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Single and repetitive low-velocity impact responses of sandwich composite structures with different skin and core considerations: A review

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ABSTRACT

Sandwich structures are fast becoming prevalent in engineering fields due to their maximal stiffness coupled with minimal mass. However, additional to the commonly examined impact responses, which are more threatening versus those of static, the highly destructive repetitive impact loading is the more realistic condition evident in applications. Also, numerous failure modes have been observed but not well characterized for the sandwich structural configurations. This article, therefore, reviews the recent research advancements in the responses of sandwich structures subjected to low-velocity impact under both single and repetitive loading cases. The definitions of low-velocity impact are first discussed to provide the scope of this review, i.e., described as $\leq$ 100 m/s by different sources. The general impact performance metrics are then presented with the prospect of introducing an overall impact behavior appraisal by combining these terms into one non-dimensional index as recently published. Additionally, the paper offers an outlook on the common failure modes of sandwich structures, the relevant mode maps for failure type identification, and the factors that influence the structural responses under low-velocity impact. The main influencing factors of low-velocity impact responses comprise facesheet and core geometrical and material configurations, impactor characteristics, hydrothermal effects, and support conditions while less affected by the loading rate. Facesheet or core crushing, facesheet or core buckling, and delamination have been identified as the main failure modes regardless of due to single or repetitive impact, with indentation, penetration, and perforation being more central to the latter. Besides, several good practices for the typically employed finite element approach for investigating sandwich structures under low-velocity impact are summarized and recommended. To underline, the parametric ranges covered in this review include applied impact energies of 0.06 – 360 J, impact velocities of 0.5 – 34.2 m/s, with repeated impact numbers up to 400 times, resulting in absorption energies of 0.01 – 396.3 J, and the determined

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impact resistance efficiency indices within 0.57 – 143.73. The general observations of main findings summarizing impact resistance benefitting configurations and potential future directions of sandwich structure development are next laid out to motivate further studies.

1. Introduction

For the past several decades, the applications of sandwich composite structures have gained appreciable popularity, especially in fields such as civil infrastructures as well as aerospace, mechanical, and marine engineering [1–10]. Even though greatly considered as just recently developed, sandwich structures had long been employed and their concept can be traced back in 1849 to Fairbairn [11,12]. The most popular first key employment of sandwich structure design is often attributed to the Mosquito aircraft in the second World War although there were many other applications before that [13]. In literature, the first scientific paper concentrating on the in-plane loading behaviors of sandwich panels was authored in 1944 by Marguerre [14,15]. Sandwich structures with a honeycomb core are broadly applied in aerospace for constructing the external and interior bodies of military and commercial spacecraft since their lightness reduces the consumption of fuel [16]. In the automotive industry, sandwich structures are used in vehicles to absorb energy thereby protecting occupants against injuries in traffic accidents [17]. Despite all these attractions, only fairly recently are sandwich structures broadly adopted in civil engineering projects, for instance, in stairs, bridge decks, landings, piers, piles, beams, columns, walls, and roof claddings [18,19].

The contemporary increased research and development tractions in sandwich structures are attributable to their considerable lightness, high flexural and transverse strength, and good resistance to corrosion [20,21]. Furthermore, sandwich structures are specifically efficient for absorbing large amounts of energy under impact loads [22]. In essence, a sandwich structure contains the bondage of a thick core placed between two thin and stiff facesheets as shown in Fig. 1 [23]. The facesheets or skins are bonded to the core with an adhesive, the assemblage of which is normally cured using heat and pressure, although some adhesives can solidify at room temperature [24]. These layers are usually of different properties and relatively weak while flexible independently. It is well known that the connecting constituents are the weakest link in structural assemblies [25]. When assembled, the product can exhibit an enhanced performance more so than the individual constituents. The skin material provides axial stiffness to the structure whereas the core acts as an energy-absorbing layer. In other words, the facesheets carry the bending loads while the core handles the shear loads. The skin material types for the sandwich structures can vary a great deal; the most common ones are steel, aluminum, and fiber-reinforced composites. The core can exist in several structural and material configurations such as foams, honeycombs, and lattices [26]. Continually-expanding nature of the studies in sandwich structures has widened hugely the design scope in the current trend towards the employment of quasi-isotropic textile composite skins [2,9], silica aerogel infill for thermo-acoustic absorption efficiency [3], novel bioinspired designs [5,6,27–32], foldcores [33,34], tube reinforcement [35], metal laminated facesheets [36,37], carbon nanotubes [38], 3D printed components [39], functionally graded skins [40], considering induced dents [41], as well as enhanced interest in repeated impact responses [7,42–44], to simply list a few.

Being an efficient absorbing system, sandwich structures often experience loadings of dynamic nature, e.g., impacts, blasting, vibrations, etc. Low-velocity impact loads are of special research interest as the resulting appearance of damage zones is often hard to identify [6,45,46]. Since impact loads infer more destructive effects while also being the commonly occurring conditions in applications, extensive works have been devoted to studying their inflicted responses and therefore resulting in diverse improvements of the structures. Impact is an instantaneous event where the exerted load intensity is several times higher than if applied statically [6]. Owing to great susceptibility to impact damage, sandwich structures in the past few decades have seen various novel designs with the continual influx and iterations of new configurations for enhancement in resistance against this particular load type [47,48], thereby they form an active research category in the technological advancement of structures. Thus, focused subjects of study include but are not limited to contact responses between the impactor and loaded material surface, structural impact behaviors, failure modes, post-impact residual properties, high-velocity impact characteristics, and soft body impactor effects. As a result, studies on impact-resistant sandwich structures remain one of the top examined subjects with the aim of achieving the highest possible energy

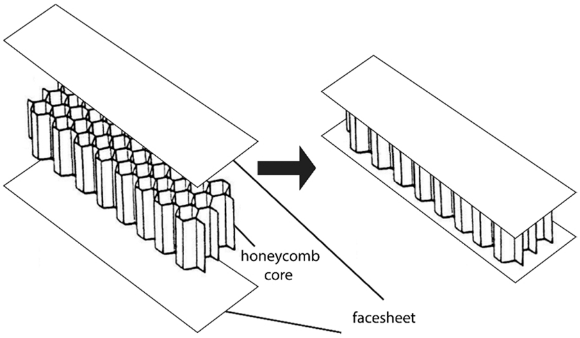

Fig. 1. Basic sandwich structure and its principal constituents.

absorption and crashworthiness in many engineering applications [16,48].

Accredited with an ever-broadening amount of research in the aforementioned aspects, this paper reviews how sandwich structures respond to single and repetitive impacts of low-velocity intensity. Such knowledge is crucial in understanding both the single and repetitive impact characteristics of sandwich structures to help analysts, designers, and practitioners to better anticipate, predict, and construct them at the site. Existing review papers on composite and sandwich structures such as [49–52] have discussed exclusively and expansively the single low-velocity impact of these structures. No review paper has thus far shed the light on the responses of sandwich structures under repetitive low-velocity impacts. Therefore, in terms of novelty, this paper is the first to review the existing scientific efforts in evaluating the repetitive low-velocity impact performances of sandwich structures for various skin and core types. The general evaluation metrics used to understand the impact behaviors of sandwich structures are then presented to offer an overview of the engineering terms adopted to examine their performance. Since diversity in impact responses is available thus making a direct comparison between designs difficult, an overall impact resistance index has been proposed for future comparative study purposes. This review also examines and discusses the failure modes experienced in the presence of single and repetitive impacts as well as failure maps constructed by previous researchers to predict the potential damage mechanisms. The commonly practiced finite element modeling choices complying with the observation of findings from both single and repetitive impact loading environments to ease decisions in simulation works are also presented. Gathering outlooks from these discussions, general observations of the typically witnessed findings are summarized, from which some of the prospective future directions are highlighted for the next phases of advancement in sandwich structure investigations and improvements. Since the most current review on the single low-velocity impact characteristics of sandwich structures was conducted in 2011 [49], this article will also cover the research studies on the single low-velocity impact between then and 2022 from the perspectives of both experiments and simulations. High-velocity impact and blasting responses of sandwich structures are, therefore, beyond the scope of the current review.

2. Definitions of low-velocity impact

Impacts are fundamentally classified in dictation by velocity into two types: low- and high-velocities impacts. There is, however, no clear dividing description that separates these two categories since no consensus has been reached by researchers on their definition. This is evident in varying descriptions in defining low- and high-velocities by different authors. Hancox [53] defined impact as the instantaneous application of force to a part of a structure. Yaghoubi et al. [54] suggested that a low-velocity impact has a loading rate from 1 to 5 m/s. Cantwell and Morton [55] described it as an impact with a velocity of lesser than 10 m/s. Abrate [56] defined a value of lower than 100 m/s as a low-velocity impact. Furthermore, Robinson and Davies [57] and Davies and Robinson [58] characterized a low-velocity impact as an incident where there is no noticeable role of the through-thickness stress wave in the stress distribution. The covered impact velocity range gathered from the articles for the current review is 0.5 – 34.2 m/s [59,60].

Under low-velocity impact, Davies and Robinson [58] asserted that a cylindrical zone beneath the impactor experiences a uniform compressive strain (ε_c) when the stress waves start to propagate through the plate, which can be expressed as:

$$\varepsilon_c = \frac{impactorvelocity}{speedofsoundinthematerial} \tag{1}$$

Forwarding from these low-range velocities, the high-velocity impact is described as a loading rate of up to 1 km/s. The hyper-velocity impact, which is more relevant to extra-galactical debris, possesses a rate typically in the range of 2–5 km/s [48]. Generally, the impact phenomenon can be categorized into two responses. The first response is based on the structural deformation, while the second one is on the loading behaviors, i.e., velocity, mass, duration, and type of impactor.

3. Assessed responses

Impact responses are commonly assessed through long-established techniques via the plotting of structural relationships, for instance, force-time, displacement-time, velocity-time, acceleration-time, force-deformation, and derived from these are energy-time and the famous product from the graph, absorbed energy. The chief response customarily determined by means of either numerical or experimental approaches is the force history of the impact incident. The force can be determined experimentally through the inte-

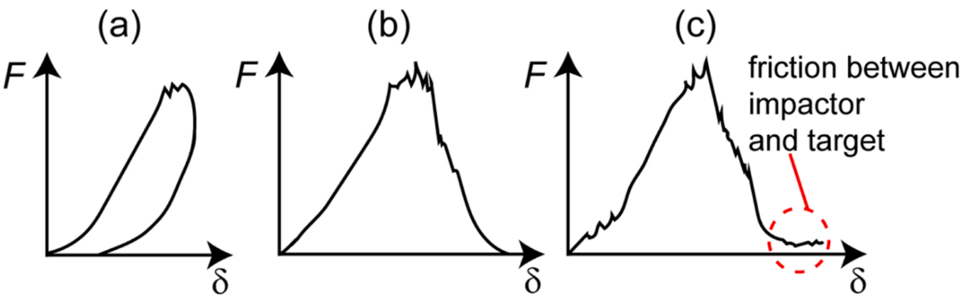

Fig. 2. Typical force-deflection curves: (a) impactor rebound (b) penetration (c) complete perforation.

gration of the deformation history or interpretation of the acceleration history produced by the accelerator or simply read by the force transducer attached to the specimen under study. The force-deformation plots in the presence of low-velocity impact typically take the forms revealed in Fig. 2 [61]. The curve loops somewhat back to the origin if there exists a rebound of the impactor. If instead, the impactor penetrates through the structure, the curve progresses away to the right side of the peak value during unloading with a small plateau region near the end of the unloading phase for full perforation, characterizing the friction between the impactor and structure. A penetration with no perforation is represented by the return of the curve back to $F = 0$ after a certain post-peak deformation. Energy-absorbing ability is the next most obligatorily assessed impact behavior of sandwich structures. The engineering parameter is commonly derived from the plateau value of the energy-time relationship as depicted in Fig. 3 [61]. The energy-time curve is itself obtained from the area under the graph of force-deformation or through progressive velocity in accordance with the period as expressed below.

$$E = \frac{m_I}{2}\left[{v_1}^2 - {v_2}^2\right] \tag{2}$$

where m_I is the mass of the impactor while v_1 and v_2 are the initial and time $= t$ impact velocities of the impactor, respectively. From the energy-time curve, the total impact energy consists of rebound and absorbed energies (E_r and E_{abs}, respectively). E_{abs} generally surges with impact velocity and transverse stiffness of panels [61]. In terms of impact performance, high energy absorption is considered a superior and preferred behavior. This is, however, offset at the cost of the irreversible deformation of the considered structures in terms of energy dissipation through numerous damage forms like fiber fracture, matrix crack, core buckling or shearing, core crushing and yielding, delamination, etc. This review finds from the current papers list the employment of the applied impact energies and absorption energies in the ranges of 0.06 – 360 J and 0.01 – 396.3 J, respectively [62–64].

Appraising the impact behaviors of sandwich structures with the aforementioned relationships independently can be less wholesome in the behaviors evaluation study as a specimen can have higher energy absorption but at the same instance experiences a great degree of damage as well. In any impact event, the objective of achieving the desired good performance of a proposed resisting structure is by having a high peak impact force and energy absorption while keeping the damage area, maximum stress, and mass as low as possible. A unifying concept has been proposed by Kueh et al. and Abo Sabah et al. [4–8] through the non-dimensional overall impact resistance efficiency index, I_e, formulated as

$$I_e = \frac{E_{abs}F_{\max}}{A_d g m_b t \sigma_{\max}} \tag{3}$$

where A_d is the area of damage, E_{abs} is the absorption energy, F_{max} is the maximum contact force, g is the acceleration of gravity, m_b is the mass of the sandwich structure, t is the structure's entire thickness, and σ_{max} is the maximum stress. For comparative purposes, the use of I_e is, thus, fair amongst sandwich structures under study due to its non-dimensional feature, which is regularized by the mass and thickness of compared specimens. The greater the I_e term, the better its overall impact performance is. I_e found from the current articles fall in the range of 0.57 – 143.73 [6,7].

4. Low-velocity impact load types

Within the realm of low-velocity impacts, the investigation of structural behaviors can be carried out from the viewpoints of single and repetitive impacts. Figs. 4 and 5 depict the typical low-velocity experimental setups for measuring the structural responses of tested samples [65,66]. Two chief components are essential; (1) the impactor's behaviors as measured with load cell, accelerometers, or digital dial indicator in evaluating the applied force and acceleration and the data acquisition device to gather, register, and process the numerical information as well as (2) specimen deformation, the responses of which are captured and recorded either with a high-speed camera or strain gages before collected and processed with the data acquisition or computer using certain software.

4.1. Single impact

The existing stock of studies on singly impacted behaviors of sandwich structures is extensive. The existing review papers on

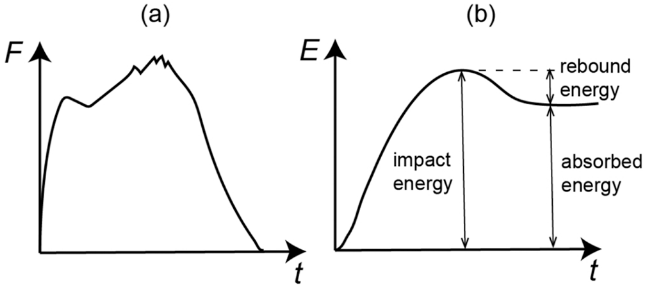

Fig. 3. (a) Force history and (b) energy history relationships of the sandwich structure under impact load.

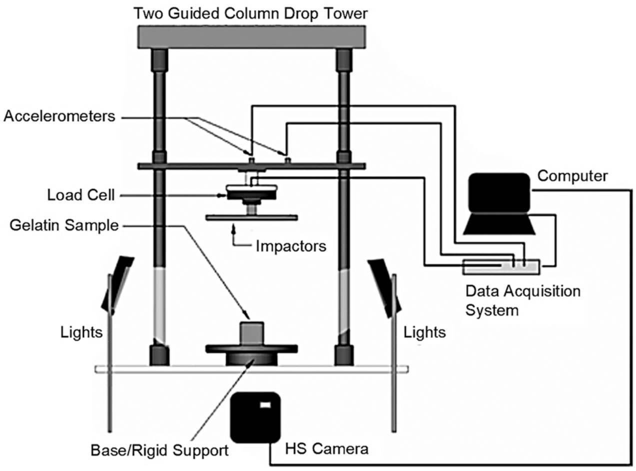

Fig. 4. Typical layout of low-velocity test setup.
(Adapted from [65]).

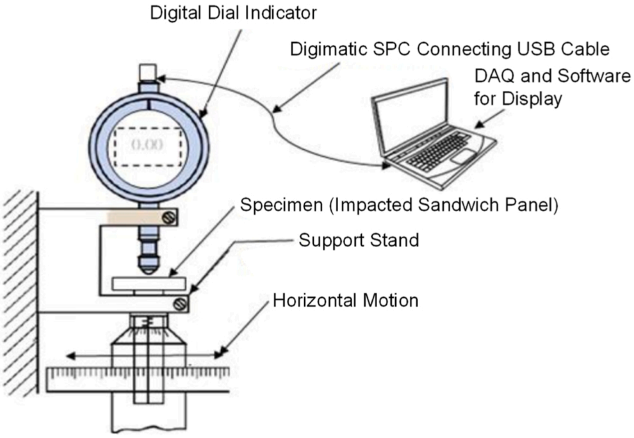

Fig. 5. Incident facesheet residual depth measurement using a high-precision micrometer gauge.
(Adapted from [66]).

various aspects of sandwich structures have covered notoriously this particular loading behavior [48,49]. Therefore, listing all available studies on single impact behaviors of sandwich structures is not attempted nor should be anticipated here. Rather, only the chief characteristics along with relevant references are discussed. Sandwich composite structures may experience single impacts during fabrication or in service. Most of the previous studies on sandwich structure responses to low-velocity impacts had concentrated on the single-hit impact at various impact energy intensities [6,67–69]. Although a single impact, especially that of a low energy level, may not typically cause visible damage to the sandwich structure [70], the load potentially reduces the residual strength [71].

In general, sandwich structures can be classified based on their general skin material and core design. Metallic and polymeric foams have been widely employed as sandwich cores due to their beneficial energy absorbance. Rajaneesh et al. [72] reported that the Polyvinyl Chloride (PVC) foam fails either by a core shear plug or a blend of conoid failure and shear plug. Hazizan et al. [73] revealed that the skin and core materials do not demonstrate any loading rate sensitivity for sandwich structures with polymeric foam in the presence of impact. Zhou et al. [74] witnessed that the perforation capacity of the polymeric foam core of sandwich plates subjected to the low-velocity impact depends chiefly on the properties of the core. With expanded polystyrene (EPS) foam core, its density was unveiled by Caliskan and Apalak [75] as more efficient in the impact energy absorption, and there was an increase of plastic dissipation energy in the facesheets. He et al. [76] concluded that the maximum impact load of aluminum honeycomb core panels is greatly affected by the side length of the core and cell wall thickness but the variation in core height inflicts negligible effect. The more rapid absorption of impact energy with largely reduced top skin deformation are the advantages found in sandwich structures with honeycomb voids infilled with metallic tubes vs those without [35].

Being one of the variants of a 2D periodic core, auxetic honeycomb structures as reentrant core are intriguing for numerous applications due to their excellent impact absorption response. For the same areal density, size, and material, Zangana et al. [77] unveiled that continuous fibers between adjacent cells of multicell corrugated core uplift the impact resistance of their proposed sandwich structures and that the trapezoidal variant displays better specific strength vs. regular honeycomb, foam, and truss cores, the sequence of deformation of which can be witnessed due to different kinetic energies in Fig. 6. It can be observed that an increase in impact energy from 25 J to 40 J raises the peak responses of both impact force and absorbed energy. A recently proposed s-shaped foldcore sandwich structure reveals greater impact strength in the case when the impactor diameter is larger than the cell span [33].

