficient composite panel for the structural walls	• connectors tensile strength, stiffness, stress-strain relationship, and cost competitiveness • connectors pull-out test and load capacity	• kind of connectors (embedded or adhesively bonded) • types of GFRPs • Kind of foam
			• panel thickness

6. Miscellaneous Themes

Yanes-Armas et al. [71] studied the structural creep behaviour of GFRP-polyurethane (PUR) web-core composite structures subjected to sustained loading. The study showed that the density of foam and the loading type must be considered to evaluate the structural behaviour of the GFRP-PUR web-core panels. The effect of creep on the web–core interaction was then investigated. The results showed the shear resistance of the GFRP webs, their dimensions and governing failure mode depended on the applied design recommendation. Finally, a design procedure to predict the overall shear resistance of the GFRP-PUR core, considering the creep effects, was presented too. Chan et al. performed experimental and numerical studies of sustainable composite biocomposites. The biocomposites were developed using plant-based materials. The laminated face sheets comprised woven hemp fabric and tree sap-based epoxy, while the core involved castor oil-based polyurethane foam reinforced with waste rice hulls ashes. Tensile, compressive and three-point bending tests were conducted. Finite element models were developed. From numerical simulation results, the composite biocomposites were found to be a structurally acceptable replacement for standard gypsum drywall [72]. Azimi et al. [73] studied a creative composite panel consisted of glass fibre composite facings and coconut coir fibre-reinforced PU foam core. The physical and mechanical properties were found to be significant at 5 wt % coconut coir fibre in PU foam cores as well as in composite composites. It was found that composite properties serve better in composite construction. Reany et al. [74] studied on composite plates with one corrugated and one flat skin with the goal to find configurations with higher strength and/or stiffness and reduced weight. The corrugations led to increased bending stiffness in one direction but, reduced in the other. Kam et al. [75] have shown the optimum design of laminated PU foam-filled composite plates with both continuous/discrete core thicknesses. Design variables subjected to strength constraint are studied via a two-level optimisation technique. Finally, a failure test of laminated composite foam-filled composite plates with different lamination arrangements was performed to validate the proposed optimal design method. Arruda et al. [76] presented numerical investigations on the creep behaviour of composite panels produced by vacuum infusion with GFRP faces and ribs, and polyurethane (PUR) and polyethylene terephthalate (PET) foam cores. The results showed that the proposed numeric models predicted the creep behaviour of the composite panels perfectly. In a similar research, Table 5 shows the summary of references [71–76].

Table 5. Summary of references [71–76].

Ref.	Goal	Investigated parameters	Variables
[71]	studying on structural creep behaviour of GFRP-polyurethane web-core composite structures subjected to sustained loading	• overall shear resistance of the GFRP-PUR core over time	• foam anisotropy • foam density loading type
[72]	Experimental and numerical studies of sustainable composite biocomposites	• uniaxial compression test • tension test • three-point flexural bending tests	• weight ratio of waste RHA/rice hulls • percentage of cooked Foam
[73]	To characterise the physical and mechanical properties and to elucidate the effect of coconut coir fibres in polyurethane foam cores and composite panels	• shear strength of the composite panel • shear strength of the foam • the flexural strength of the composite panel • the flexural stiffness of the composite panel • density of foam • flexural modulus of the composite panel • flexural modulus of the foam • bearing capacity of the composite panel • bearing capacity of the foam	• Amount of coconut coir fibres
[74]	Study on composite panels with one corrugated and one flat skin in order to find configurations with higher strength and/or stiffness and reduced weight	• panel strength • panel stiffness • panel weight • uniaxial buckling • shear buckling	• skin configuration (corrugated and flat) • corrugation geometry • material properties
[75]	Introducing a new method for optimum design of laminated composite panels	• optimal design parameters • optimal weight	• method of design (continuous and discrete core thickness) • lamination arrangements
[76]	Numerical investigations on the creep behaviour of composite panels	• creep behaviour	• kind of foam

7. Conclusions

According to the above comprehensive discussion, the following conclusions can be drawn.