Qi et al. [78] found that combining a steel plate and an auxetic sandwich panel containing honeycomb cores with hexagonal re-entrant cells is superior to that of conventional honeycomb cores. Corrugated cores, such as triangular, rectangular, and trapezoidal types, have been instrumental in the development of sandwich structures in offering excellent impact energy absorption and resistance. The damage of sandwich structures with trapezoidal corrugated aluminum core and carbon fiber reinforced polymer (CFRP) facesheets due to low-velocity impact relies strongly on the impactor geometry, location, and energy resulting in fiber fracture, matrix crack, and

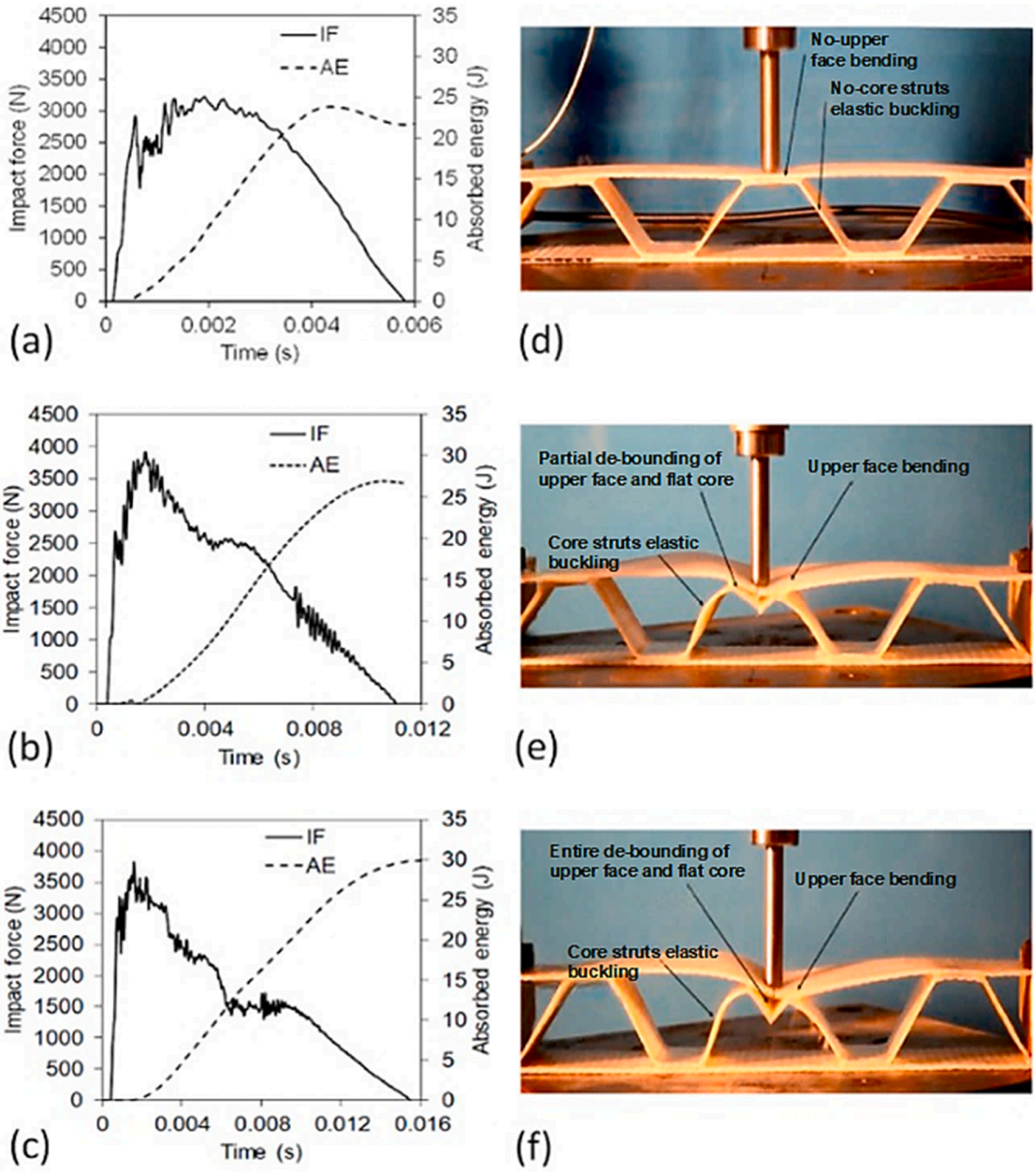

Fig. 6. Sandwich impact test at low-velocity with three different kinetic energies of ~ 25 J, 33 J, and 40 J as well as force-time responses in (a) through (c) and the corresponding images taken at maximum displacement in (d) through (f).
(Adapted from [77]).

delamination of the skins with core buckling [79]. Impacted by metal foam projectiles, Rubino et al. [80] witnessed that stainless-steel sandwich beams integrated with a Y-frame/corrugated core display better impact performance than monolithic materials. This is attributed to the strengthening mechanism by means of inertial stabilization in the core members [81]. The metal foam and corrugated core for sandwich beams demonstrate the best impact performance vs. that of stainless-steel sandwich type under metal foam projectiles [82].

In contrast to the 2D periodic cores, the 3D types enhance the impact responses by offering a set of core cavities for cellular foams infill. The post-impact residual tensile strength of sandwich structures containing the carbon fiber composite latticed core can be classified into several stages corresponding to impact energies and amplitudes, via the influence of different stacking sequences [83]. A slight rise in the maximum impact load and shorter contact duration was observed in the PU foam-filled pyramidal lattice core sandwich plates [84]. Two-phase energy absorption advantage can be spotted in sandwich structures with textile-reinforced composite foldcores, thereby opening wide options for the altercation of impact performance through the constituent and shape variations in design [85]. Significant enhancements in initial damage initialization load and energy absorption with reduced damage area can be achieved by adding pins in hybrid foam-filled honeycomb sandwich structures to better resist low-velocity impacts [86]. He et al. [87] revealed that the X-frame metal core maximizes the specific flexural stiffness and impact resistance of sandwich structures with CFRP skins and alloy aluminum cores.

Using different facesheets and core thicknesses, Tan et al. [88] examined the responses of sandwich beams under a single impact and observed that the core shear is the prominent failure state. Fig. 7 displays the plastic hinges formed due to core shear failure under impact in their evaluated specimens. These plastic hinges aid in amplifying the impact resistance of their assessed structures. Additionally, an inclined core crack, typically about 45° from the main beam axis, can be noticed especially in specimen D-3, which is common for shear failure under flexural load. Zhang et al. [89] investigated the foamed sandwich structures subjected to a single low-velocity impact and discovered that their perforation resistance is proportional to the density of the foam. With a stacking sequence of [± 45/core/ ± 45] where core = balsa wood or PVC foam, Atas and Cevim [90] identified that balsa core specimens exhibit higher stiffness than those with PVC core, the former of which experiences greater contact force but lower deflection at small impact energy levels. But, for the balsa core sandwich structures, attributed to relatively poorer bondage between the glass/epoxy facesheet and balsa wood, the dominant damage mode is the facesheet-core debonding alongside fiber flexural breakage as the impact load increases.

Compression after impact (CAI) behaviors of sandwiches are among the widely examined responses attributed to significant damage like debonding in assemblage incurred after exposure to impact. The corresponding structural reaction is a compilation of several nonlinearities: (1) geometrical non-linear characteristics due to the neutral plane shifting by the resulted dent, (2) material nonlinearity in the core, and (3) plastic or damage response of the facesheets [91,92]. Post-impact, sandwich structures are more vulnerable to compression specifically when loaded along the axial direction as debonding, even if small in intensity, can be further enhanced. Ye et al. [93] noticed that with the same thickness, the residual strength of honeycomb sandwich plates under the quasi-static indentor load is lower than that of low-velocity impact but more similar to that of repetitive quasi-static indentation and that the damage is better defined by volume than by thickness. The corresponding normal strain distributions during indentation in the rear facesheet are revealed in Fig. 8 under 8.5, 10, 11.5, and 13 mm drop displacements (Fig. 8(a), (b), (c), and (d), respectively). The normal strains are distributed in terms of butterfly-like shapes in the x-direction (Fig. 8(a-1) to (d-1)) while occur bulbous in the y-direction (Fig. 8(a-2) to (d-2)). Both the x- and y-directions strains are symmetrically divided, with the left and right sites of the central line in the former under compression and tension, respectively. The central area for strain in the y-direction experiences tension while those above and below are in compression. Yang et al. [94] reported that sandwich panels with carbon fiber (C) facesheet have degraded impact performance compared with those with glass fiber (G) sheets. Moreover, the hybridized panel with a stacking sequence of [C_2/G_2/Foam core/G_2/C_2] offers greater peak contact force and absorbance by having carbon fiber as the sacrificial component during contact, i.e., when it is placed near the outer position.

Reductions of 18% and 30% compressive strength in aluminum honeycomb sandwich panels were found by Tariq et al. [41] in the occurrences of 10 mm and 15 mm diameter dents, respectively. Impact damage correlates directly with impact energy whereas CAI strength is related inversely for sandwich plates with aluminum facesheets and Nomex honeycomb core [95]. For aluminum alloy 5754 sandwiching aluminum 3003 core panels, the facesheet thickness influences the impact behavior the most but the core thickness

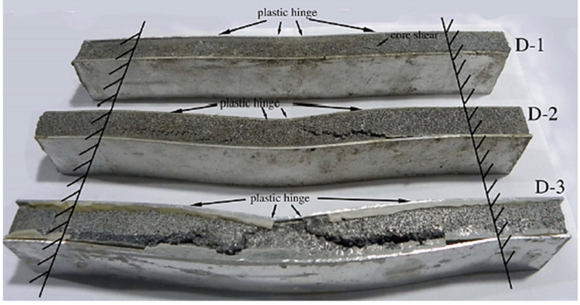

Fig. 7. Core shear failure of sandwich beams under a single impact velocity.
(Adapted from [88]).

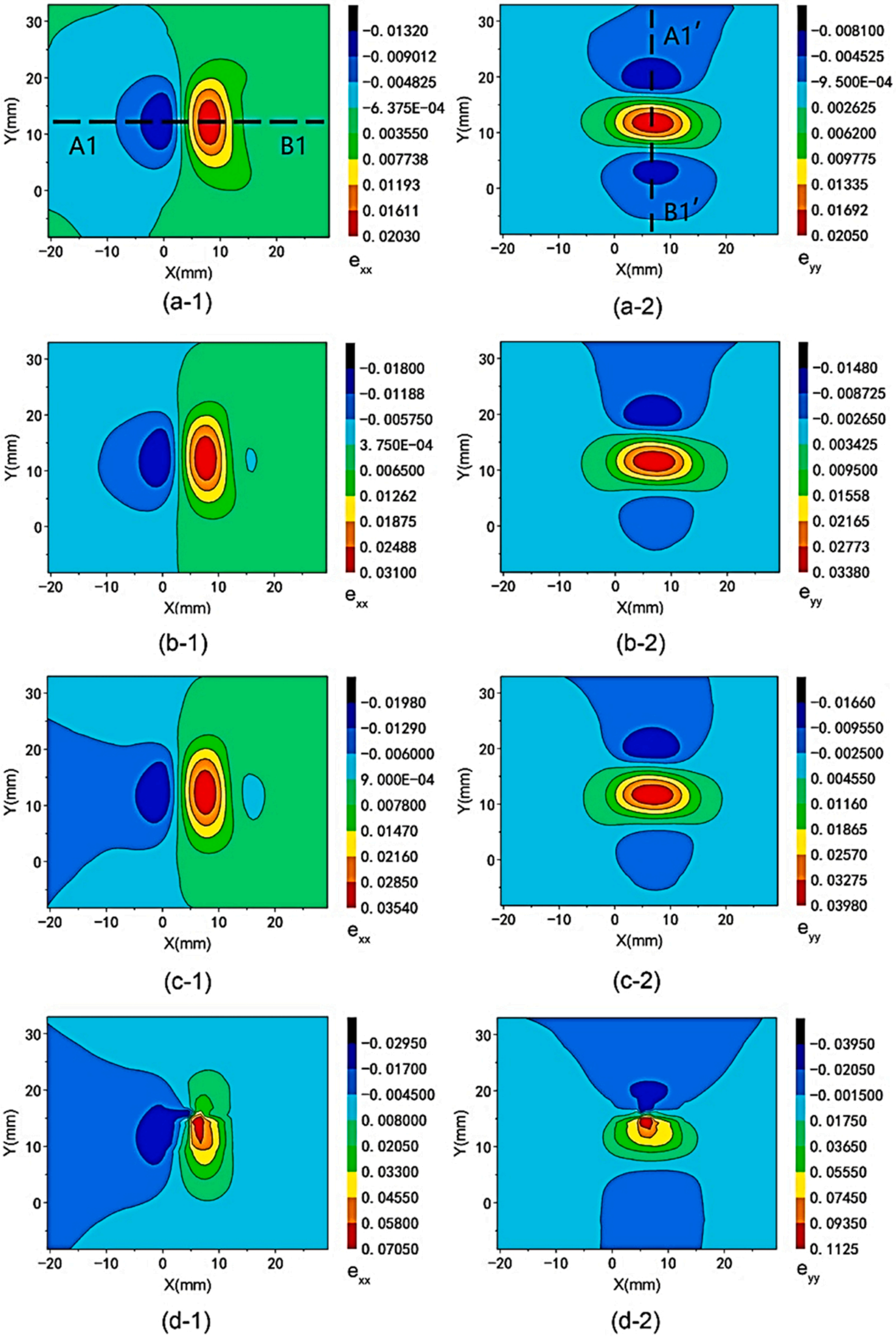

Fig. 8. Distributions of normal strain in the rear facesheet of honeycomb sandwich plates: in the x-direction from (a-1) to (d-1) and in the y-direction from (a-2) to (d-2) where (a) – (d) designate drop displacements of 8.5, 10, 11.5, and 13 mm, respectively.
(Adapted from [93]).

imposes a negligible effect on the strength [96]. To handle cracks formation on the lower surface of plywood structures, Yellur et al. [97] optimized the utility vehicle segment and found that at an impact energy of 100 J, a honeycomb sandwich board with the [0/90/90/0/core/0/90/90/0] arrangement mode performs the best under low-velocity impact.

In expanding the design envelope, bio-inspired concepts are gaining strong traction in the development of novel sandwich structures recently. The lightweight sandwich structure with the double-sine corrugated cores as inspired by peacock mantis shrimp's dactyl strike was observed to enhance the energy absorbance via a reduced initial maximum load vs. the conventional sinusoidal, triangular corrugated core types [98]. Abo Sabah et al. [6] proposed a woodpecker head-inspired sandwich beam configuration with a superiority of 2.7–5.7 times greater impact resistance efficiency than conventional design. Sandwich honeycombs made with carbon fiber based on the recurrent zone of the dactyl club exhibited 60.9% and 106% improved contact forces in contrast to honeycomb sandwiches with plain-woven and unidirectional skins, respectively [28]. An upgraded impact performance can be similarly found in the same design but with basalt fiber [27]. Wu et al. [99] modeled physically the honeycomb core CFRP panels based on the turtle's shell with the observations that there is more impact energy absorption but a smaller highest load compared to conventional sandwich configuration. By inserting small pipes at junctions of the honeycomb core wall, beetle forewing-inspired sandwich panels illustrated up to five times greater compression and energy regulation than the conventional honeycombs [100,101]. Using the design of the mollusk shell nacre, better regulation of load as well as lowered fiber damage and laminae delamination were witnessed in plates with changing interlocking and undulating laminates [29].

Plants have also provided rich inspiration for engineering structure designs. By inspecting the mechanical features of the tropical spiky fruit, *durian*, San Ha et al. [31] observed theoretically that its round combined with thorny profile and mesocarp materials portrays great energy absorption, a beneficial feature for packing applications. Following the design of macrofiber reinforcement organization of Palmetto wood, Haldar and Bruck [102] found a growth in elastic energy absorption and bending strength in the foam core fused with pultruded carbon bars. Furthermore, amplifications in rigidity, maximum load, and energy absorbance were seen in the sandwich plates with the leaf configuration mimicry [32,103,104]. An enhancement in crashworthiness was found in coconut mesocarp core sandwich designs vs. those with corrugated metal [105].

4.2. Repetitive impact

In real life, structures are not only subjected to single impact loadings. Rather repetitively loaded conditions are more commonplace. For instance, marine structures are often prone to repetitive impacts when being slammed by water currents. Pile caps experience fracture and damage when being driven into the soil as a result of repetitive impacts caused by the hydraulic hammer.

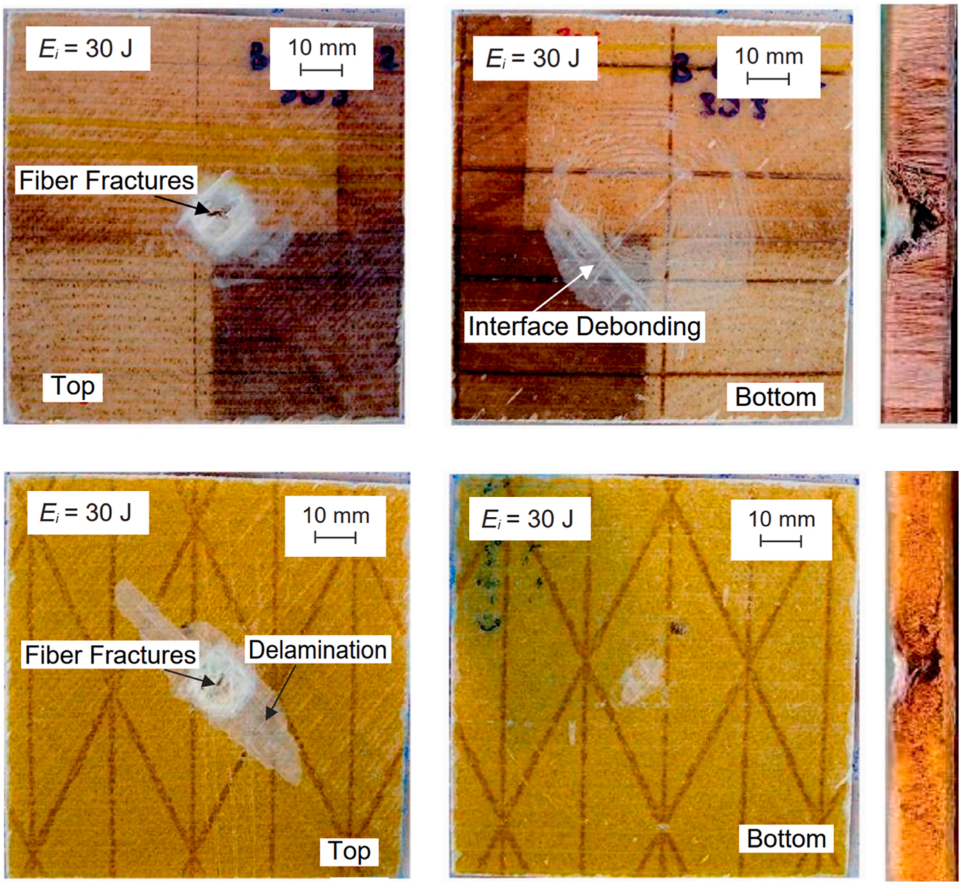

Fig. 9. Damage of sandwich composites made from foam core and balsa when struck with an impact energy of 30 J.
(Adapted from [90]).

Furthermore, floors of factories, heavy good stores, and laboratories possess high damage tendencies when being impacted by heavy objects and tool drops. According to a collision survey, ships and offshore structures both experience repetitive impacts other than waves. From 1976 through 1982 in the United Kingdom alone, 107 collision incidents occurred in the North Sea as the ships arrived or left the offshore structures [106]. Therefore, repetitive impacts are of great concern for various practical reasons. However, little is known about the behaviors of structures in the presence of such loadings.