- Energy absorption and dynamic behaviour, bending and shear behaviour, edgewise and flatwise compression/tension behaviour and delamination/deboning themes comprise 30%, 40%, 11% and 11% of related studies, respectively, over the last two decades. Also, 8% of related studies over the last two decades are related to the whole of other themes (Figure 23).
- First two categories represent the 70% of the studies. The direct use of the results of these two categories of studies in the seismic design of building panels can be a reasonable reason for this amount of studies.
- Energy absorbing capacity, flexural stiffness and shear strength of composite panels account 27%, 15% and 12% of studied parameters, respectively.
- Torsional behaviour of foam-filled panels and their connections are neglected absolutely and could be suggested for future researches.
- Over the past 22 years, the number of these studies has increased by at least two hundred percent during each five-year period relative to the previous period. However, over the past five years, this increase was approximately four hundred percent, indicating the interest and attention of researchers to the importance of the structural performance of foam-filled composite panels (Figure 24).
- Studies on the structural performance of foam-filled composite panels from 1998 to 2017 have a uniform continental distribution between America, Asia & Oceania and Europe (Figure 25).

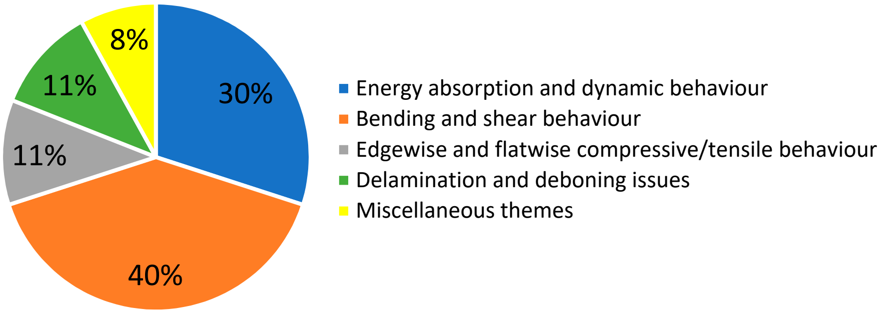

Figure 23. Percentages of different research themes regarding the structural performance of foam-filled composite panels from 1998 to 2017.

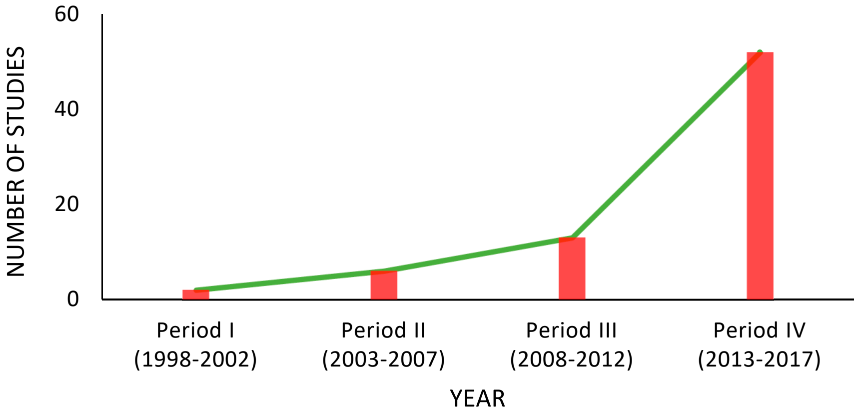

Figure 24. Growing up of studies on the structural performance of foam-filled composite panels from 1998 to 2017.

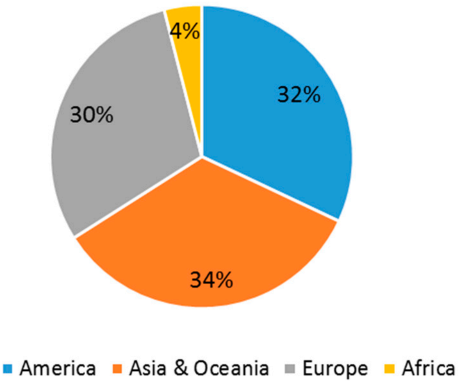

Figure 25. Continental distribution of studies on the structural performance of foam-filled composite panels from 1998 to 2017.