Repetitive impact behaviors of sandwich structures are a fairly recent investigation subject. Thus, the relevant responses are relatively new. Atas and Sevim [90] investigated physically the reaction of glass/epoxy composite sandwiches with cores of PVC foam and balsa wood in the presence of repetitive low-velocity impacts. As shown in Fig. 9, the damage modes caused by repetitive impacts are: top and bottom skins fiber fractures, core fractures, debonding between skins and core, and delamination of the glass/epoxy sheets. It has been reported that specimens experience the first catastrophic failure, which is initiated from the impacted site. Also, the delamination oriented in the fiber direction of the top facesheet second layer becomes more intense in the foam core sandwich structures. In comparison, the damage region is concentrated around the top facesheet impacted area in balsa core sandwich samples. The absorbing energy and moment parameters of sandwich composite structures due to low-velocity repetitive impacts were calculated by Torre and Kenny [107]. It was concluded that the decrease in the energy absorption during the impact event is compensated by the reduction produced by the moment channeled to the bottom skin. It was found that by decreasing the impact energy, the impact number causing full perforation is increased. Balcı et al. [108] experimentally examined single and repetitive impact reactions of repaired sandwich structures with honeycomb core used in Airbus cargo boards. Their results showed that the repairing process increases the panels' damage resistance and the load capacity (230% increase).

Abo Sabah et al. [7] proposed a new bioinspired sandwich beam to enhance the low-velocity repetitive impact performance of sandwich structures. Their bioinspired sandwich beam proves to be more effective in resisting both single and repetitive impacts than the conventional design. Ozdemir et al. [109] assessed the low-velocity repetitive impact resistance of a bio-sandwich with E-glass fiber laminas and balsa core with the finding that the perforating number of impacts is inversely proportional to the impact energy. The work also introduced an equation to determine the number of impacts causing full perforation of the sandwich structure. Guo et al. [110] also found that the elastic energy increases with the impact number whereas the plastic deformation is inversely proportional to the impact number.

In general, the damage exerted by repeated impacts is best described by volume rather than by depth as the residual strength declines with the increase in damage volume at the same damage depth [93]. For honeycomb core sandwich structures, the compressive deformations broaden gradually before reaching densification. Both top and bottom facesheets play an essential role in repeated impact energy absorption. The bottom facesheet deformation mode shifts from the global bending, which is common for a low-velocity impact response, to the coupling of the global bending and local indentation. Furthermore, the accumulation of plastic deformation and energy absorption under repeated impact loads can be effectively modulated by the wall thickness and length of honeycomb cells as well as the facesheet thickness [110]. For higher impact energy values, it is found that both sandwich composites with either foam or balsa core attain nearly the same repeated impact number to perforation. On the other hand, as the impact energy decreases, the number of repeated impacts until perforation rises for foam core samples vs that employing balsa wood [90]. It is noted that the repeated impact numbers conducted by the currently reviewed works cover that up to 400 times [90]. Most repeated impact numbers are carried out up to 10 times only [110–112].

5. Factors influencing the impact responses of sandwich structures

Low-velocity impacts can cause damage to facesheets, core, and the facesheet-core interface as discussed earlier. Unfortunately, these damages are oftentimes barely visible under crude inspection. Even so, their effects on reducing the strength and stiffness of the material are rather significant [113]. Therefore, the next series of subsections aims to present some of the factors that influence the impact responses of sandwich structures.

5.1. Thickness and stacking sequence of the facesheet

A surge in the number of impacts extends reasonably the matrix cracking, fiber failure, and delamination of laminated assembly [114]. The front and back facesheets of sandwich plates respond distinctively to the increase in impact numbers and impact energy where there is greater deterioration in the residual load capacity of the front facesheets than those of the back [63]. Atas at el. [115] studied the impact behavior of foamed sandwich composite boards with diverse skin thicknesses under impact. It was found that increasing the skin thickness raises the sandwich's impact resistance thereby allowing the structure to deflect more before reaching failure. It was also noticed that increasing the skin thickness leads to a linear increase in the perforation threshold. Wang et al. [116] reported that increasing the thickness of the skin of a sandwich panel causes a decrease in the absorption energy-impact energy ratio and contact period and a rise in the peak load. Huo et al. [64] identified that skin thickness has a significant influence on the mechanical response of a sandwich structure due to impact loading whether the material of the skin is ductile or brittle. The facesheet thickness does not only influence the mechanical behavior of the sandwich but it significantly influences the overall impact performance of the sandwich structure [75,117,118]. Therefore, it can be gathered that increasing the thickness of the skin will make the structure more resistant to impacts. However, it will compromise the mass of the structure. Therefore, new research aiming to produce special formulas or maps to optimize the relationship between the skin thickness and the mass of the sandwich structure is of great applicability.

Mohmmed et al. [119] studied the impact reaction of foamed sandwich composite panels with various stacking sequences under impact. It is noticed that the skin stacking sequences influence the impact peak load and failure mode of the sandwich structure. Yang et al. [94] also noted that the stacking sequence greatly influences the damage mode of sandwich structures under low-velocity impact loadings. This can be inspected in the resulting distinctive fracture morphologies as depicted in Fig. 10 due to different through-thickness skin and core arrangements. Fig. 10(I) – (VI) denote different stacking sequences of the studied specimens: [C_4/F/C_4], [C_2/G_2/F/G_2/C_2], [G_2/C_2/F/C_2/G_2], [G/C/G/C/F/C/G/C/G], [G/C_2/G/F/G/C_2/G], and [G_4/F/G_4], respectively, where C, G, and F define carbon fabric, glass fabric, and foam core. It is discovered that the stacking sequence of the facesheet affects the shape and size of delamination during the impact event as well, the two chief damage modes of which are facesheet wrinkling and foam buckling from the CAI test. Wang et al. [83] found that degradation of the remaining tensile strength of the sandwich structures hinges on the stacking sequence. Fard et al. [120] reported, however, that the facesheet stacking sequence has a minimal consequence on the impact force and the contact period. At 40 J impact energy, a 31.6% higher maximum load can be achieved in the inter-ply hybrid foam core sandwich plate vs the specimens where the carbon layer is nearing the outer surface where Kevlar interfaces with the facesheet [66].

5.2. Core thickness, density, and number

Core materials have lower mechanical capacities compared to skins due to their low density and thus they also influence the damage initiation of sandwich structures [121]. The core thickness of a sandwich structure significantly controls its impact behavior [122] and the damage mode [123] under impact loading. For thin cores, the crushing spreads in the plane of the damage, but it propagates across the panel thickness in thick cores. Gunes and Arslan [124] experimentally investigated the low-velocity behaviors of sandwich structures containing aluminum honeycomb and constructed a realistic model to predict the consequences of the core cell size on the sandwich structural responses under low-velocity impacts. It was discovered that the core cell size plays a significant role in the behaviors of sandwich structures with aluminum honeycomb. When the cell size is reduced, both the stability and stiffness of the structure are improved. Ozdemir et al. [109] examined the effects of core thickness on the low-velocity impact behaviors of sandwich structures with balsa wood core. It is remarked that the perforation threshold rises with the core thickness. Although the thickness of the core enhances the impact resistance of the sandwich structure, it jeopardizes the mass of the whole structure. Increasing the core thickness helps increase the elastic behavior and perforation threshold of the sandwich structure. It also increases the absorbed energy. However, it reduces the maximum contact force [125]. Thus, it can be noted that the effects of core thickness are similar to that of the skin by improving the sandwich structure performance under low-velocity impacts but increasing the overall mass of the sandwich.

The effects of changing the density of the foam core of sandwich structures attributed to low-velocity impact were assessed by Caliskan and Apalak [75]. It is noticed that increasing the density of the core reduces the permanent deflection of the sandwich for numerous impact energies as demonstrated in Fig. 11. Mcquigg and Kapania [126] indicated that core density dictates the damage mode of the sandwich structures under impact as well. Zhang et al. [127] explored physically and computationally the effects of core density on the CAI strength in sandwich structures with pyramidal truss cores. It was noticed that as the core density increases, the CAI strength increases too. Similarly, Hassan and Cantwell [128] investigated the effects of core properties on the perforation resistance of sandwich structures containing foam core under low-velocity impact loadings. It is remarked the improved toughness of the structures follows an increase in core density. Loganathan and Shivanand [129] stated that increasing the core density helps increase the sandwich energy absorption. Therefore, the core density can have a direct effect on deflection, energy absorption, and damage mechanisms of sandwich structures in the presence of low-velocity impacts.

Dual-core sandwich structures have been of interest as the subject of study recently. Heimbs et al. [85] appraised the responses of dual-core sandwich structures with those of single-core attributed to low-velocity impact. Their dual-core was of aramid and carbon fiber-reinforced polymer parted by a CFRP sheet. It was found that the dual-core structure exhibits greater strength and stiffness

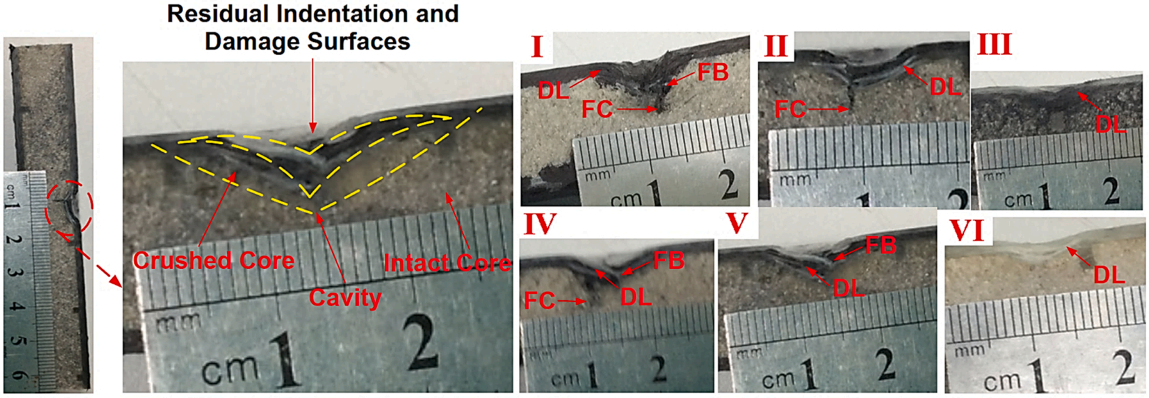

Fig. 10. Foam core sandwich panels' transverse fracture morphology after impact. Note: FB = fiber breaking, DL = delamination, and FC = foam cracking
(Adapted from [94]).

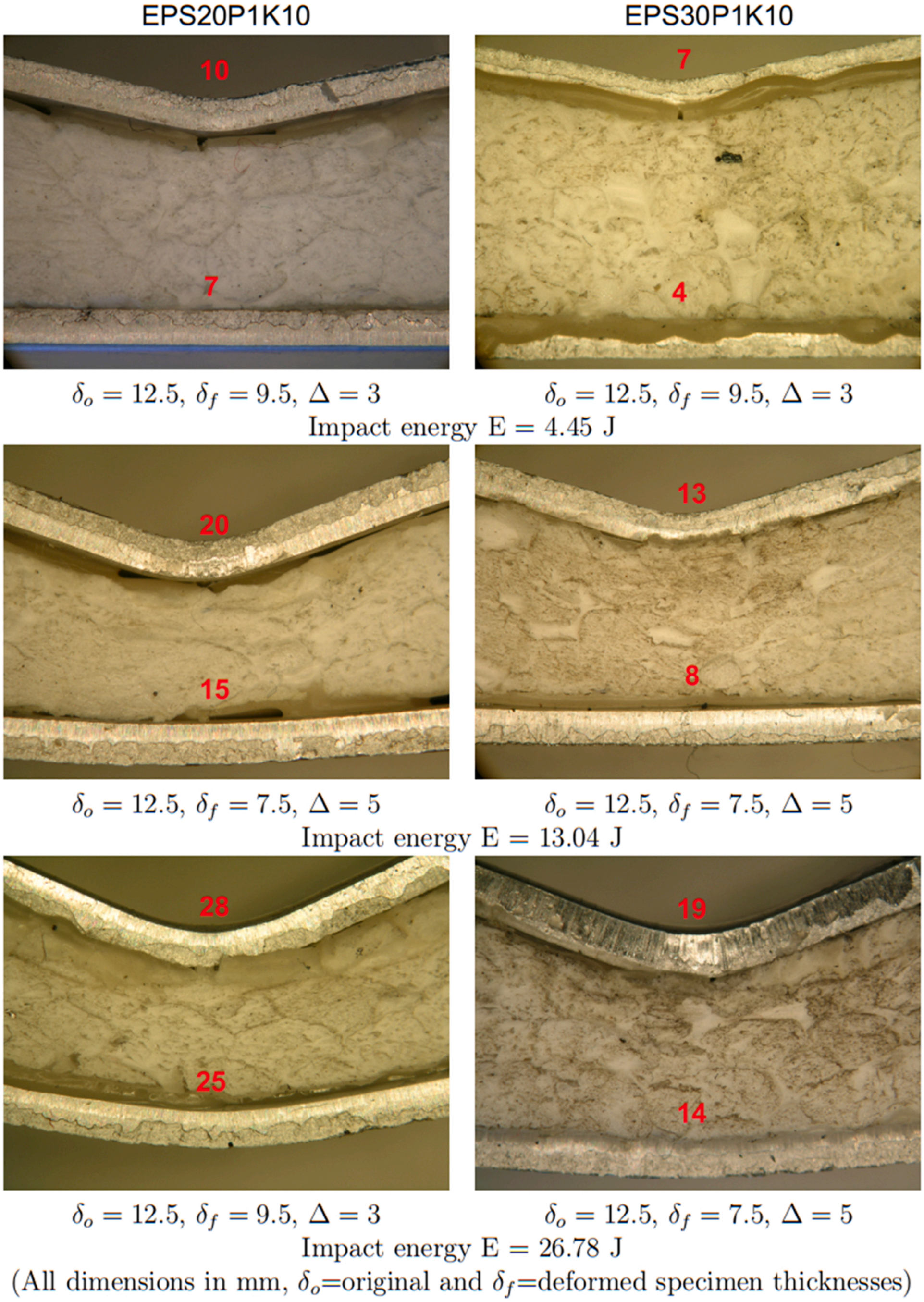

Fig. 11. Effects of the foam core density for impact energies of ~ 4.5, 13, and 26.8 J on variations in the after-impact thickness of the central impact region (facesheet of 1 mm and foam core of 10 mm).
(Adapted from [75]).

properties. Kılıçaslan et al. [130] assessed the impact responses of corrugated and trapezoidal aluminum cores and aluminum skin sandwich structures. Their studied outcomes revealed that the chief deformations are the advancing fin folding of the corrugated core and flexure of skins and interlayers. Abo Sabah et al. [6,7] combined two different types of cores in a sandwich beam: a viscoelastic rubber core and an aluminum honeycomb core to boost the single and repetitive low-velocity impact performance of lightweight sandwich structures. Fig. 12 reveals that the damage areas of the conventional honeycomb core sandwich beams (HSB) are consistently much greater than their bioinspired designs (BHSB). It was found that the novel inclusion of the rubber layer reduces the damage by 60 – 95% vs. the conventional sandwich beams at different impact energy levels. From these studies, it can be concluded that the dual-core sandwich configuration is more effective in terms of impact performance than the single-core system.

One of the exciting common reinforcement techniques to improve the stiffness of the sandwich structure and alleviate core failure is through-thickness stitching [131]. Lascoup et al. [132] reported that stitching greatly improves stiffness and strength capabilities as noticed from their performed low-velocity impact tests. It was also found by Xia and Wu [133] that stitching boosts the impact performance during a low-velocity impact. Lascoup et al. [134] and Samlal et al. [135] observed that cross-pattern and 45° stitches enhance considerably the impact performance of foam-core sandwich structures.

5.3. Impactor mass, geometry, and velocity

The effects of impactor mass, geometry, and velocity have been of major concern in many studies. It was well defined that greater impactor mass yields higher deflection and longer impact duration [49,136]. Fig. 13 displays the typical impactor shapes found in scholastic works. Flores Johnson and Li [137] studied the response of polymethacrylimide foam core sandwich structures being indented with conical and truncated, flat-face indentors. The conical indentors cause a smaller damage area compared to that of the truncated, flat-face ones. Cylindrical impactors cause more indentation than conical impactors due to mass equivalence [138]. Kurşun et al. [139] examined the influences of impactor profile on the low-velocity impact reaction of sandwich panels. It was found that the impact damage modes are affected by the impactor shape, and similar results were obtained by Liu et al. [79] for hybrid sandwich structures with a corrugated core. The cone-shaped impactor was found as absorbing the highest impact energy whereas the flat type performs the same in the perforation-free cases. The impactor shape also influences the energy absorption characteristics [130,140]. Wang et al. [116] indicated that the maximum load and impact energy are directly proportional to the impactor geometry while the contact duration is inversely proportional to the impactor size.

Higher impact velocity results in greater contact force, deflection, and energy-absorption capability of the structure, but inflicts no influence on the impact duration [49,141]. St-Pierre et al. [142] examined the effects of impact velocity on stainless steel corrugated core sandwich panels and found that beneath 10 m/s, the inertial behavior raises the maximum impact force beyond the quasi-static value. However, for velocities from 10 to 100 m/s, the force equilibrium of the sandwich's upper and lower skins is vanished. Chen et al. [143] developed a numerical model to inspect the effects of impact velocity on the absorbed energy and concluded that the impact velocity greatly influences the absorption energy of the sandwich structures. Thus, the impactor's geometry and velocity can affect the damage area of the impacted structure as well as the energy absorption.

Furthermore, existing studies have put focus on the consideration of the effects of soft body impactors. This behavior is important to mimic and examine the problem of bird strikes on aircraft engines in particular the sandwich-formed fan blades. While rigid bodies typically inflict dent that conforms to the impactor shape, a nearly uniform core crushing on the other hand is created by soft bodies under the impact location. Hard-body impactors are often assessed by steel balls in freefall drop testing setups. This loading type is more threatening to the structural strength of the sandwich structures [16]. Soft-body impactors for certification of building components include, for instance, the double twin-tire, spheroconical bag [144], accidental bird impactors [145], etc, which are potentially dangerous to existing sandwich structures as well as envelopes [146]. Since the applied velocities are customarily higher than those defined under low-velocity impacts (≥ 100 m/s), it is noted that the relevant applications are outside the scope of the current review [147,148].

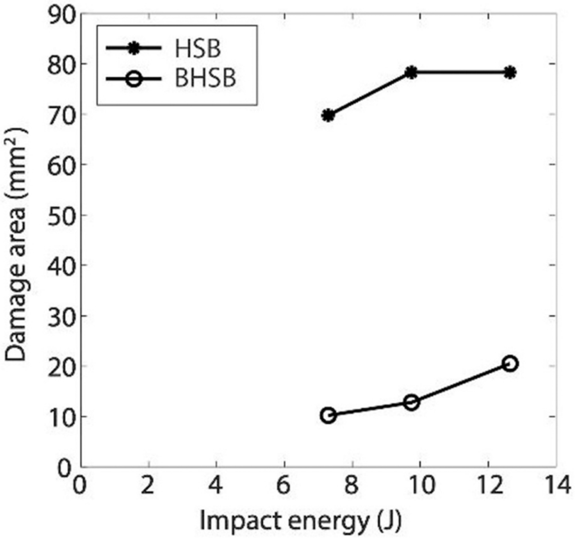

Fig. 12. Damage area for different impact energies for sandwich beams containing honeycomb core (HSB) vs bioinspired design (BHSB). Adapted from [6]).

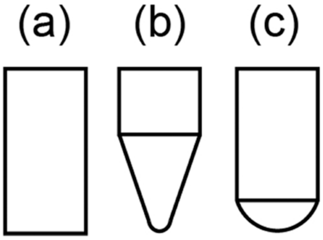

Fig. 13. Impactor geometry: (a) flat, (b) cone, and (c) hemisphere.

5.4. Temperature and moisture

Impact energy absorption is greatly affected by temperature where the peak force declines with the temperature uprising [149,150]. At 23 °C, matrix damage and delamination are the governing failure modes but the main mechanisms are fiber fracture and severe penetration at − 70 °C for the front facesheet [151]. Back facesheet failure appears in terms of fiber breakage and delamination but only at − 70 °C. In terms of the core, shearing and debonding are the main issues at low temperatures. Water immersion degrades the material properties of sandwich structures with E-glass/epoxy skins vs. those with fiber or metal [36]. Longer water immersion reduces the tensile, flexural, and impact strength due to water infiltration into the fiber/matrix interface [152]. A significantly reduced CAI behavior was also reported for open-edge sandwich panels with foam core after being exposed to hydrothermal conditions [153].

5.5. Support condition

Simple, fully fixed (clamping), and free boundary conditions are the typical edge supporting systems found in sandwich structures. Support conditions have been instrumental in influencing the impact response in the case of large mass impact, but negligible so for small mass impact. More edge restraint enhances the stiffness of sandwich structures, thereby yielding greater contact force but lower deflection, i.e., more damaging [6,154].

5.6. Loading rate

Sandwich cores made of metallic, polymer, or foam are sensitive to loading rate under high-velocity impact specifically in small mass impact loading [155,156]. It was reported that near the high-speed impact definition, the load rate effects become more apparent in the sandwich structural responses [157]. The influence of the loading rate, which is rather low in low-velocity impact, can be safely neglected [49]. The difference if any does not justify the additional investigative effort within the low-velocity impact regime.

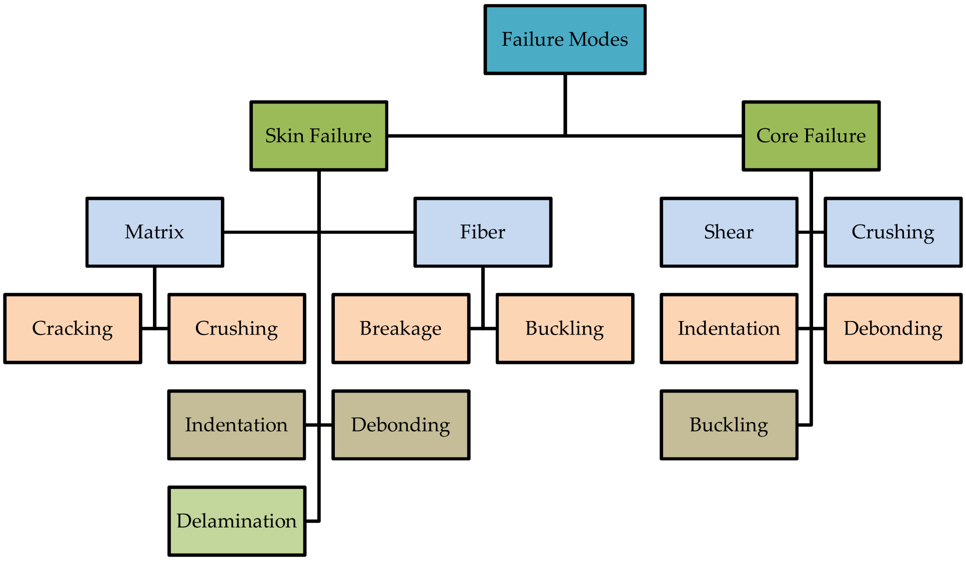

Fig. 14. Low-velocity failure modes of sandwich structures.

6. Failure modes

The flowchart in Fig. 14 unveils the failure types of the skin and core of sandwich structures under low-velocity impact. Single low-velocity impacts cause a severe reduction in the compressive strength, residual strength, and reliability of sandwich structures although the load does not usually produce visible damage [112]. Many studies [60,158–160] have examined the failure types of sandwich structures due to single impacts of low-velocity intensity. The failure mechanisms are generalized into three major modes: matrix cracking and fiber breakage mode, delamination mode, and core failure mode. Like laminates, damage to the sandwich structure's top skin is mainly caused by the local deformation around the area of contact while its core damage is chiefly inflicted by the transverse contact pressure [49].

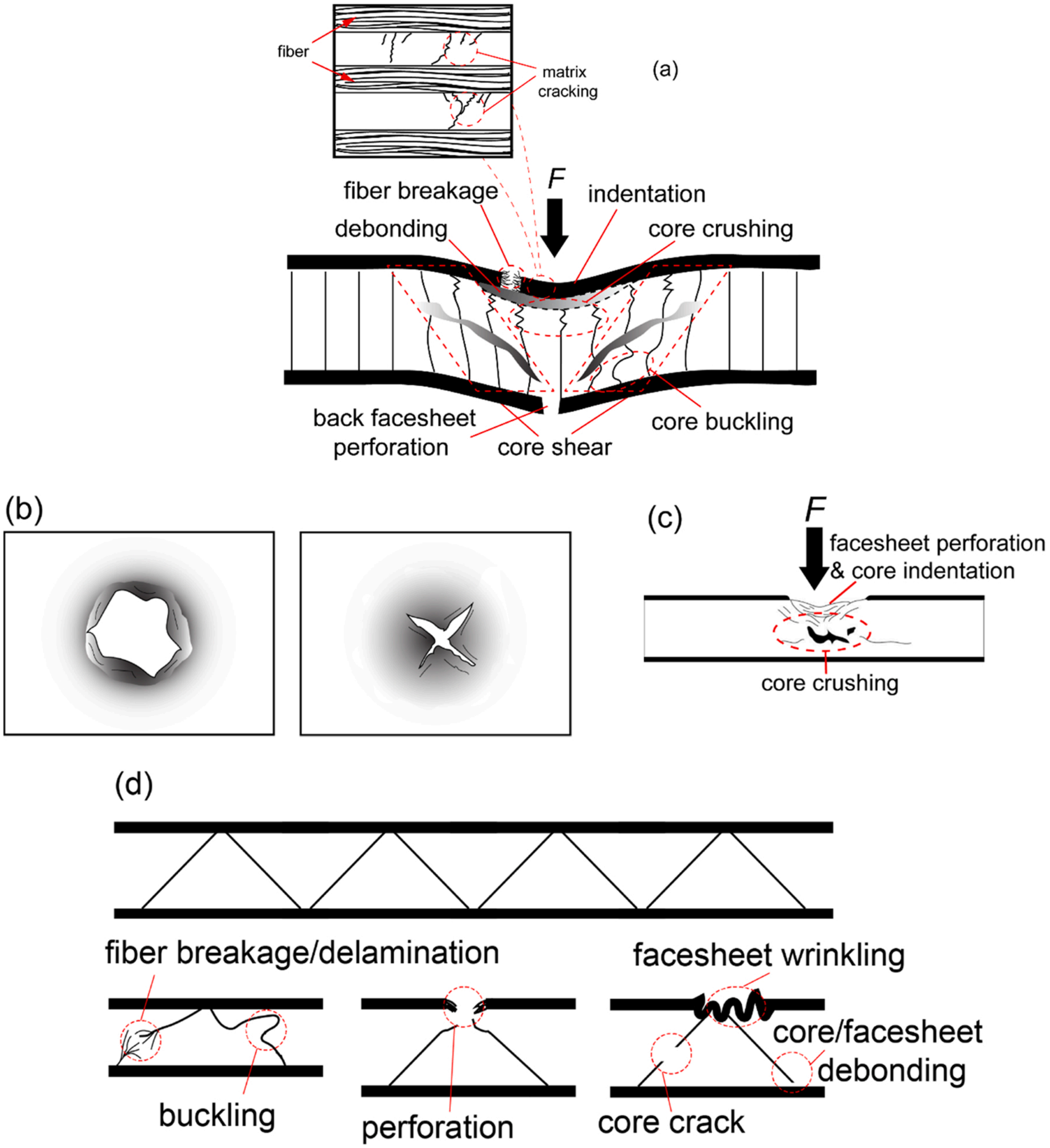

Fig. 15. Common failure modes for a diversity of sandwich structures: (a) Fiber reinforced polymer (FRP) facesheet/metal honeycomb core (b) front and back FRP facesheets fracture and perforation (plane view) (c) FRP skin/foam core (d) FRP facesheet/truss core.

6.1. Failure modes under single impact

Fig. 15 depicts some commonly observed failure modes that appear in numerous distinctive designs of sandwich structures under impact loads. A skin under low-velocity impacts is prone to several failures: matrix, fiber, delamination, and indentation. Debonding may also occur between the skin and the core of the structure [49]. The core failures are various depending on the types of design hired on the structures. Core shear, buckling, crushing as well as members buckling and fracture are just some typically noticed kinds in the presence of impacts.

Table 1 summarizes some of the previous studies on single low-velocity impacts of sandwich structures and their associated modes of failure. Irrespective of their location, the steel foam cores of sandwich panels subjected to low-velocity impact typically fail by shear plug [72]. It has been witnessed that the principal damage state under low-velocity impact is delamination for hybrid corrugated core sandwich structures. Furthermore, fiber breakage and matrix damage caused by flexural load and indentation are the governing failure types as impact energy increases [79].

Wang et al. [161] and Morada et al. [122] reported that the skins of their sandwich structures experience matrix crushing. The matrix failure can be either cracking or crushing. Matrix cracking predominantly occurs before the other modes due to the properties mismatch between the fibers and the matrix. It initiates in the form of cracks parallel to the direction of the fibers, and sometimes debonding between the matrix and fibers may occur. A particular crack form called “shear cracks” can appear under the edges of the impactor. Cracks often form in the outer sheet of thick composite skins attributed to the huge contact stresses under the impact. On the contrary, the bottom sheet of thin composite skins experiences cracks in such incidents due to bending stresses. Due to the increased energy of impact, the propagation of cracks can reach the interface of the succeeding layer. Then, the interfacial matrix cracks develop to generate interlaminar stresses that subsequently allow the manifestation of delamination. With increased energy, fiber breakage often advances the development of the indentation on the surface of the top skin, which leads to eventual serious damage.

The facesheet fiber of composites can also have two forms of failure: breakage and micro-buckling. Fiber breakage is a common mode of failure in sandwich structures, and it is mostly accompanied by matrix cracking and/or debonding [162]. Wang et al. [161]

Table 1
Mechanisms of damage of sandwich structures under single low-velocity impacts.

Type of facesheet	Type of core	Initial Impact Energy [J]	Type of failure	Refs.
Plain weave carbon fabrics	A closed-cell polyurethane foam	7.5–30	Matrix crack; Matrix crushing; Fiber micro-buckling	[161]
Aluminum 2024-T3	Balsa wood; Cork; Polypropylene honeycomb; Polystyrene foam	43, 85, and 120	Debonding; Core cracking; Core crushing	[169]
T350 carbon fiber reinforced polymer (CFRP)	Dual-core (aluminum honeycomb and rubber)	7.28, 9.74, and 12.63	Matrix cracking	[6]
CFRP	Aluminum alloy	10, 20, and 50	Fiber breakage; Matrix cracking; Delamination; Debonding; Indentation	[79]
Woven Kevlar fabrics	PVC foam	10, 20, 30, 40, 50, and 60	Matrix cracking; Fiber breakage; Core indentation; Delamination	[159]
CFRP	Nomex honeycomb	22.25	Matrix cracking; Delamination	[170]
CFRP	2A12-T4 aluminum	5, 10, 20, 40, and 70	Matrix cracking; Delamination; Indentation	[71]
CFRP	AA3003 aluminum alloy	5, 10, and 40	Matrix cracking; Fiber fracture; Core crushing	[76]
Woven fabric cloth	Foam	30	Matrix cracking; Debonding; Fiber breakage; Buckling	[94]
Glass fiber reinforced polymer (GFRP)	Foam	35	Matrix cracking; Fiber breakage; Delamination; Indentation	[60]
E-glass fabric	PVC foam	30 and 60	Matrix cracking; Delamination; Buckling	[171]
Weaved carbon fabric	Foam	5, 15, and 25	Matrix cracking; Foam cracking; Delamination; Penetration	[166]
CFRP	Aluminum honeycomb	28.9	Matrix cracking; Fiber breakage; Indentation	[172]
CFRP/GFRP	Honeycomb	20–290	Fiber breakage; Delamination; Crushing	[173]
GFRP	Honeycomb	7–50	Matrix cracking; Debonding	[174]

observed fiber micro-buckling of 3 K T300B carbon plain fabrics when investigating the impact response of foam-core sandwich boards. Similarly, Li et al. [163] reported that their sandwich structure consisting of foam core and carbon fiber skins experiences fiber breakage in the top skin of the sandwich. Thus, it can be concluded that matrix and fiber breakage happen before the other modes during the impact event.

Delamination is the separation between layers due to the loss of adhesion. It occurs in the facesheet of the sandwich structure, especially at higher energies [164]. Li et al. [163] reported that interfacial delamination is one of the major damage modes in thin sandwich structures. Delamination of the facesheet reduces the load capacity of the sandwich structure thereby causing a drop in the impact resistance. The main cause of delamination is the bending–stiffness mismatch between the sandwich layers and is primarily related to delamination fracture toughness [165]. According to Zhu and Chai [160], delamination in sandwich structures appears when either the bonding strength or the interlaminar shear strength is exceeded since delamination reduces the strength of a sandwich to less than half of the original strength [166]. It contributes significantly to the deterioration of overall structural performance. There are various dominant types of failure that the core of a sandwich structure can experience during a single low-velocity impact: cracking failure (shear), crushing failure, buckling failure, debonding, and indentation. Many studies have investigated the core failure modes under low-velocity impacts to seek viable solutions [59,167,168].

6.2. Failure modes under repetitive impacts

Table 2 summarizes previous studies on repetitive low-velocity impacts of sandwich structures and their associated modes of failure. The damage mechanisms of repetitive impacts remain hugely mysterious as there are currently not many available studies. Some researchers have shed light on the responses of sandwich structures attributed to repetitive low-velocity impacts. Akatay et al. [112] reported that sandwich structures experience a significant reduction in compressive strength when subjected to repetitive impacts. Mines et al. [175] examined the impact behaviors of sandwich composite boards with PVC foam core and balsa wood core. It

Table 2

Modes of damage of sandwich structures under repetitive low-velocity impacts.

Type of facesheet	Type of core	Initial Impact Energy [J]	Number of Impacts	Type of failure	Refs.
Glass fiber reinforced polymer (GFRP)	Polyvinyl chloride (PVC) foam	5, 10, 20, 30, 40, and 50	7	Fiber breakage; Matrix cracking; Delamination; Indentation	[43]
Al/SiC functionally graded plasma sprayed (FGPS) face plate	Aluminum honeycomb	260	4	Indentation; Cracking; Delamination, Core buckling; Core plastic folding deformation	[40]
Aluminum alloy panel	Aluminum alloy corrugated core	10, 20, and 40	19 for long span 60 for short span	Indentation; Core buckling; Cracking; Penetration; “Pseudo-shakedown” phenomenon	[44]
E-glass ± 45 biaxial stitch bonded non- crimp fabrics	PVC foam or balsa wood	5 – 60	0 – 400	Facesheet fracture; Matrix cracking; Delamination; Core buckling; Core shear fracture; Debonding; Penetration; Perforation	[90]
Aluminum alloy panel	Aluminum honeycomb	5, 10, and 20	3	Cracking; Indentation; Penetration	[93]
Aluminum alloy panel	Aluminum honeycomb	5, 7.5, 10, 15, and 20	6	Indentation; Core buckling and crushing; Delamination; Cracking; Penetration; Perforation	[42]
Mild steel	Aluminum foam	54	10	Indentation; Global transverse bending; Local compression	[110]
Carbon fiber rein-forced polymer	Aluminum honeycomb	13.5, 15.55, and 21.43	5	Matrix cracking; Fiber breakage; Core shear; Indentation	[8]
Carbon fiber rein-forced polymer	Aluminum honeycomb	7.28, 9.74, and 12.63	5	Indentation; Matrix cracking; Fiber breakage; Core shear; Core buckling; Core cracking; Delamination; Perforation	[7]
Top skin: E-glass and carbon Bottom skin: Carbon and Kevlar	CoreCell Polyvinyl Chloride (PVC)	15, 17.5, and 20	27	Penetration; Indentation	[177]
E-glass reinforced polypropylene	Balsa wood	10 – 80	98	Fiber fracture; Delamination; Core transverse fracture	[109]
Mild steel	Aluminum foam	4.5, 9, 18, 36, 54, 72, 90, 160, 240, 300, and 360	76	Penetration; Indentation; Facesheet rupture; Core crushing	[63]
Woven fiberglass reinforced phenolic laminate	Nomex honeycomb	1, 2, 3, 4, 5, 6, 7, and 8	162	Skin buckling; Penetration; Cracking; Core shear; Core crushing; Core buckling	[108]
Fiberglass reinforced epoxy	Aluminum honeycomb	3, 10, 20, 40, 50, and 70	81	Penetration	[112]
[1]Glass fabric (GL) [2]Graphite fabric	Graphite fabric (GR) Glass fabric	32 32	69 33	Delamination; Matrix cracking; Indentation	[70]

Annotation: Hybrid composites with [1]GL/GR/GL and [2]GR/GL/GR configurations was found that principal damage modes are: fiber cracks at upper and lower skins, core shear fractures, delamination of adjacent glass–epoxy sheets, and skin/core debonding. Palazotto et al. [62] tested sandwich panels made up of graphite-epoxy material and steel core under a range of impact energies. The sandwich panels undergo several damages such as shear cracks, delamination, and debonding. Chen et al. [121] simulated the water impact loading of sandwich boat structures considering three different cores: Nomex honeycomb, polyimide foam, and pinned foam. Their results show that the Nomex honeycomb core sandwiches start to show damage at impact energies close to 550 J in the form of core crushing. The foam sandwich panels do not show any initiation of damage until the impact energy is beyond 1200 J. Therefore, it is concluded that sandwich structures with foam core can improve the resistance of the structure to wave impact.