Author Contributions: S.N. and P.S.; Methodology, S.N. and F.S.; Formal Analysis, B.S. and S.N.; Data Curation, S.N. and F.T.; Writing-Original Draft Preparation, S.N. and B.S.; Writing-Review & Editing, B.S. and P.S., Supervision.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bomberg, M.T.; Lstiburek, J.W. *Spray Polyurethane Foam in External Envelopes of Buildings*; Taylor & Francis: Abingdon, UK, 1998.
2. Cousins, K. *Polymers in Building and Construction*; Rapra Technology Limited: Shropshire, UK, 2002.
3. Sharafi, P.; Samali, B.; Ronagh, H.; Ghodrat, M. Automated spatial design of multi-story modular buildings using a unified matrix method. *Autom. Constr.* **2017**, *82*, 31–42. [CrossRef]
4. Wu, Z.; Liu, W.; Wang, L.; Fang, H.; Hui, D. Theoretical and experimental study of foam-filled lattice composite panels under quasi-static compression loading. *Compos. Part B Eng.* **2014**, *60*, 329–340. [CrossRef]
5. Nasirzadeh, R.; Sabet, A.R. Study of foam density variations in composite composite panels under high velocity impact loading. *Int. J. Impact Eng.* **2014**, *63*, 129–139. [CrossRef]
6. Wang, J.; Waas, A.M.; Wang, H. Experimental study on the low-velocity impact behavior of foam-core composite panels. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Honolulu, HI, USA, 23–26 April 2012.
7. Wang, J.; Waas, A.M.; Wang, H. Experimental and numerical study on the low-velocity impact behavior of foam-core composite panels. *Compos. Struct.* **2013**, *96*, 298–311. [CrossRef]
8. Zhang, G.; Wang, B.; Ma, L.; Wu, L.; Pan, S.; Yang, J. Energy absorption and low velocity impact response of polyurethane foam filled pyramidal lattice core composite panels. *Compos. Struct.* **2014**, *108*, 304–310. [CrossRef]
9. He, Y.; Zhang, X.; Long, S.; Yao, X.; He, L. Dynamic mechanical behavior of foam-core composite composite structures subjected to low-velocity impact. *Arch. Appl. Mech.* **2016**, *86*, 1605–1619. [CrossRef]
10. Rizov, V.; Shipsha, A.; Zenkert, D. Indentation study of foam core composite composite panels. *Compos. Struct.* **2005**, *69*, 95–102. [CrossRef]
11. Sachse, S.; Poruri, M.; Silva, F.; Michalowski, S.; Pielichowski, K.; Njuguna, J. Effect of nanofillers on low energy impact performance of composite structures with nanoreinforced polyurethane foam cores. *J. Compos. Struct. Mater.* **2014**, *16*, 173–194.
12. Hua, Y.; Akula, P.K.; Gu, L. Experimental and numerical investigation of carbon fiber composite panels subjected to blast loading. *Compos. Part B Eng.* **2014**, *56*, 456–463. [CrossRef]
13. Ahmed, S.; Galal, K. Effectiveness of FRP composite panels for blast resistance. *Compos. Struct.* **2017**, *163*, 454–464. [CrossRef]