Abo Sabah et al. [7] investigated the failure states of a bioinspired sandwich beam under repetitive low-velocity impacts using different impact energies, i.e., 7.28 J, 9.74 J, and 12.63 J. This new system condenses the damage area by 50 – 80% compared to the existing conventional sandwich beam, with matrix cracking, core shear, and core crushing as the principal failure modes. Mines et al. [176] developed predictive models to observe the relation between the constituent material properties and the behavior of sandwich panels under repetitive low-velocity impacts. It was noticed that the perforation of the panels is dominant under repetitive impacts

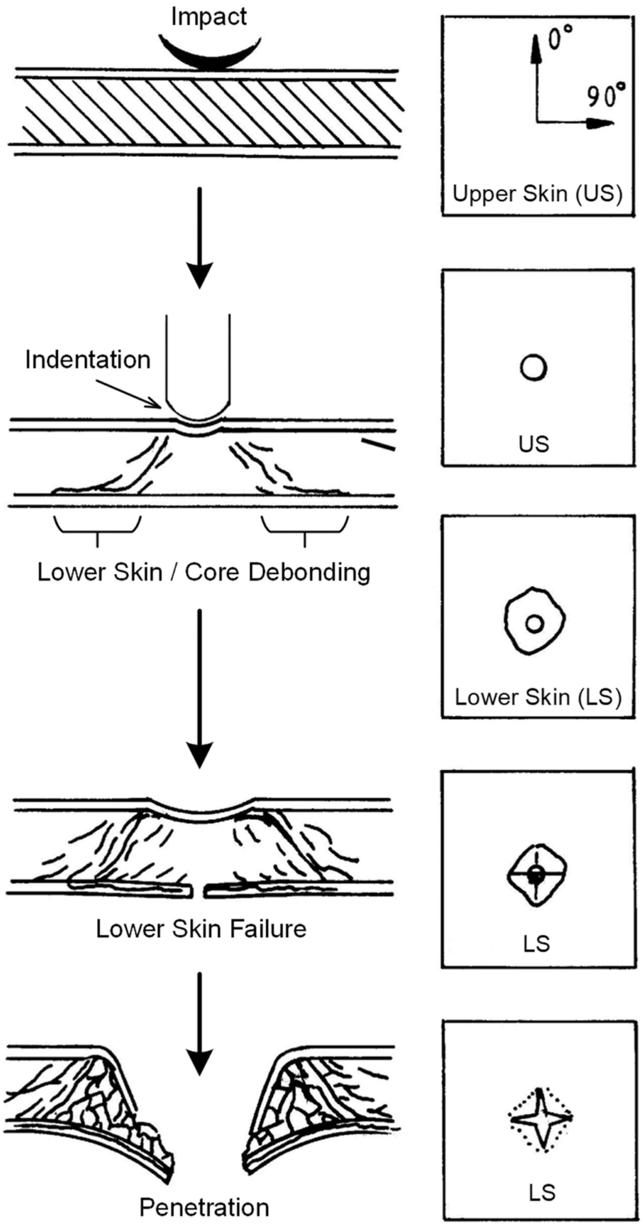

Fig. 16. Damage sequence for Coremat panel under impact.
(Adapted from [176]).

irrespective of their constituent material properties. Figs. 16 and 17 show the damage sequences due to the repetitive low-velocity impacts for the Coremat panel and Aerolam panel (honeycomb core), respectively [176]. It can be seen that different types of core will significantly affect the performance of the sandwich composite structures, specifically the energy absorption parameter. A series of repetitive low-velocity impacts were conducted by Tan and Akil [37] on sandwich composites of metal skins and a polypropylene honeycomb core with the impact energies varied between 3.92 J and 19.62 J, with the primary failure modes of skin delamination and global bending. Balcı et al. [108] investigated the repetitive impact behavior of refurbished honeycomb sandwich structures adopted in Airbus cargo panels. The panels made up of fiberglass skins and Nomex honeycomb cores were subjected to different energy levels (1–162 J). It was reported that the panels experience full penetration, core fracture, and buckling.

Ozdemir et al. [109] studied the behaviors of a bioinspired sandwich beam under repetitive impacts unveiling that the failure types are perforation, delamination, fiber fracture, and matrix breakage. Guo et al. [110] detected indentation and deflection of front and back skins when examining the dynamic behaviors of sandwich panels containing aluminum foam under repetitive impacts. Similarly, Dai et al. [42] examined the repetitive impact response of honeycomb sandwich structures using different impact energies ranging from 5 to 20 J with perforation as the dominating mode. The impact number, which results in full perforation, reduces as the impact energy increases. It is obvious from the aforementioned studies that both single and repetitive low-velocity impacts have similar modes of failure: Facesheet or core crushing, facesheet or core buckling, and delamination. However, indentation, penetration, and perforation are more distinctively central to the failure characteristics of those under repetitive low-velocity impacts since this load type drastically reduces the strength of the sandwich structure. Additionally, repeatedly impacted structures commonly experience a catastrophic drop in compressive strength [112].

7. Failure mode maps for sandwich structures

The topic of failure mode maps has not been covered by any review before. Failure mode maps are two-dimensional diagrams developed based on real experimental results to offer help in determining the dominantly experienced final deformations in the design stage. This was also recently adopted in the steel-concrete sandwich study [178]. Designers can employ these maps to predict and get

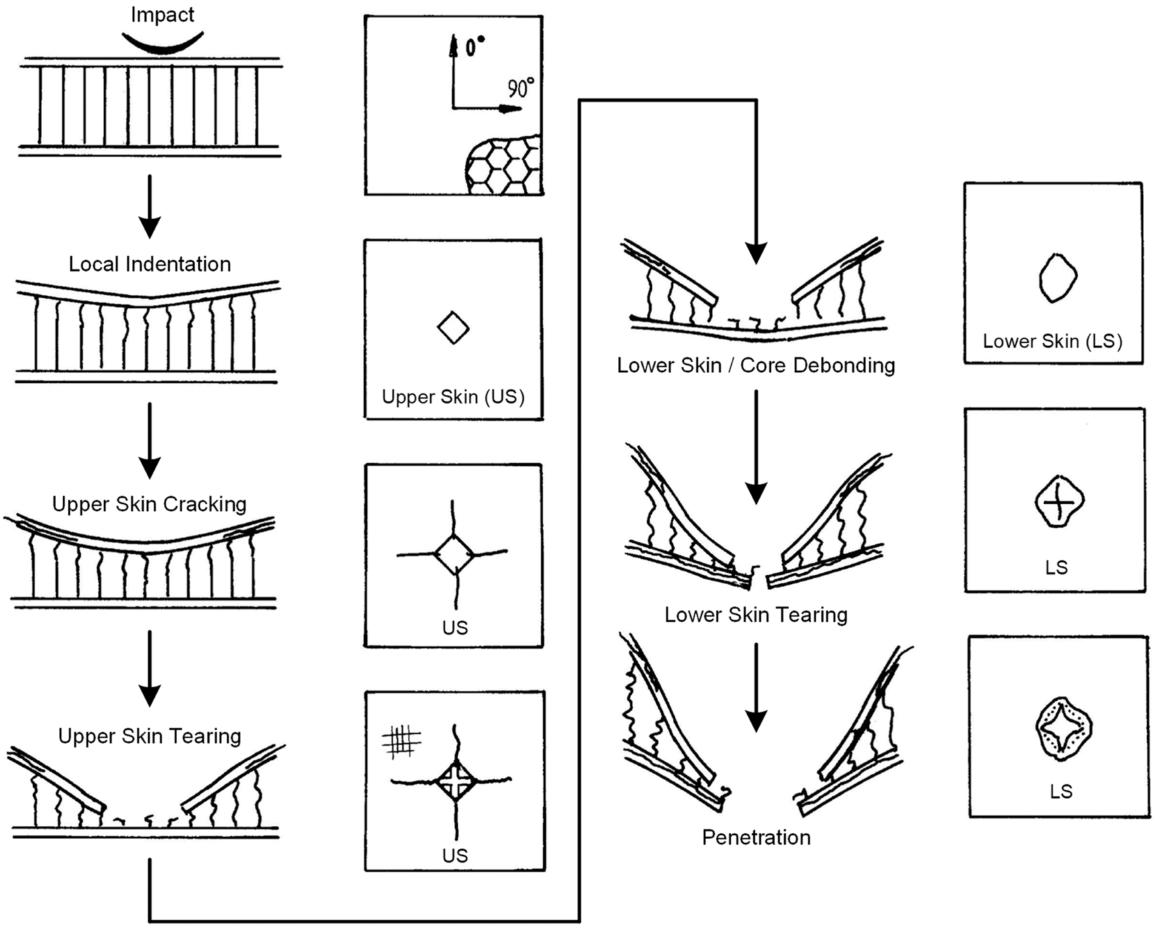

Fig. 17. Damage sequence for Aerolam panel with honeycomb core under impact.
(Adapted from [176]).

an approximate grasp of the damage mechanisms that the structure may experience under impact loading. Following the right failure mode, a better prediction can then be made. This makes it both cheaper and more time-saving without having to conduct a detailed analysis.

The maps for failure modes of sandwich beams have been studied since the late 1980 s. Triantafillou [179] and Triantafillou and Gibson [180] were the pioneers in the construction of failure-type maps for sandwich structures. Triantafillou and Gibson [180,181] investigated the influences of the skins and core variables on the failure modes of a sandwich structure and formulated what is now defined as Gibson's model. The model assumes that ductile facesheet such as aluminum and steel form plastic hinges whereas brittle ones like carbon fiber-reinforced polymer and glass fiber-reinforced polymer show an elastic response until failure. Fig. 18(a) depicts the general failure mode map developed by Zhu and Chai [160] for the CFRP facesheets sandwiching a Nomex honeycomb core. The chief modes portrayed include core buckling, matrix tensile damage, and matrix shear damage.

Ductile skin sandwich structures normally experience failure in the bottom skin while the dominant failure mode of brittle sandwich structures is micro-buckling, which occurs in the top skin. McCormack et al. [182] and Ashby et al. [183] developed the failure model for a sandwich beam to estimate both the initial and peak failure loads relying on the deformation such as face wrinkling, face yielding, core buckling, indentation, and core yielding as generally summarized in Fig. 18(b). Yu et al. [184] modified Gibson's model to develop a low-velocity impact failure map employing the quasi-static behavior of sandwich beams. Employing quasi-static bending tests on the sandwich beams and based on the results, a failure map for predicting failure modes of sandwich structures under low-velocity impacts was constructed. Three failure modes are presented on the map: face yield, core shear, and indentation. The map does not represent a fully realistic response of sandwich structures in the impact event since it was drawn based on a set of quasi-static tests.

Recently, Abo Sabah et al. [8] produced a set of maps for failure modes of bio-inspired sandwich beams due to repetitive low-velocity impact based on real data from the laboratory tests as showcased in Fig. 18(c). It appears that the main modes experienced by honeycomb sandwich beams with added viscoelastic layer during repeated impact are indentation, core shear, as well as matrix cracking and fiber breaking (MCFB). All the previous studies that developed sandwich structure failure maps were restricted to data from the quasi-static flexural tests only even in relating failure modes to the impact incident. The failure maps produced by Abo Sabah et al. [8] offer great compliance to permit the strength alterations due to the degradation of component layers after each repetitive impact. The study also produced mathematical expressions to further facilitate the prediction of the expected failure modes. The accuracy of their developed maps to predict failure modes under repetitive low-velocity varies between 85.7% and 100%.

8. Common finite element modeling (FEM) practice

Numerical modeling is needed for the advancement of sandwich structures. Fig. 19 discloses the typical FEM modeling settings for a sandwich system assembly following the standardized conditions prescribed in physically performed low-velocity impact tests [185]. The main components are the impactor simulating the drop mass impact load, the sandwich structure model simulating the targeted

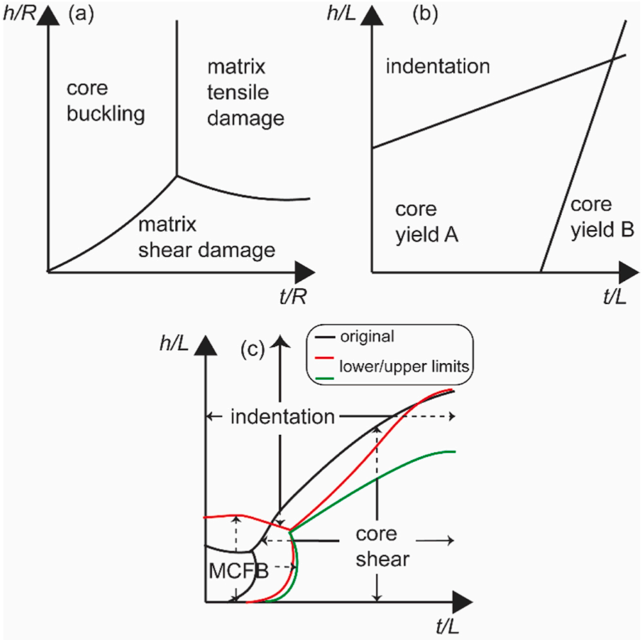

Fig. 18. Failure mode map: (a) CFRP facesheet/Nomex honeycomb core (single impact) (b) Al facesheet/Al foam core (single impact) (c) CFRP facesheet/rubber core+Al honeycomb core (repetitive impact). Note:Al = Aluminum, MCFB = matrix cracking and fiber breaking, h = core thickness, L = sample length, R = impactor radius, and t = facesheet thickness.

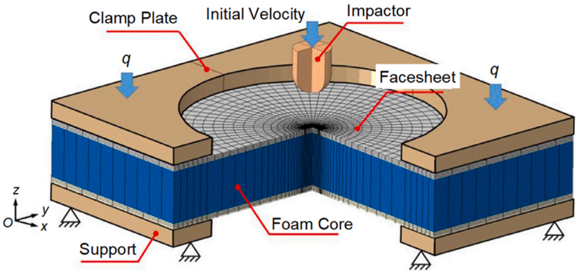

Fig. 19. FEM model of sandwich structure under the low-velocity impact.
(Adapted from [185]).

specimen, and the clamping plates plus supports as the boundary conditions. Numerical models offer efficiency in exploring the behaviors of both components and the entire structural assembly while decreasing both cost and time in comparison to experimental studies [186–188]. There exist different numerical approaches to examine the behaviors of sandwich structures. In keeping with the scope of the current review and due to the popularity as well as capability of finite element methods, only works relevant to these techniques within the recent 10 years are discussed.

Since finite element modeling methods can be proficiently optimized and can be straightforwardly accustomed to fit any complicated configuration, researchers have employed numerous commercially available finite element software, for instance, ABAQUS, ANSYS, LS-DYNA, etc [4,5189]. to model the low-velocity impact incident of sandwich structures. Thus, finite element models can be deemed sufficiently powerful while regularly hired to visualize the reaction and damage states of sandwich structures [190,191].

Fig. 20 exhibits the typical sandwich beam model simulated either with shell elements, for the facesheet and honeycomb core, or solid elements for the honeycomb (by equivalence approach) or foam core. To model small deformations, the classical lamination theory can be utilized. von Kármán strains are needed for large deformations of thin laminates, by ignoring effects from the plane displacements. The first or higher-order shear deformation theory is obligatory for modeling thick laminates. Damage of the composite facesheets or core constituents is often simulated with stress- or strain-based failure criteria [34] as well as Puck, Tsai-Hill, Tsai-Wu, Chang-Chang, or Hashin description [6–8] integrated with the stiffness or strength degradation functionality. These models have incorporated the elastoplastic stress-strain expression with relevant yield and ultimate information (ductile and shear damage criterion) for both the composite or metal-based skin/core whose data is commonly procured from the experimental observation [6,8,142,167,192–194]. For the crushing of cellular core type, the crushable foam model in ABAQUS has also been employed [69,116]. The contact of impactor-sandwich structure can be varied depending on the availability of actual data, which are defined based on normal

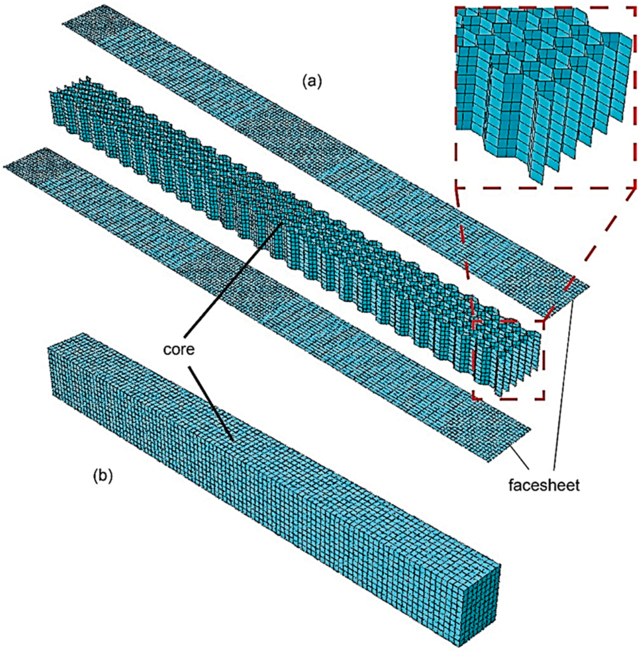

Fig. 20. Simulation of sandwich structure model with (a) shell and (b) solid elements.

and tangential behaviors, e.g., hard contact expression in the former case and frictionless or with nominal frictional coefficient in the latter case using the penalty, kinematic, or equation expression as algorithm [7,142]. Interfacial relations between main layers are often simulated with full interaction characteristics through general or self-contact by the automated realization of the solver due to proximity [4,42,130,142,195] or partial interaction with the interface layer in between [69,85].

Zhu and Chai [49] utilized ABAQUS/Explicit to model the initiation and formation of damage of sandwich structures under single impact loading of low-velocity intensity. Burlayenko and Sadowski [196] also hired the same software to perform the steady-state dynamic and free vibrations analyses of sandwich plates subjected to single low-velocity impacts. By executing Hou and Hashin failure criteria with the user-prescribed subroutine, VUMAT, in ABAQUS/Explicit, Santiuste et al. [197] were able to predict the sandwich beam modes of failure under a single impact. Their computational results of displacement and loading perfectly match the laboratory results. Ivañez and Sanchez-Saez [198] visualized the response of low-velocity impact of sandwich beams with honeycomb core using ABAQUS. The obtained results of the models were used to verify the collected data from experimental works under a single low-velocity impact load. Shell and solid elements were employed in meshing the core and skins, respectively. Based on the Hou failure criteria, the VUMAT subroutine was developed to model the skin behavior. It is discovered that the core governs the structure's energy absorbance, especially at a small energy range. Griškevičius et al. [199] conducted experimental and numerical tests on honeycomb sandwich structures using LS-DYNA. It was found that the honeycomb core of the structure absorbs impact load more than the top skin. The core absorbs around 50–95% of the impact energy while the top skin absorbs around 7–35%. Due to high computational demand by solid elements, symmetries can be employed to simulate only a quarter portion of the structure by introducing a proper set of boundary conditions as demonstrated in Fig. 21 [157].

Heimbs et al. [85] constructed dynamic finite element models with LS-DYNA to examine the single low-velocity impact response of sandwich structures containing foldcores reinforced by textiles. It is revealed that the foldcore structures exhibit favorable impact responses. St-Pierre et al. [142], Boonkong et al. [200], Kurşun et al. [139], Xu et al. [201], Chen et al. [170], and Dimassi and Herrmann [202] studied the behaviors of sandwich structures due to single low-velocity impact using finite element modeling as well and found that simulation can be a good indicator for what occurs in the experiment and can give very accurate results and simultaneously saves time and cost. Aluminum honeycomb sandwich panels in the threat of ice-wedge impact were studied by Wu et al. [203] adopting the 3D nonlinear finite element model by describing the load with a concrete constitutive model in the FE software, ANSYS/LS-DYNA. The plastic deformation energy of the structures as well as kinetic and fracture energies of the ice load were derived based on the impact energy noticing that the energy dissipation of broken ice rises substantially with the impact energy and thickness of facesheets, whereas energy absorption is contributed increasingly by the ice energy dissipation. To overcome the absence of transverse shear of using non-linear springs to model the Nomex honeycomb core of a sandwich panel with CFRP skins, Audibert et al. [167] introduced the compression/shear coupling in the core model with elasto-plastic-damage description for the composite skins using a user subroutine in ABAQUS with a good model-experiment correlation as the outcome.

Abo Sabah et al. [7] were the pioneers who developed the finite element modeling technique for repetitive low-velocity impacts using ABAQUS/Explicit. The shell elements were employed to model the sandwich beams with the damage descriptions under various impact energies. Good agreement between modeled and measured structural responses was reported. Repetitive low-velocity impact loading behaviors of sandwich structures with honeycomb were also modeled by Dai et al. [42] with ABAQUS/Explicit with "tie"-type full interfacial interaction for 3D solid and 2D shell elements, respectively, of the aluminum skins and core with Johnson-Cook failure description. It was claimed that the discrepancies between the model and experiment, which elevate with the impact energy, are inevitable since their adopted damage model did not corroborate well with the real material from the aspects of bonding, boundary conditions, and modeled material constants. So far, there are not many studies that have modeled the repetitive low-velocity impacts of sandwich structures as the process is both effort- and computationally-taxing.

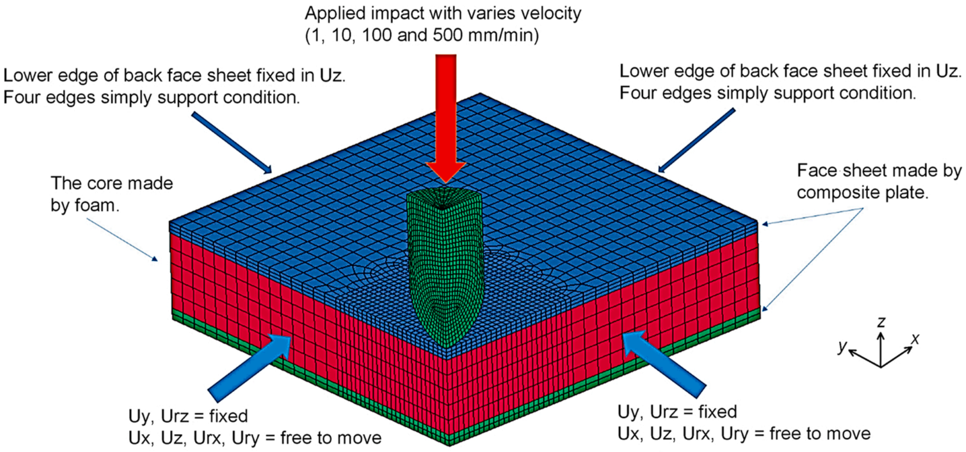

Fig. 21. Applied load and boundary conditions of a quarter FEM model of sandwich structure.
Adapted from [157]).

In the existing literature, researchers have commonly employed two types of elements to model sandwich structures: solid and shell elements. However, it is highly recommended to use shell elements when modeling the thin wall constituents, such as laminated skins, honeycomb cores, foldcores, egg-box cores, etc. as this will minimize the computational time. Moreover, several researchers [204–207] reported that using solid elements, especially when modeling the impact damage, results in difficulties and inaccuracy. Although computational memory-saving efforts like homogenization had gained some interest to reduce the massive element number used in FE simulation [1208–212], it remains to be seen the degree of efficacy these methods could display when employed in the impact loading studies as the inherent responses are more localized both in terms of deformation and the resulted damage. High-accuracy models are those that use cohesive elements for delamination simulation as well as nonlinearities and combined progressive failure models in material descriptions comprising complex failure modes. Even so, while many models manage to address certain physical behaviors well, other equally important effects are poorly captured [147]. Thus, extensive efforts are still needed in the advancement of the current numerical techniques.

9. General observations

Since many different designs have been continually proposed and studied to improve on previously available structures and due to diverse findings from these studies, it is not straightforward to extrapolate and recommend any one type of design for general engineering applications. The assessed engineering performance can be widely varied relying very much on the material and geometrical configurations, fabrication techniques, which diverse hugely from one method to another, loading and boundary conditions, etc. Nevertheless, some general observations gathered from the current list of publications can be summarized, noting surely that it is an actively evolving research area, thus, some descriptions may be updated from time to time. Some recommendations are included in the followings.

For the facesheet design, raising its thickness increases the sandwich's impact resistance, peak load, and perforation threshold. Also, placing the carbon fiber layer for laminated facesheets near the outer position raises impact performance. From the core type viewpoint, foam cores either made from polymers or metals generally perform better when produced in a graded form where varying densities are superior to uniform ones. Surely, different material types constructed sandwich structures exhibit varying impact responses with cores containing greater energy dissipating ability demonstrating better responses. Also, the impacted interfacial failure mechanism between the skins and core governs the absorbed energy of the structure. The areal density of lattice-like core sandwich structures is the main absorbing component. For crashworthiness, progressive crushing is the mode administrating the sandwich failure comprising polymeric or metallic cores. A metallic foam core sandwich is less performing in perforation than a solid monolithic variant. For honeycomb sandwich and foldable panels, the facesheet and wall thickness are, respectively, the principal absorbing constituents. Additionally, multi-hinges plastic deformation offers extra energy absorption in tailorable foldable cores, which are superior to the honeycomb sandwich structures. This observation is replicated in corrugated core structures with buckling and fracture as the governing failure mode. This behavior is, however, absent in empty lattice core sandwich panels. Such ability is enhanced by the geometrical parameters, like thickness and core density, in auxetic core structures. To maximize the impact resistance of aluminum panels with honeycomb core, the side length of the core and cell wall thickness can be altered. To achieve this, a smaller cell span should be adopted by designs using an s-shaped foldcore. Adding pins helps in reducing damage area and improves the initial damage initialization load and energy absorption. Effectively modulating the length and wall thickness of honeycomb cells as well as the facesheet thickness can beneficially alter the plastic deformation accumulation and energy absorption performances under repeated impact loads. Furthermore, the perforation threshold generally rises with the core thickness while increasing the absorbed energy absorbance. The same effect can be attained by raising the core density, from which the CAI strength increases with an improved toughness too. The employment of a dual-core structure reveals greater stiffness and strength while the introduction of stitching improves hugely these properties. For instance, cross-pattern and 45° stitches elevate greatly the impact resistance of foam-core sandwich structures. To enhance the crashworthiness of honeycomb core sandwich structures, an infilled foam is recommended. This applies to the lattice core types as well. For tube-like core types, this is influenced by their placement configuration and enhanced also by infilled foam even though it is less perforation relevant. 3D periodic cores for sandwich structures elevate impact resistance compared to 2D types due to additional cavities for infill material insertion for extra strengthening. Overall, the most dominant failure modes are facesheet or core crushing, facesheet or core buckling, and delamination for both single and repetitive impact environments, whereas indentation, penetration, and perforation are more distinctive to the repetitive impact conditions.

From the impactor's perspective, the conical shape causes a lower damage area vs. truncated, flat-face ones. Cylindrical types inflict greater indentation than conical impactors for the same mass. More considerable impact velocity exerts higher contact force, deflection, and energy absorbance of the targeted structures. Rigid bodies impose impactor shape-conforming dent whereas an approximately uniform core crushing is generated by soft body impactors beneath the impact zone. Both the environmental hydrothermal effects, i.e., temperature and moisture changes, generally lower the tensile, flexural, and impact strength of sandwich structures. Hence, these conditions should be minimized and modulated in applications. From the computational aspect, shell elements are recommended for thin or lattice-like materials, e.g., laminated facesheets, foldcores, honeycomb cores, egg-box cores, etc. rather than adopting an equivalent solid. However, solid elements are recommended for foam and solid cores. To make a good interaction, the "tie"-type full interfacial relationship for linking 3D solid and 2D shell elements can be adopted. To improve accuracy, it is only reasonable to adopt simulation with the material descriptions containing cohesive elements for delamination as well as nonlinearities and progressive failure models to cover various complex failure modes. Additional to the current approaches of performance assessment and seeing the scattered coverage of findings from various different designs and scales, it is worthwhile to determine for comparative purposes the impact response of sandwich structures adopting an overall resistance measuring term similar to that proposed in References [4–7]. In this case, a fair comparison of impact response can be made.

10. Future directions

There are numerous potential paths for future studies and continual improvements of the sandwich structures as follows.

- Having presented various beneficial designs of sandwich composite structures in handling the presence of impact loading of low velocity, it is worthwhile to explore these configurations under the high-velocity loading environment. Due to never-ending conflicts that heighten the possibility of wars, accidental blasts, and terrorist attacks, one of the ongoing research interests lies in the construction of better defensive structures for ballistic and blasting protection to safeguard civilians from the threat of highly destructive while life-threatening weaponries involved in the event. The highly dynamic nature of the blasting load presents some challenges in characterizing the load-deformation effects on the considered structures both in the aspects of experiment and modeling. The former is somewhat hampered by the high cost, complex facility, and tedious, not forgetting that it poses all sorts of safety risks, environmental hazards, time-consuming, lowly repetitive, and unsuitable for wide-range parametric study in carrying out the test. The obvious solution next is through simulation, which understandably involves a high learning curve and computational resources in the best mimicry of the actual condition. Having stated this, there are some recent good signs of progress made in the study of the blasting behaviors of sandwich structures [78,213,214]. Due to alerting task in diminishing vulnerability of existing and future buildings and structures, studies in improving the protective measures in handling this dynamically threatening load is highly commended in future works.
- Water slamming load on marine sandwich structures is a recent research endeavor. The study consists of local water repetitive slamming on a part of a ship hull for a short-term duration, during which high localized pressure can induce substantial local structural damage. The investigation considers not only the sandwich structures but also the hydrodynamic slamming of the aquatic load plus the fluid-structure interaction between the two chief bodies in contact [215,216]. Hence, the challenge embeds in the multi-physical nature of the problem.
- For repetitive impact study purposes, it is recommended to select the low-velocity impact energy range between 3 J and 110 J [112]. Since most repetitive impact load numbers are carried up to 10 times only, for extensive long-lasting performance aims, it is suggested that this limit can be increased up to 100 or until perforation is attained.
- The non-dimensional impact resistance efficiency index, I_e, proposed by Kueh et al. and Abo Sabah et al. [4–7] can be adopted in the assessment of numerous existing and future designs of sandwich structures such that a global chart not unlike that of material selection prepared by Ashby et al. [217] can be generated for analysis and design purposes. The practice provides a fair comparison of impact including other added performances of sandwich structures for diverse types of design on one chart. The effort may begin by charting all available main designs onto the I_e map.
- Environmental effects like temperature and moisture variations affecting the geometrical stability and therefore also the impact performances of sandwich structures are another set of assessed metrics worth investigating since exposure to conditions different from ambient proves to be a threat to the impact resistances [151,218].
- Sandwich structures in fire incidents face the hazards of structural failure from material properties deterioration, thermally exerted stresses, and charring [38,219]. The material and structural performances of sandwich structures post-fire are often in a declined state due to damage formed during the loading. Hence, their safe continual usage is governed, similar somewhat to CAI, by the residual characteristics. Granted there are existing studies on fire and post-fire behaviors of sandwich structures including remedial techniques by flame retardants and protection [220,221], but many existing sandwich designs are only appraised in terms of their mechanical behaviors. Also, a more realistic modeling technique must consider the multi-physical treatment including the effects of fluid-structure interaction.
- From the manufacturing perspective, hand layup and supervised production remain one of the preparation techniques employed, thereby hindering the massive production output within a short period. Additive fabrication or more automated and innovative fabrication is preferred for the solution. To make a leapfrog advancement, the production process should inevitably look at chained manufacturing that contains all theoretical modeling, analysis, design, optimization, build, and testing in a single combined package. In the design and optimization phases, it is worthwhile to introduce in compatible with the industrial revolution (IR4) age the machine learning method permitting the involvement of artificial intelligence in the experience and decision-making event to diminish errors contributed by humans [222–224]. Moreover, simple design expression in the performance-aligned sizing of the component can be formulated to ease the pre-fabrication activities, which may comprise a broad set of diverse parameters [225–227].
- It is now increasingly challenging to advance the readily outstanding structural performance of existing sandwich designs. Understandably, the development of sandwich structures is a continual progressive research attraction, with newly thought configurations continually proposed and evaluated including new skin and core materials [228–231]. The design envelope can be stretched broader by exploring new ideas and concepts excavated from the observation inspired by natural designs available in the animal and plant kingdoms. Such an effort proves worthwhile to further the improvement of the impact resistance of sandwich structures as witnessed in many current relevant works as readily reviewed [4–8,30,98,102,232,233], especially with the emergence of works employing the 3D printing technology [39,234,235]. The navigation of the quest to find the most performing design is far from over as structural concepts inspired by millions of species are waiting to be discovered and applied.
- Moreover, many studies remain faithful to the investigation of the structural element performance, such as beams, columns, piles, etc. The graduation of these designs to the actual applications with practical loading conditions, e.g., hypervelocity load on outer

space structures [236,237], bird strike soft body impact [147], thermal, microwave, and acoustic attenuation [238–240], automotive and railway parts [60,241], marine structures [242,243], bridges [244], etc., to name a few, should be the next chapters in the history of the sandwich structures development.

11. Conclusions

This paper reviews the responses of sandwich structures in the presence of single and repetitive low-velocity impacts as extracted from recent scholarly works. The following general conclusions can be drawn:

- Gathered from the reviewed articles, the covered parametric ranges are applied impact energies within 0.06 – 360 J, impact velocities of 0.5 – 34.2 m/s, with repeated impact numbers up to 400 times, resulting in absorption energies of 0.01 – 396.3 J, and the determined impact resistance efficiency indices within 0.57 – 143.73.
- The definition of a low-velocity impact is controversial and there is no consensus on defining it; several velocities of up to 100 m/s have been proposed. The high-velocity impact has been described as a loading intensity of up to 1 km/s while hypervelocity load involves 2–5 km/s applied velocities.
- Impact responses can be expressed into two categories, i.e., structural deformation and impact load behaviors: impactor's velocity, mass, period, as well as soft-body or hard-body type.
- The main performance metrics adopted to evaluate the impact resistance of sandwich structures are force-time, displacement-time, velocity-time, acceleration-time, force-deformation, energy-time, and energy absorption by experiment or numerical approaches. It is recommended from this review paper that there should be an integrated, non-dimensional term that combines all chief metrics gathered from these performance terms for an overall impact performance assessment as that proposed by previous researchers (e.g., non-dimensional impact resistance efficiency index, I_e) to appraise fairly the efficiency of diversifying sandwich structures.
- Low-velocity loading types can be further grouped into single and repetitive impacts. Impact damage depends highly on the skin and core types and configurations. Common failure modes include fiber breakage, matrix cracking, skin perforation, skin-core debonding, skin delamination, skin and core indentation, core crushing, core shear, core buckling, core crack, and skin wrinkling. Regardless of single or repetitive impact, the highest potential modes are facesheet or core crushing, facesheet or core buckling, and delamination.
- 3D periodic cores, such as PU foam-filled pyramidal lattice, textile-reinforced composite foldcore, pin-associated hybrid foam-filled honeycomb, X-frame, etc. are superior to 2D core types, for instance, auxetic honeycomb, hexagon re-entrant, trapezoidal and multi-cell corrugated, Y-frame, S-shaped foldcore, etc. due to additional core cavities for infills thus providing extra strengthening.
- CAI performance is largely reduced for both single and repetitive impact behaviors as prior impact introduces damage thereby making axial compressive resistance of structure more vulnerable to further damage and eventually failure.
- The design envelope for better impact resistance has been expanded through configurations inspired by nature from either animal or plant kingdom. Impact resistance is comparatively improved in both single and repetitive impact load environments through the introduction of bioinspired solutions.
- The damage behaviors of both single and repetitive impacts may be similar, repetitive impacts are dominated by indentation, penetration, and perforation and are more destructive since they compromise further the strength and integrity of the sandwich structures. Even so, repetitive impact behavior though more realistic is comparatively less studied compared to single impact. In general, impact energy rises with impact number. The plastic deformation correlates inversely with the impact number. Lower impact energy causes a higher impact number to full perforation.
- Available failure mode maps are still mainly based on the static loading environment. Map guided by impact loading is still scarce. To date, there are several maps of failure mode developed for the sake of predicting the damage mechanisms of sandwich structures attributed to single low-velocity impacts but only one study considers the repetitive impact cases. The main modes of failure exhibited in the maps are core buckling, matrix tensile damage, matrix shear damage, indentation, core shear, core yield, matrix cracking, and fiber breakage. More work is needed to gather all failure modes experienced by various diversifying configurations of sandwich structures, especially in the presence of impact loading.
- The factors that affect the resistance of the sandwich structures vary based on the nature of the impact load and the structure and are not easy to control. This includes the thickness and stacking sequence of skin, core thickness, core density, core number, impactor mass, impactor velocity, impactor geometry, temperature and moisture (environmental effects), and support condition. Loading rate can be safely neglected for low-velocity impact studies.
- In general, increasing the thicknesses of the facesheet and core, including the thicknesses of core cells plus reducing the cell size (in, e.g., foldable, auxetic, and s-shape foldcore), which raises the density of the core, improves impact resistance, peak load, and perforation threshold although these come with the disadvantage of an overall mass increase. Graded polymeric or metallic foam cores are superior to those ungraded. A better progressive crushing resistance of the core helps in boosting the impact performance of the sandwich structures. The novel foldable or auxetic cores display multi-hinges plastic deformation in achieving an improved impact response. Innovations, such as pin addition, dual-core, stitch, infilled cores, etc. all exhibit heightened impact responses.
- Flat-faced and cylindrical impactors are both more damaging creating greater damage area compared to that conical in the presence of impact load.
- Hydrothermal conditions deteriorate the impact performance of sandwich structures.
- There exist various numerical approaches to investigate the behaviors of sandwich structures under single low-velocity impacts, but a lot remains to be accomplished to numerically investigate the responses of sandwich structures under repetitive impacts.

Common finite element modeling techniques employ shell and solid elements. It is highly recommended that shell elements are used to model thin wall components as solid elements have been reported to show low accuracy and are computationally time-consuming. The best models remain those that employ cohesive elements for delamination as well as nonlinearities and combined progressive failure models in material descriptions comprising complex failure modes.

- Future directions proposed to expand the applicability of the sandwich structures in other foreseeable areas include ballistic and blasting behaviors of buildings and armored human wears, water slamming characteristics of marine structures, overall impact resistance index expansion, environmental impacts, fire loading, singly integrated fabrication chain, moisture and temperature considerations, machine learning, bioinspired configuration, and actual loading condition studies since safeguarding the sustainability of both material and structural performance in ensuring the overall longevity remains the utmost priority of all engineering structures advancements.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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References