14. Yang, P.; Shams, S.S.; Slay, A.; Brokate, B.; Elhajjar, R. Evaluation of temperature effects on low velocity impact damage in composite composite panels with polymeric foam cores. *Compos. Struct.* **2015**, *129*, 213–223. [CrossRef]
15. Taraghi, I.; Fereidoon, A. Non-destructive evaluation of damage modes in nanocomposite foam-core composite panel subjected to low-velocity impact. *Compos. Part B Eng.* **2016**, *103*, 51–59. [CrossRef]
16. Kavianiboroujeni, A.; Cloutier, A.; Rodrigue, D. Low Velocity Impact Behaviour of Asymmetric Three-layer Composite Composite Structures with and Without Foam Core. *Polym. Polym. Compos.* **2017**, *25*, 381. [CrossRef]
17. Huang, S.-Y.; Lou, C.W.; Yan, R.; Lin, Q.; Li, T.T.; Chen, Y.S.; Lin, J.H. Investigation on structure and impact-resistance property of polyurethane foam filled three-dimensional fabric reinforced composite flexible composites. *Compos. Part B Eng.* **2017**, *131*, 43–49. [CrossRef]
18. Feli, S.; Mahdipour Jalilian, M. Three-dimensional solution of low-velocity impact on composite panels with hybrid nanocomposite face sheets. *Mech. Adv. Mater. Struct.* **2017**, *25*, 579–591. [CrossRef]
19. Feli, S.; Jalilian, M. Theoretical model of low-velocity impact on foam-core composite panels using finite difference method. *J. Compos. Struct. Mater.* **2017**, *19*, 261–290.
20. Jiang, L.; Hu, H. Low-velocity impact response of multilayer orthogonal structural composite with auxetic effect. *Compos. Struct.* **2017**, *169*, 62–68. [CrossRef]
21. Yan, R.; Wang, R.; Lou, C.W.; Huang, S.Y.; Lin, J.H. Quasi-static and dynamic mechanical responses of hybrid laminated composites based on high-density flexible polyurethane foam. *Compos. Part B Eng.* **2015**, *83*, 253–263. [CrossRef]
22. Ghalami-Choobar, M.; Sadighi, M. Investigation of high velocity impact of cylindrical projectile on composite panels with fiber–metal laminates skins and polyurethane core. *Aerosp. Sci. Technol.* **2014**, *32*, 142–152. [CrossRef]
23. Velecela, O.; Soutis, C. Prediction of crushing morphology of GRP composite composite panels under edgewise compression. *Compos. Part B Eng.* **2007**, *38*, 914–923. [CrossRef]
24. Mamalis, A.; Manolakos, D.E.; Ioannidis, M.B.; Papapostolou, D.P. On the crushing response of composite composite panels subjected to edgewise compression: Experimental. *Compos. Struct.* **2005**, *71*, 246–257. [CrossRef]
25. George, T.; Deshpande, V.S.; Sharp, K.; Wadley, H.N. Hybrid core carbon fiber composite composite panels: Fabrication and mechanical response. *Compos. Struct.* **2014**, *108*, 696–710. [CrossRef]
26. Rostamiyan, Y.; Norouzi, H. Flatwise Compression Strength and Energy Absorption of Polyurethane Foam-Filled Lattice Core Composite Panels. *Strength Mater.* **2016**, *48*, 801–810. [CrossRef]
27. Abdi, B.; Azwan, S.; Abdullah, M.R.; Ayob, A.; Yahya, Y. Comparison of foam core composite panel and through—Thickness polymer pin–reinforced foam core composite panel subject to indentation and flatwise compression loadings. *Polym. Compos.* **2016**, *37*, 612–619. [CrossRef]
28. Mirzapour, A.; Beheshty, M.H.; Vafayan, M. The response of composite panels with rigid polyurethane foam cores under flexural loading. *Iran. Polym. J.* **2005**, *14*, 1082–1088.
29. Sharaf, T.; Shawkat, W.; Fam, A. Structural performance of composite wall panels with different foam core densities in one-way bending. *J. Compos. Mater.* **2010**, *44*, 2249–2263. [CrossRef]
30. Manalo, A. Structural behaviour of a prefabricated composite wall system made from rigid polyurethane foam and Magnesium Oxide board. *Constr. Build. Mater.* **2013**, *41*, 642–653. [CrossRef]
31. Dawood, M.; Taylor, E.; Ballew, W.; Rizkalla, S. Static and fatigue bending behavior of pultruded GFRP composite panels with through-thickness fiber insertions. *Compos. Part B Eng.* **2010**, *41*, 363–374. [CrossRef]
32. Wang, L.; Liu, W.; Wan, L.; Fang, H.; Hui, D. Mechanical performance of foam-filled lattice composite panels in four-point bending: Experimental investigation and analytical modeling. *Compos. Part B Eng.* **2014**, *67*, 270–279. [CrossRef]
33. Mostafa, A.; Shankar, K.; Morozov, E. Independent analytical technique for analysis of the flexural behaviour of the composite composite panels incorporated with shear keys concept. *Mater. Struct.* **2015**, *48*, 2455–2474. [CrossRef]
34. Mostafa, A.; Shankar, K.; Morozov, E. Behaviour of PU-foam/glass-fibre composite composite panels under flexural static load. *Mater. Struct.* **2015**, *48*, 1545–1559. [CrossRef]