[1] A.B.H. Kueh, Buckling of sandwich columns reinforced by triaxial weave fabric composite skin-sheets, Int. J. Mech. Sci. 66 (2013) 45–54, https://doi.org/10.1016/j.ijmecsci.2012.10.007.
[2] M.Y. Al-Fasih, A.B.H. Kueh, M.H. W. Ibrahim, Failure behavior of sandwich honeycomb composite beam containing crack at the skin, PLoS One 15 (2020), e0227895, https://doi.org/10.1371/journal.pone.0227895.
[3] L.T. Tay, Y.Y. Lee, A.B.H. Kueh, Y.H. Lee, Flatwise and edgewise compression strengths of sandwich panel with silica aerogel mat, in: Proceedings of the IOP Conference Series: Materials Science and Engineering, Vol. 1101, IOP Publishing, 2021, p. 12001.
[4] A.B.H. Kueh, Y.Y. Siaw, Impact resistance of bio-inspired sandwich beam with side-arched and honeycomb dual-core, Compos. Struct. 275 (2021), 114439, https://doi.org/10.1016/j.compstruct.2021.114439.
[5] A.B.H. Kueh, C.-Y. Tan, M.Y. Yahya, M.U. Wahit, Impact resistance efficiency of bio-inspired sandwich beam with different arched core materials, Steel Compos. Struct. 44 (2022) 105–117, https://doi.org/10.12989/scs.2022.44.1.105.
[6] S.H. Abo Sabah, A.B.H. Kueh, M.Y. Al-Fasih, Comparative low-velocity impact behavior of bio-inspired and conventional sandwich composite beams, Compos. Sci. Technol. 149 (2017) 64–74, https://doi.org/10.1016/j.compscitech.2017.06.014.
[7] S.H. Abo Sabah, A.B.H. Kueh, M.Y. Al-Fasih, Bio-inspired vs. conventional sandwich beams: a low-velocity repeated impact behavior exploration, Constr. Build. Mater. 169 (2018) 193–204, https://doi.org/10.1016/j.conbuildmat.2018.02.201.
[8] S.H. Abo Sabah, A.B.H. Kueh, N.M. Bunnori, Failure mode maps of bio-inspired sandwich beams under repeated low-velocity impact, Compos. Sci. Technol. 182 (2019), 107785, https://doi.org/10.1016/j.compscitech.2019.107785.
[9] M.Y. Al-Fasih, A.B.H. Kueh, W. Ibrahim, Flexural Behavior of Sandwich Beams with Novel Triaxially Woven Fabric Composite Skins, Steel Compos. Struct. 34 (2020) 299–308, https://doi.org/10.12989/scs.2020.34.2.299.
[10] N.A. Fleck, I. Sridhar, End compression of sandwich columns, Compos. Part A Appl. Sci. Manuf. 33 (2002) 353–359, https://doi.org/10.1016/S1359-835X(01)00118-X.
[11] A.K. Noor, W.S. Burton, C.W. Bert, Computational models for sandwich panels and shells, Appl. Mech. Rev. 49 (1996) 155–199, https://doi.org/10.1115/1.3101923.
[12] Fairbairn, W. *An Account of the Construction of the Britannia and Conway Tubular Bridges, with a Complete History of Their Progress*; John Weale: London, 1849;
[13] K.A.Test Feichtinger, Methods and performance of structural core materials-1. Static properties, J. Reinf. Plast. Compos. 8 (1989) 334–357, https://doi.org/10.1177/073168448900800402.
[14] K. Marguerre, The optimum buckling load of a flexibly supported plate composed of two sheets joined by a light weight filler when under longitudinal compression, Dtsch. Viertaljahrsschrift fur Lit. und Giests Gesch. DVL (ZWB UM1360/2) 11 (1944) 5.
[15] J.R. Vinson, Sandwich Structures, Appl. Mech. Rev. 54 (2001) 201–214, https://doi.org/10.1115/1.3097295.
[16] B. Castanié, C. Bouvet, M. Ginot, Review of composite sandwich structure in aeronautic applications, Compos. Part C. Open Access 1 (2020), 100004, https://doi.org/10.1016/j.jcomc.2020.100004.
[17] Donga, A. Application of Sandwich Beam in Automobile Front Bumper for Frontal Crash Analysis, Wichita State University, 2011.
[18] D. Mathijsen, Composite sandwich structures: the new milestone in bridge building, Reinf. Plast. 57 (2013) 17–23, https://doi.org/10.1016/S0034-3617(13)70185-1.
[19] A.B.H. Kueh, Editorial scope – structure and material edition, J. Civ. Eng. Sci. Technol. 13 (2022) 1–5, https://doi.org/10.33736/jcest.4568.2022.
[20] M.M. Gauthier, Engineered Materials Handbook, Vol. 1, ASM International, 1995. ISBN 0871702835.
[21] A. Komorek, P. Przybyłek, R. Szczepaniak, J. Godzimirski, M. Rośkowicz, S. Imiłowski, The influence of low-energy impact loads on the properties of the sandwich composite with a foam core, Polym. (Basel) 14 (2022) 1566, https://doi.org/10.3390/polym14081566.
[22] F. Tarlochan, Sandwich structures for energy absorption applications: a review, Mater. (Basel) 14 (2021) 4731, https://doi.org/10.3390/ma14164731.
[23] Callister, W.D. Wiley: Materials Science and Engineering: An Introduction, 8th Edition - William D. Callister, David G. Rethwisch; 2010;
[24] Armstrong, K.B.; Graham Bevan, L.; Cole II, W.F. *Care and Repair of Advanced Composites*; 2nd ed.; SAE International: Warrendale, Pennsylvania, 2005;
[25] T.C. Siang, M.M. Tahir, S.P. Ngian, A.B.H. Kueh, Experimental investigation on slip-in connection for cold-formed steel channel sections double, Adv. Mater. Res. 250–253 (2011) 1038–1041, https://doi.org/10.4028/www.scientific.net/AMR.250-253.1038.
[26] Hassan, M.Z. The Low Velocity Impact Response of Sandwich Structures, University of Liverpool, 2012.

[27] Q. Han, H. Qin, Z. Han, J. Zhang, S. Niu, Y. Sun, S. Shi, Study on mechanical properties of multi-structure dactyl-inspired sandwich honeycomb with basalt fiber, Compos. Struct. 247 (2020), 112467, https://doi.org/10.1016/j.compstruct.2020.112467.

[28] Q. Han, H. Qin, Z. Liu, Z. Han, J. Zhang, S. Niu, W. Zhang, Y. Sun, S. Shi, Experimental investigation on impact and bending properties of a novel dactyl-inspired sandwich honeycomb with carbon fiber, Constr. Build. Mater. 253 (2020), 119161, https://doi.org/10.1016/j.conbuildmat.2020.119161.

[29] V. Nguyen-Van, S. Wickramasinghe, A. Ghazlan, H. Nguyen-Xuan, P. Tran, Uniaxial and biaxial bioinspired interlocking composite panels subjected to dynamic loadings, Thin-Walled Struct. 157 (2020), 107023, https://doi.org/10.1016/j.tws.2020.107023.

[30] T.G. Aguirre, L. Fuller, A. Ingrole, T.W. Seek, B.B. Wheatley, B.D. Steineman, T.L.H. Donahue, S.W. Donahue, Bioinspired material architectures from bighorn sheep horncore velar bone for impact loading applications, Sci. Rep. 10 (2020) 1–14.

[31] N. San Ha, G. Lu, D. Shu, T.X. Yu, Mechanical properties and energy absorption characteristics of tropical fruit durian (Durio zibethinus), J. Mech. Behav. Biomed. Mater. 104 (2020), 103603, https://doi.org/10.1016/j.jmbbm.2019.103603.

[32] Q. Lin, W. Jia, H. Wu, A.B.H. Kueh, Y. Wang, K. Wang, J. Cai, Wrapping deployment simulation analysis of leaf-inspired membrane structures, Aerospace 8 (2021) 218, https://doi.org/10.3390/aerospace8080218.

[33] Y. Deng, N. Zhou, X. Li, X. Wang, G. Wei, H. Jia, Dynamic response and failure mechanism of S-Shaped CFRP foldcore sandwich structure under low-velocity impact, Thin-Walled Struct. 173 (2022), 109007, https://doi.org/10.1016/j.tws.2022.109007.

[34] Y. Chen, X. Zeng, Y. Deng, G. Wei, Investigation on manufacturing and low-velocity impact performance of all-composite sandwich structure with S-type foldcore, Compos. Struct. (2022), 115539, https://doi.org/10.1016/j.compstruct.2022.115539.

[35] Y. Zhang, L. Yan, C. Zhang, S. Guo, Low-velocity impact response of tube-reinforced honeycomb sandwich structure, Thin-Walled Struct. 158 (2021), 107188, https://doi.org/10.1016/j.tws.2020.107188.

[36] M. Najafi, A. Darvizeh, R. Ansari, Characterization of moisture effects on novel agglomerated cork core sandwich composites with fiber metal laminate facesheets, J. Sandw. Struct. Mater. 22 (2020) 1709–1742, https://doi.org/10.1177/1099636218789613.

[37] C.Y. Tan, H.M. Akil, Impact response of fiber metal laminate sandwich composite structure with polypropylene honeycomb core, Compos. Part B Eng. 43 (2012) 1433–1438, https://doi.org/10.1016/j.compositesb.2011.08.036.

[38] F. Luo, C. Ma, Y. Tang, L. Zhou, Y. Ding, G. Chen, Sandwich-structured flexible PVA/CS@ MWCNTs composite films with high thermal conductivity and excellent electrical insulation, Polymers 14 (2022) 2512, https://doi.org/10.3390/polym14122512.

[39] S.-Y. Jhou, C.-C. Hsu, J.-C. Yeh, The dynamic impact response of 3d-printed polymeric sandwich structures with lattice cores: numerical and experimental investigation, Polym. (Basel) 13 (2021) 4032, https://doi.org/10.3390/polym13224032.

[40] D. Muniraj, V.M. Sreehari, Damage assessment of sandwich structures with al/sic functionally graded plasma sprayed faceplates subjected to single and repeated impacts, Compos. Struct. 287 (2022), 115369, https://doi.org/10.1016/j.compstruct.2022.115369.

[41] F. Tariq, M. Uzair, M. Shifa, Residual compressive strength of aluminum alloy honeycomb sandwich panel in the presence of multiple impact dents, J. Sandw. Struct. Mater. 24 (2022) 1189–1205, https://doi.org/10.1177/10996362211036987.

[42] X. Dai, T. Yuan, Z. Zu, H. Ye, X. Cheng, F. Yang, Experimental investigation on the response and residual compressive property of honeycomb sandwich structures under single and repeated low velocity impacts, Mater. Today Commun. 25 (2020), 101309, https://doi.org/10.1016/j.mtcomm.2020.101309.

[43] H. Zniker, B. Ouaki, S. Bouzakraoui, M. EbnTouhami, H. Mezouara, Energy absorption and damage characterization of GFRP laminated and PVC-foam sandwich composites under repeated impacts with reduced energies and quasi-static indentation, Case Stud. Constr. Mater. 16 (2022), e00844, https://doi.org/10.1016/j.cscm.2021.e00844.

[44] Y. Zeng, J. Liu, Y. Zhao, Experimental research on the repeated impacts behavior of aluminum corrugated-core sandwich structures, Shock Vib. 20 (2022) 1–14, https://doi.org/10.1155/2022/4644029.

[45] S. Gopinath, R. Ayashwarya, V.R. Kumar, P.R. Prem, A.R. Chandra murthy, C.K. Madheswaran, R.N. Iyer, Low velocity impact behaviour of ultra high strength concrete panels, Sadhana 39 (2014) 1497–1507, https://doi.org/10.1007/s12046-014-0280-3.

[46] S.H. Abo Sabah, A.B.H. Kueh, Finite element modeling of laminated composite plates with locally delaminated interface subjected to impact loading, Article 954070, Sci. World J. 2014 (2014), https://doi.org/10.1155/2014/954070.

[47] V. Birman, G.A. Kardomateas, Review of current trends in research and applications of sandwich structures, Compos. Part B Eng. 142 (2018) 221–240, https://doi.org/10.1016/j.compositesb.2018.01.027.

[48] Q. Ma, M.R.M. Rejab, J.P. Siregar, Z. Guan, A review of the recent trends on core structures and impact response of sandwich panels, J. Compos. Mater. 55 (2021) 2513–2555, https://doi.org/10.1177/0021998321990734.

[49] G.B. Chai, S. Zhu, A review of low-velocity impact on sandwich structures, Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl. 225 (2011) 207–230, https://doi.org/10.1177/1464420711409985.

[50] M.O.W. Richardson, M.J. Wisheart, Review of low-velocity impact properties of composite materials, Compos. Part A Appl. Sci. Manuf. 27 (1996) 1123–1131, https://doi.org/10.1016/1359-835X(96)00074-7.

[51] S. Agrawal, K.K. Singh, P.K. Sarkar, Impact damage on fibre-reinforced polymer matrix composite–a review, J. Compos. Mater. 48 (2014) 317–332, https://doi.org/10.1177/0021998312472217.

[52] F.D. Morinière, R.C. Alderliesten, R. Benedictus, Modelling of impact damage and dynamics in fibre-metal laminates–a review, Int. J. Impact Eng. 67 (2014) 27–38, https://doi.org/10.1016/j.ijimpeng.2014.01.004.

[53] N.L. Hancox, An Overview of the Impact Behaviour of Fibre-Reinforced Composites, Woodhead Publishing, Cambridge, UK, 2000.

[54] A. Seyed Yaghoubi, Y. Liu, B. Liaw, Stacking sequence and geometrical effects on low-velocity impact behaviors of GLARE 5 (3/2) fiber–metal laminates, J. Thermoplast. Compos. Mater. 25 (2012) 223–247.

[55] W.J. Cantwell, J. Morton, The impact resistance of composite materials—a review, composites 22 (1991) 347–362, https://doi.org/10.1016/0010-4361(91)90549-V.

[56] S. Abrate, Impact on Composite Structures, Cambridge University Press, 1998. ISBN 0521473896.

[57] P. Robinson, G.A.O. Davies, Impactor mass and specimen geometry effects in low velocity impact of laminated composites, Int. J. Impact Eng. 12 (1992) 189–207, https://doi.org/10.1016/0734-743X(92)90408-L.

[58] G.A.O. Davies, P. Robinson, Predicting failure by debonding/delamination, *SEE N 93-21507 07-24*, AGARD, Debonding/Delamination Compos 28 (1992). *SEE N 93-21507 07-24*.

[59] Q. Qin, X. Zheng, J. Zhang, C. Yuan, T.J. Wang, Dynamic response of square sandwich plates with a metal foam core subjected to low-velocity impact, Int. J. Impact Eng. 111 (2018) 222–235, https://doi.org/10.1016/j.ijimpeng.2017.09.011.

[60] A. Sakly, A. Laksimi, H. Kebir, S. Benmedakhen, Experimental and modelling study of low velocity impacts on composite sandwich structures for railway applications, Eng. Fail. Anal. 68 (2016) 22–31, https://doi.org/10.1016/j.engfailanal.2016.03.001.

[61] N. Jones, Energy-absorbing effectiveness factor, Int. J. Impact Eng. 37 (2010) 754–765, https://doi.org/10.1016/j.ijimpeng.2009.01.008.

[62] E.J. Herup, A.N. Palazotto, Low-velocity impact damage initiation in graphite/epoxy/nomex honeycomb-sandwich plates, Compos. Sci. Technol. 57 (1998) 1581–1598, https://doi.org/10.1016/S0266-3538(97)00089-4.

[63] K. Guo, L. Zhu, Y. Li, T.X. Yu, A. Shenoi, Q. Zhou, Experimental investigation on the dynamic behaviour of aluminum foam sandwich plate under repeated impacts, Compos. Struct. 200 (2018) 298–305, https://doi.org/10.1016/j.compstruct.2018.05.148.

[64] X. Huo, G. Sun, H. Zhang, X. Lv, Q. Li, Experimental study on low-velocity impact responses and residual properties of composite sandwiches with metallic foam core, Compos. Struct. 223 (2019), 110835, https://doi.org/10.1016/j.compstruct.2019.04.007.

[65] S. Sathiya Naarayan, J. Dhayanidhi, B. Nagarajappa, Y. Vorkady, S. Chandra, Behavior of organic gelatin/phenolic micro balloon composite under compressive loading, static and low velocity impact, Indian J. Eng. Mater. Sci. 22 (2015) 618–630.

[66] S. Samlal, R. Santhanakrishnan, Low-velocity impact behavior of foam core sandwich panels with inter-ply and intra-ply carbon/kevlar/epoxy hybrid face sheets, Polym. (Basel) 14 (2022) 1060, https://doi.org/10.3390/polym14051060.

[67] A.J. Turner, M. Al Rifaie, A. Mian, R. Srinivasan, Low-velocity impact behavior of sandwich structures with additively manufactured polymer lattice cores, J. Mater. Eng. Perform. 27 (2018) 2505–2512, https://doi.org/10.1007/s11665-018-3322-x.

[68] M. Elamin, B. Li, K.T. Tan, Impact damage of composite sandwich structures in arctic condition, Compos. Struct. 192 (2018) 422–433, https://doi.org/10.1016/j.compstruct.2018.03.015.

[69] J. Zhou, Z.W. Guan, W.J. Cantwell, The impact response of graded foam sandwich structures, Compos. Struct. 97 (2013) 370–377, https://doi.org/10.1016/j.compstruct.2012.10.037.

[70] E. Sevkat, B. Liaw, F. Delale, B.B. Raju, Effect of repeated impacts on the response of plain-woven hybrid composites, Compos. Part B Eng. 41 (2010) 403–413, https://doi.org/10.1016/j.compositesb.2010.01.001.

[71] W. He, J. Liu, S. Wang, D. Xie, Low-velocity impact response and post-impact flexural behaviour of composite sandwich structures with corrugated cores, Compos. Struct. 189 (2018) 37–53, https://doi.org/10.1016/j.compstruct.2018.01.024.

[72] A. Rajaneesh, I. Sridhar, S. Rajendran, Relative performance of metal and polymeric foam sandwich plates under low velocity impact, Int. J. Impact Eng. 65 (2014) 126–136, https://doi.org/10.1016/j.ijimpeng.2013.11.012.

[73] M.A. Hazizan, W.J. Cantwell, The low velocity impact response of foam-based sandwich structures, Compos. Part B Eng. 33 (2002) 193–204, https://doi.org/10.1016/S1359-8368(02)00009-4.

[74] J. Zhou, M.Z. Hassan, Z. Guan, W.J. Cantwell, The low velocity impact response of foam-based sandwich panels, Compos. Sci. Technol. 72 (2012) 1781–1790, https://doi.org/10.1016/j.compscitech.2012.07.006.

[75] U. Caliskan, M.K. Apalak, Low velocity bending impact behavior of foam core sandwich beams: experimental, Compos. Part B Eng. 112 (2017) 158–175, https://doi.org/10.1016/j.compositesb.2016.12.038.

[76] W. He, S. Lu, K. Yi, S. Wang, G. Sun, Z. Hu, Residual flexural properties of CFRP sandwich structures with aluminum honeycomb cores after low-velocity impact, Int. J. Mech. Sci. 161 (2019), 105026, https://doi.org/10.1016/j.ijmecsci.2019.105026.

[77] S. Zangana, J. Epaarachchi, W. Ferdous, J. Leng, P. Schubel, Behaviour of continuous fibre composite sandwich core under low-velocity impact, Thin-Walled Struct. 158 (2021), 107157, https://doi.org/10.1016/j.tws.2020.107157.

[78] C. Qi, A. Remennikov, L.-Z. Pei, S. Yang, Z.-H. Yu, T.D. Ngo, Impact and close-in blast response of auxetic honeycomb-cored sandwich panels: experimental tests and numerical simulations, Compos. Struct. 180 (2017) 161–178, https://doi.org/10.1016/j.compstruct.2017.08.020.

[79] J. Liu, W. He, D. Xie, B. Tao, The effect of impactor shape on the low-velocity impact behavior of hybrid corrugated core sandwich structures, Compos. Part B Eng. 111 (2017) 315–331, https://doi.org/10.1016/j.compositesb.2016.11.060.

[80] V. Rubino, V.S. Deshpande, N.A. Fleck, The dynamic response of end-clamped sandwich beams with a Y-frame or corrugated core, Int. J. Impact Eng. 35 (2008) 829–844, https://doi.org/10.1016/j.ijimpeng.2007.10.006.

[81] M.T. Tilbrook, D.D. Radford, V.S. Deshpande, N.A. Fleck, Dynamic crushing of sandwich panels with prismatic lattice cores, Int. J. Solids Struct. 44 (2007) 6101–6123, https://doi.org/10.1016/j.ijsolstr.2007.02.015.

[82] D.D. Radford, N.A. Fleck, V.S. Deshpande, The response of clamped sandwich beams subjected to shock loading, Int. J. Impact Eng. 32 (2006) 968–987, https://doi.org/10.1016/j.ijimpeng.2004.08.007.

[83] B. Wang, L.-Z. Wu, L. Ma, J.-C. Feng, Low-velocity impact characteristics and residual tensile strength of carbon fiber composite lattice core sandwich structures, Compos. Part B Eng. 42 (2011) 891–897, https://doi.org/10.1016/j.compositesb.2011.01.007.

[84] G. Zhang, B. Wang, L. Ma, L. Wu, S. Pan, J. Yang, Energy absorption and low velocity impact response of polyurethane foam filled pyramidal lattice core sandwich panels, Compos. Struct. 108 (2014) 304–310, https://doi.org/10.1016/j.compstruct.2013.09.040.

[85] S. Heimbs, J. Cichosz, M. Klaus, S. Kilchert, A.F. Johnson, Sandwich structures with textile-reinforced composite foldcores under impact loads, Compos. Struct. 92 (2010) 1485–1497, https://doi.org/10.1016/j.compstruct.2009.11.001.

[86] R.S. Jayaram, V.A. Nagarajan, K.P. Vinod Kumar, Compression and low velocity impact response of sandwich panels with polyester pin-reinforced foam filled honeycomb core, J. Sandw. Struct. Mater. 21 (2019) 2014–2030, https://doi.org/10.1177/1099636218792675.