35. Tuwair, H.; Hopkins, M.; Volz, J.; ElGawady, M.A.; Mohamed, M.; Chandrashekhara, K.; Birman, V. Evaluation of composite panels with various polyurethane foam-cores and ribs. *Compos. Part B Eng.* **2015**, *79*, 262–276. [CrossRef]
36. Mathieson, H.; Fam, A. High cycle fatigue under reversed bending of composite panels with GFRP skins and polyurethane foam core. *Compos. Struct.* **2014**, *113*, 31–39. [CrossRef]
37. Kumar, M.V.; Soragaon, B. Fabrication and evaluation of multilayered polyurethane foam core composite panels for static flexural stiffness. *Procedia Eng.* **2014**, *97*, 1227–1236. [CrossRef]
38. Garrido, M.; Correia, J.R.; Keller, T.; Cabral-Fonseca, S. Creep of Composite Panels with Longitudinal Reinforcement Ribs for Civil Engineering Applications: Experiments and Composite Creep Modeling. *J. Compos. Constr.* **2016**, *21*, 04016074. [CrossRef]
39. Junes, A.; Larbi, A.S. An indirect non-linear approach for the analysis of composite panels with TRC facings. *Constr. Build. Mater.* **2016**, *112*, 406–415. [CrossRef]
40. Kakroodi, A.R.; Khazabi, M.; Maynard, K.; Sain, M.; Kwon, O.S. Soy-based polyurethane spray foam insulations for light weight wall panels and their performances under monotonic and static cyclic shear forces. *Ind. Crops Prod.* **2015**, *74*, 1–8. [CrossRef]
41. Mostafa, A. Numerical analysis on the effect of shear keys pitch on the shear performance of foamed composite panels. *Eng. Struct.* **2015**, *101*, 216–232. [CrossRef]
42. Sharaf, T. Flexural Behaviour of Composite Panels Composed of Polyurethane Core and GFRP Skins and Ribs. Ph.D. Thesis, Queen's University, Kingston, ON, Canada, 2010.
43. Sharaf, T.; Fam, A. Experimental investigation of large-scale cladding composite panels under out-of-plane transverse loading for building applications. *J. Compos. Constr.* **2010**, *15*, 422–430. [CrossRef]
44. Sharaf, T.; Fam, A. Numerical modelling of composite panels with soft core and different rib configurations. *J. Reinf. Plast. Compos.* **2012**, *31*, 771–784. [CrossRef]
45. Sharaf, T.; Fam, A. Analysis of large scale cladding composite panels composed of GFRP skins and ribs and ribs and polyurethane foam core. *Thin-Walled Struct.* **2013**, *71*, 91–101. [CrossRef]
46. Mastali, M.; Valente, I.B.; Barros, J.A.; Gonçalves, D.M. Development of innovative hybrid composite panel slabs: Experimental results. *Compos. Struct.* **2015**, *133* (Suppl. C), 476–498. [CrossRef]
47. Mastali, M.; Valente, I.B.; Barros, A.O. Development of innovative hybrid composite panel slabs: Advanced numerical simulations and parametric studies. *Compos. Struct.* **2016**, *152* (Suppl. C), 362–381. [CrossRef]
48. Mastali, M.; Valente, I.; Barros, J.A. Flexural performance of innovative hybrid composite panels with special focus on the shear connection behavior. *Compos. Struct.* **2017**, *160*, 100–117. [CrossRef]
49. Dawood, M.; Taylor, E.; Rizkalla, S. Two-way bending behavior of 3-D GFRP composite panels with through-thickness fiber insertions. *Compos. Struct.* **2010**, *92*, 950–963. [CrossRef]
50. Amir Fam, T.S. Flexural performance of composite panels comprising polyurethane core and GFRP skins and ribs of various configurations. *Compos. Struct.* **2010**, *92*, 2927–2935.
51. Garrido, M.; Correia, J.R.; Keller, T. Effects of elevated temperature on the shear response of PET and PUR foams used in composite composite panels. *Constr. Build. Mater.* **2015**, *76*, 150–157. [CrossRef]
52. Garrido, M.; Correia, J.R.; Keller, T. Effect of service temperature on the shear creep response of rigid polyurethane foam used in composite composite floor panels. *Constr. Build. Mater.* **2016**, *118*, 235–244. [CrossRef]
53. Shams, A.; Stark, A.; Hoogen, F.; Hegger, J.; Schneider, H. Innovative composite structures made of high performance concrete and foamed polyurethane. *Compos. Struct.* **2015**, *121*, 271–279. [CrossRef]
54. Kim, J.H.; Lee, Y.S.; Park, B.J.; Kim, D.H. Evaluation of durability and strength of stitched foam-cored composite structures. *Compos. Struct.* **1999**, *47*, 543–550. [CrossRef]
55. Labans, E.; Kalnins, K.; Bisagni, C. Flexural behavior of composite panels with cellular wood, plywood stiffener/foam and thermoplastic composite core. *J. Compos. Struct. Mater.* **2017**, 1099636217699587. [CrossRef]
56. Abdolpour, H.; Kalnins, K.; Bisagni, C. Development of a composite prototype with GFRP profiles and composite panels used as a floor module of an emergency house. *Compos. Struct.* **2016**, *153*, 81–95. [CrossRef]
57. Jayaram, R.; Nagarajan, V.A.; Kumar, K.P. Polyester Pinning Effect on Flexural and Vibrational Characteristics of Foam Filled Honeycomb Composite Panels. *Latin Am. J. Solids Struct.* **2017**, *14*, 1314–1326. [CrossRef]
58. Reis, E.M.; Rizkalla, S.H. Material characteristics of 3-D FRP composite panels. *Constr. Build. Mater.* **2008**, *22*, 1009–1018. [CrossRef]

59. Mathieson, H.; Fam, A. Numerical modeling and experimental validation of axially loaded slender sandwich panels with soft core and various rib configurations. *Eng. Struct.* **2016**, *118*, 195–209. [CrossRef]
60. Mohamed, M.; Anandan, S.; Huo, Z.; Birman, V.; Volz, J.; Chandrashekhara, K. Manufacturing and characterization of polyurethane based composite composite structures. *Compos. Struct.* **2015**, *123*, 169–179. [CrossRef]
61. Abdi, B.; Azwan, S.; Abdullah, M.R.; Ayob, A.; Yahya, Y.; Xin, L. Flatwise compression and flexural behavior of foam core and polymer pin-reinforced foam core composite composite panels. *Int. J. Mech. Sci.* **2014**, *88*, 138–144. [CrossRef]
62. Saeed Nemati, P.S. *Bijan Samali, Shahab Khakpour, Compressive Behaviour of Modular Polyurethane Foam-Filled Composite Panels with 3-D High Density Polyethylene Skins*; Centre for Infrastructures Engineering (CIE), Western Sydney University: Sydney, Australia, 2017; pp. 1–21.
63. Koissin, V.; Shipsha, A.; Skvortsov, V. Compression strength of composite panels with sub-interface damage in the foam core. *Compos. Sci. Technol.* **2009**, *69*, 2231–2240. [CrossRef]
64. Jakobsen, J.; Bozhevolnaya, E.; Thomsen, O.T. New peel stopper concept for composite structures. *Compos. Sci. Technol.* **2007**, *67*, 3378–3385. [CrossRef]
65. Chen, M.; Zhou, G.; Wang, J. On mechanical behavior of looped fabric reinforced foam composite. *Compos. Struct.* **2014**, *118*, 159–169. [CrossRef]
66. Miron, M.C.; Constantinescu, D.M. Strain fields at an interface crack in a composite composite. *Mech. Mater.* **2011**, *43*, 870–884. [CrossRef]
67. Sharma, R.S.; Raghupathy, V. Influence of core density, core thickness, and rigid inserts on dynamic characteristics of sandwich panels with polyurethane foam as core. *J. Reinf. Plast. Compos.* **2010**, *29*, 3226–3236. [CrossRef]
68. Sharma, S.; Krishna, M.; Murthy, H.N. Delamination during drilling in polyurethane foam composite composite structures. *J. Mater. Eng. Perform.* **2006**, *15*, 306–310. [CrossRef]
69. Mostafa, A.; Shankar, K.; Morozov, E. Effect of shear keys diameter on the shear performance of composite composite panel with PVC and PU foam core: FE study. *Compos. Struct.* **2013**, *102*, 90–100. [CrossRef]
70. Rodrigo Lameiras, J.B.; Isabel Valente, B.; Miguel, A. Development of composite panels combining fibre reinforced concrete layers and fibre reinforced polymer connectors. Part I: Conception and pull-out tests. *Compos. Struct.* **2013**, *105*, 446–459. [CrossRef]
71. Yanes-Armas, S.; de Castro, J.; Keller, T. Long-term design of FRP-PUR web-core composite structures in building construction. *Compos. Struct.* **2017**, *181*, 214–228. [CrossRef]
72. Chan, K.E. Experimental and numerical studies of sustainable composite bio-composites derived from plant-based resources. *J. Compos. Struct. Mater.* **2017**, *19*, 192–215. [CrossRef]
73. Azmi, M.A.; Abdullah, H.; Idris, M.I. Properties of polyurethane foam/coconut coir fiber as a core material and as a composite composites component. In *IOP Conference Series: Materials Science and Engineering*; IOP Publishing: Bristol, UK, 2013.
74. Reany, J.; Grenestedt, J.L. Corrugated skin in a foam core composite panel. *Compos. Struct.* **2009**, *89*, 345–355. [CrossRef]
75. Kam, T.; Lai, F.; Chao, T. Optimum design of laminated composite foam-filled composite plates subjected to strength constraint. *Int. J. Solids Struct.* **1999**, *36*, 2865–2889. [CrossRef]
76. Arruda, M. Numerical modelling of the creep behaviour of GFRP composite panels using the Carrera Unified Formulation and Composite Creep Modelling. *Compos. Struct.* **2017**, *183*, 103–113. [CrossRef]