[87] W. He, J. Liu, S. Wang, D. Xie, Low-velocity impact behavior of X-frame core sandwich structures–experimental and numerical investigation, Thin-Walled Struct. 131 (2018) 718–735, https://doi.org/10.1016/j.tws.2018.07.042.

[88] Z.H. Tan, H.H. Luo, W.G. Long, X. Han, Dynamic response of clamped sandwich beam with aluminium alloy foam core subjected to impact loading, Compos. Part B Eng. 46 (2013) 39–45, https://doi.org/10.1016/j.compositesb.2012.10.044.

[89] G. Zhang, B. Wang, L. Ma, J. Xiong, L. Wu, Response of sandwich structures with pyramidal truss cores under the compression and impact loading, Compos. Struct. 100 (2013) 451–463, https://doi.org/10.1016/j.compstruct.2013.01.012.

[90] C. Atas, C. Sevim, On the impact response of sandwich composites with cores of balsa wood and PVC foam, Compos. Struct. 93 (2010) 40–48, https://doi.org/10.1016/j.compstruct.2010.06.018.

[91] B. Castanié, Y. Aminanda, C. Bouvet, J.-J. Barrau, Core crush criterion to determine the strength of sandwich composite structures subjected to compression after impact, Compos. Struct. 86 (2008) 243–250, https://doi.org/10.1016/j.compstruct.2008.03.032.

[92] Y. Aminanda, B. Castanié, J.-J. Barrau, P. Thevenet, Experimental and numerical study of compression after impact of sandwich structures with metallic skins, Compos. Sci. Technol. 69 (2009) 50–59, https://doi.org/10.1016/j.compscitech.2007.10.045.

[93] H. Ye, X. Dai, T. Yuan, J. Zhou, J. Zhang, S. Shao, Residual compression property and response of honeycomb sandwich structures subjected to single and repeated quasi-static indentation, Rev. Adv. Mater. Sci. 60 (2021) 404–417, https://doi.org/10.1515/rams-2021-0033.

[94] B. Yang, Z. Wang, L. Zhou, J. Zhang, L. Tong, W. Liang, Study on the low-velocity impact response and CAI behavior of foam-filled sandwich panels with hybrid facesheet, Compos. Struct. 132 (2015) 1129–1140, https://doi.org/10.1016/j.compstruct.2015.07.058.

[95] A. Gilioli, C. Sbarufatti, A. Manes, M. Giglio, Compression after impact test (CAI) on NOMEX™ honeycomb sandwich panels with thin aluminum skins, Compos. Part B Eng. 67 (2014) 313–325, https://doi.org/10.1016/j.compositesb.2014.07.015.

[96] T. Topkaya, M.Y. Solmaz, Investigation of low velocity impact behaviors of honeycomb sandwich composites, J. Mech. Sci. Technol. 32 (2018) 3161–3167, https://doi.org/10.1007/s12206-018-0619-5.

[97] M.R. Yellur, H. Seidlitz, F. Kuke, K. Wartig, N. Tsombanis, A low velocity impact study on press formed thermoplastic honeycomb sandwich panels, Compos. Struct. 225 (2019), 111061, https://doi.org/10.1016/j.compstruct.2019.111061.

[98] X. Yang, J. Ma, Y. Shi, Y. Sun, J. Yang, Crashworthiness investigation of the bio-inspired Bi-directionally corrugated core sandwich panel under quasi-static crushing load, Mater. Des. 135 (2017) 275–290, https://doi.org/10.1016/j.matdes.2017.09.040.

[99] Y. Wu, Q. Liu, J. Fu, Q. Li, D. Hui, Dynamic crash responses of bio-inspired aluminum honeycomb sandwich structures with CFRP panels, Compos. Part B Eng. 121 (2017) 122–133, https://doi.org/10.1016/j.compositesb.2017.03.030.

[100] J. Chen, X. Zhang, Y. Okabe, K. Saito, Z. Guo, L. Pan, The deformation mode and strengthening mechanism of compression in the beetle elytron plate, Mater. Des. 131 (2017) 481–486, https://doi.org/10.1016/j.matdes.2017.06.014.

[101] X. Zhang, J. Xie, J. Chen, Y. Okabe, L. Pan, M. Xu, The beetle elytron plate: a lightweight, high-strength and buffering functional-structural bionic material, Sci. Rep. 7 (2017) 1–7, https://doi.org/10.1038/s41598-017-03767-w.

[102] S. Haldar, H.A. Bruck, Mechanics of composite sandwich structures with bioinspired core, Compos. Sci. Technol. 95 (2014) 67–74, https://doi.org/10.1016/j.compscitech.2014.02.011.

[103] Z. Sun, S. Shi, X. Guo, X. Hu, H. Chen, On compressive properties of composite sandwich structures with grid reinforced honeycomb core, Compos. Part B Eng. 94 (2016) 245–252, https://doi.org/10.1016/j.compositesb.2016.03.054.

[104] Z. Sun, D. Li, W. Zhang, S. Shi, X. Guo, Topological optimization of biomimetic sandwich structures with hybrid core and CFRP face sheets, Compos. Sci. Technol. 142 (2017) 79–90, https://doi.org/10.1016/j.compscitech.2017.01.029.

[105] T. Liu, S. Hou, X. Nguyen, X. Han, Energy absorption characteristics of sandwich structures with composite sheets and bio coconut core, Compos. Part B Eng. 114 (2017) 328–338, https://doi.org/10.1016/j.compositesb.2017.01.035.

[106] Standing, R.G.; Brendling, W. Collisions of Attendant Vessels with Offshore Installations. Part 2: Detailed Calculations. 1985.

[107] L. Torre, J.M. Kenny, Impact testing and simulation of composite sandwich structures for civil transportation, Compos. Struct. 50 (2000) 257–267, https://doi.org/10.1016/S0263-8223(00)00101-X.

[108] O. Balcı, O. Çoban, M.Ö. Bora, E. Akagündüz, E.B. Yalçin, Experimental investigation of single and repeated impacts for repaired honeycomb sandwich structures, Mater. Sci. Eng. A 682 (2017) 23–30, https://doi.org/10.1016/j.msea.2016.11.030.

[109] O. Ozdemir, N. Oztoprak, H. Kandas, Single and repeated impact behaviors of bio-sandwich structures consisting of thermoplastic face sheets and different balsa core thicknesses, Compos. Part B Eng. 149 (2018) 49–57, https://doi.org/10.1016/j.compositesb.2018.05.016.

[110] K. Guo, L. Zhu, Y. Li, T.X. Yu, Numerical study on mechanical behavior of foam core sandwich plates under repeated impact loadings, Compos. Struct. 224 (2019), 111030, https://doi.org/10.1016/j.compstruct.2019.111030.

[111] Y. Zhang, Y. Li, K. Guo, L. Zhu, Dynamic mechanical behaviour and energy absorption of aluminium honeycomb sandwich panels under repeated impact loads, Ocean Eng. 219 (2021), 108344.

[112] A. Akatay, M.Ö. Bora, O. Çoban, S. Fidan, V. Tuna, The influence of low velocity repeated impacts on residual compressive properties of honeycomb sandwich structures, Compos. Struct. 125 (2015) 425–433, https://doi.org/10.1016/j.compstruct.2015.02.057.

[113] Abot, J.L.; Daniel, I.M.; Gdoutos, E.E. Failure Mechanisms of Composite Sandwich Beams under Impact Loading. In Proceedings of the Proceedings of the 14th European Conference on Fracture, Cracow; 2002; pp. 13–19.

[114] F.D. Morinière, R.C. Alderliesten, M.Y. Tooski, R. Benedictus, Damage evolution in GLARE fibre-metal laminate under repeated low-velocity impact tests, Cent. Eur. J. Eng. 2 (2012) 603–611, https://doi.org/10.2478/s13531-012-0019-z.

[115] C. Atas, U. Potoğlu, The effect of face-sheet thickness on low-velocity impact response of sandwich composites with foam cores, J. Sandw. Struct. Mater. 18 (2016) 215–228, https://doi.org/10.1177/1099636215613775.

[116] J. Wang, A.M. Waas, H. Wang, Experimental and numerical study on the low-velocity impact behavior of foam-core sandwich panels, Compos. Struct. 96 (2013) 298–311, https://doi.org/10.1016/j.compstruct.2012.09.002.

[117] W. He, L. Yao, X. Meng, G. Sun, D. Xie, J. Liu, Effect of structural parameters on low-velocity impact behavior of aluminum honeycomb sandwich structures with CFRP face sheets, Thin-Walled Struct. 137 (2019) 411–432, https://doi.org/10.1016/j.tws.2019.01.022.

[118] C. Liu, Y.X. Zhang, J. Li, Impact responses of sandwich panels with fibre metal laminate skins and aluminium foam core, Compos. Struct. 182 (2017) 183–190, https://doi.org/10.1016/j.compstruct.2017.09.015.

[119] R. Mohmmed, F. Zhang, B. Sun, B. Gu, Finite element analyses of low-velocity impact damage of foam sandwiched composites with different ply angles face sheets, Mater. Des. 47 (2013) 189–199, https://doi.org/10.1016/j.matdes.2012.12.016.

[120] K.M. Fard, S.M.R. Khalili, S.H. Forooghy, M. Hosseini, Low velocity transverse impact response of a composite sandwich plate subjected to a rigid blunted cylindrical impactor, Compos. Part B Eng. 63 (2014) 111–122, https://doi.org/10.1016/j.compositesb.2014.03.011.

[121] L. Chen, B. Du, J. Zhang, H. Zhou, D. Li, D. Fang, Numerical study on the projectile impact resistance of multi-layer sandwich panels with cellular cores, Lat. Am. J. Solids Struct. 13 (2016) 2876–2895.

[122] G. Morada, R. Ouadday, A. Vadean, R. Boukhili, Low-velocity impact resistance of ATH/Epoxy core sandwich composite panels: experimental and numerical analyses, Compos. Part B Eng. 114 (2017) 418–431, https://doi.org/10.1016/j.compositesb.2017.01.070.

[123] K.S. Raju, B.L. Smith, J.S. Tomblin, K.H. Liew, J.C. Guarddon, Impact damage resistance and tolerance of honeycomb core sandwich panels, J. Compos. Mater. 42 (2008) 385–412, https://doi.org/10.1177/0021998307088596.

[124] R. Gunes, K. Arslan, Development of numerical realistic model for predicting low-velocity impact response of aluminium honeycomb sandwich structures, J. Sandw. Struct. Mater. 18 (2016) 95–112, https://doi.org/10.1177/1099636215603047.

[125] T.K. Demircioğlu, F. Balıkoğlu, O. İnal, N. Arslan, Ay, A. Ataş, Experimental investigation on low-velocity impact response of wood skinned sandwich composites with different core configurations, Mater. Today Commun. 17 (2018) 31–39, https://doi.org/10.1016/j.mtcomm.2018.08.003.

[126] McQuigg, T.; Kapania, R.; Scotti, S.; Walker, S. Compression after Impact on Honeycomb Core Sandwich Panels with Thin Facesheets, Part 1: Experiments. In Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference 20th AIAA/ASME/AHS Adaptive Structures Conference 14th AIAA; 2012; p. 1703.

[127] G. Zhang, B. Wang, L. Ma, J. Xiong, J. Yang, L. Wu, The residual compressive strength of impact-damaged sandwich structures with pyramidal truss cores, Compos. Struct. 105 (2013) 188–198, https://doi.org/10.1016/j.compstruct.2013.05.016.

[128] M.Z. Hassan, W.J. Cantwell, The influence of core properties on the perforation resistance of sandwich structures–an experimental study, Compos. Part B Eng. 43 (2012) 3231–3238, https://doi.org/10.1016/j.compositesb.2012.03.012.

[129] S.B. Loganathan, H.K. Shivanand, Effect of core thickness and core density on low velocity impact behavior of sandwich panels with PU foam core, J. Miner. Mater. Charact. Eng. 3 (2015) 164, https://doi.org/10.4236/jmmce.2015.33019.

[130] C. Kılıçaslan, M. Güden, İ.K. Odacı, A. Taşdemirci, The impact responses and the finite element modeling of layered trapezoidal corrugated aluminum core and aluminum sheet interlayer sandwich structures, Mater. Des. 46 (2013) 121–133, https://doi.org/10.1016/j.matdes.2012.09.059.

[131] O. Dorival, P. Navarro, S. Marguet, C. Petiot, M. Bermudez, D. Mesnagé, J.-F. Ferrero, Experimental results of medium velocity impact tests for reinforced foam core braided composite structures, J. Sandw. Struct. Mater. 20 (2018) 106–129, https://doi.org/10.1177/1099636216650990.

[132] B. Lascoup, Z. Aboura, K. Khellil, M. Benzeggagh, On the mechanical effect of stitch addition in sandwich panel, Compos. Sci. Technol. 66 (2006) 1385–1398, https://doi.org/10.1016/j.compscitech.2005.09.005.

[133] F. Xia, X. Wu, Study on impact properties of through-thickness stitched foam sandwich composites, Compos. Struct. 92 (2010) 412–421, https://doi.org/10.1016/j.compstruct.2009.08.016.

[134] B. Lascoup, Z. Aboura, K. Khellil, M. Benzeggagh, Impact response of three-dimensional stitched sandwich composite, Compos. Struct. 92 (2010) 347–353, https://doi.org/10.1016/j.compstruct.2009.08.012.

[135] S. Samlal, V. Paulson, R. Santhanakrishnan, Effect of stitching angle on impact characteristics of sandwich panels, Int. J. Innov. Res. Sci. Eng. Technol. 4 (2015) 30–34.

[136] H.M. Wen, T.Y. Reddy, S.R. Reid, P.D. Soden, Indentation, penetration and perforation of composite laminate and sandwich panels under quasi-static and projectile loading, Proc. Key Eng. Mater. ; Trans. Tech. Publ. Vol. 141 (1998) 501–552.

[137] E.A. Flores-Johnson, Q.M. Li, Experimental study of the indentation of sandwich panels with carbon fibre-reinforced polymer face sheets and polymeric foam core, Compos. Part B Eng. 42 (2011) 1212–1219, https://doi.org/10.1016/j.compositesb.2011.02.013.

[138] A. Khalkhali, N. Geran Malek, M. Bozorgi Nejad, Effects of the impactor geometrical shape on the non-linear low-velocity impact response of sandwich plate with CNTRC face sheets, J. Sandw. Struct. Mater. 22 (2020) 962–990, https://doi.org/10.1177/1099636218778998.

[139] A. Kurşun, M. Şenel, H.M. Enginsoy, E. Bayraktar, Effect of impactor shapes on the low velocity impact damage of sandwich composite plate: experimental study and modelling, Compos. Part B Eng. 86 (2016) 143–151, https://doi.org/10.1016/j.compositesb.2015.09.032.

[140] Z. Li, Z. Zheng, J. Yu, Low-velocity perforation behavior of composite sandwich panels with aluminum foam core, J. Sandw. Struct. Mater. 15 (2013) 92–109, https://doi.org/10.1177/1099636212454538.

[141] I.M. Daniel, Impact response and damage tolerance of composite sandwich structures. In *Dynamic failure of materials and structures*, Springer, 2009, pp. 191–233.

[142] L. St-Pierre, V.S. Deshpande, N.A. Fleck, The low velocity impact response of sandwich beams with a corrugated core or a Y-frame core, Int. J. Mech. Sci. 91 (2015) 71–80, https://doi.org/10.1016/j.ijmecsci.2014.02.014.

[143] P. Chen, W. Niu, X. Yan, G. Lu, Theoretical model for dynamic response of aluminum foam sandwich targets by truncated cone-nosed projectiles, J. Sandw. Struct. Mater. 20 (2018) 249–267, https://doi.org/10.1177/1099636216664288.

[144] A. Bez, C. Bedon, G. Manara, C. Amadio, G. Lori, Calibrated numerical approach for the dynamic analysis of glass curtain walls under spheroconical bag impact, Buildings 11 (2021) 154, https://doi.org/10.3390/buildings11040154.

[145] C. Bedon, M.V. Santi, Simplified procedure for capacity check of historic monolithic glass windows under soft-body collision/bird-strike, Symmetry 14 (2022) 2198, https://doi.org/10.3390/sym14102198.

[146] C. Bedon, M.V. Santi, Vulnerability and structural capacity assessment of historic glass facades under bird-strike, Math. Probl. Eng. (2022) *2022*, https://doi.org/10.1155/2022/6059466.
[147] R. Vignjevic, J. Campbell, K. Hughes, M. Orłowski, S. Garcea, P. Withers, J. Reed, Soft body impact resistance of composite foam core sandwich panels with unidirectional corrugated and tubular reinforcements, Int. J. Impact Eng. 132 (2019), 103320, https://doi.org/10.1016/j.ijimpeng.2019.103320.
[148] Y. Zhou, Y. Sun, T. Huang, Impact responses of slender composite plates for bird-strike testing of fan blades, Lat. Am. J. Solids Struct. (2019) *16*, https://doi.org/10.1590/1679-78255809.
[149] M.D. Erickson, A.R. Kallmeyer, K.G. Kellogg, Effect of temperature on the low-velocity impact behavior of composite sandwich panels, J. Sandw. Struct. Mater. 7 (2005) 245–264, https://doi.org/10.1177/1099636205048636.
[150] A. Salehi-Khojin, M. Mahinfalah, R. Bashirzadeh, B. Freeman, Temperature effects on kevlar/hybrid and carbon fiber composite sandwiches under impact loading, Compos. Struct. 78 (2007) 197–206, https://doi.org/10.1016/j.compstruct.2005.09.005.
[151] M.H. Khan, M. Elamin, B. Li, K.T. Tan, X-ray micro-computed tomography analysis of impact damage morphology in composite sandwich structures due to cold temperature arctic condition, J. Compos. Mater. 52 (2018) 3509–3522, https://doi.org/10.1177/0021998318785671.
[152] C.H.N. Reddy, C.H. Rajeswari, T. Malyadri, S.N.S.S. Hari, Effect of moisture absorption on the mechanical properties of jute/glass hybrid sandwich composites, Mater. Today Proc. 45 (2021) 3307–3311, https://doi.org/10.1016/j.matpr.2020.12.639.
[153] O. Ishai, C. Hiel, M. Luft, Long-term hygrothermal effects on damage tolerance of hybrid composite sandwich panels, Composites 26 (1995) 47–55, https://doi.org/10.1016/0010-4361(94)P3629-F.
[154] M. Yang, P. Qiao, Impact and damage prediction of sandwich beams with flexible core considering arbitrary boundary effects, J. Sandw. Struct. Mater. 9 (2007) 411–444, https://doi.org/10.1177/1099636207067135.
[155] D.W. Zhou, W.J. Stronge, Low velocity impact denting of hssa lightweight sandwich panel, Int. J. Mech. Sci. 48 (2006) 1031–1045, https://doi.org/10.1016/j.ijmecsci.2006.05.011.
[156] F. Zhu, G. Lu, D. Ruan, Z. Wang, Plastic deformation, failure and energy absorption of sandwich structures with metallic cellular cores, Int. J. Prot. Struct. 1 (2010) 507–541, https://doi.org/10.1260/2041-4196.1.4.507.
[157] A. Farokhi Nejad, Rahimian Koloor, Syed Hamzah, M.Y. Yahya, Mechanical behaviour of pin-reinforced foam core sandwich panels subjected to low impact loading, Polymers 13 (2021), https://doi.org/10.3390/polym13213627.
[158] R. Olsson, Mass criterion for wave controlled impact response of composite plates, Compos. Part A Appl. Sci. Manuf. 31 (2000) 879–887, https://doi.org/10.1016/S1359-835X(00)00020-8.
[159] I. Taraghi, A. Fereidoon, Non-destructive evaluation of damage modes in nanocomposite foam-core sandwich panel subjected to low-velocity impact, Compos. Part B Eng. 103 (2016) 51–59, https://doi.org/10.1016/j.compositesb.2016.08.009.
[160] S. Zhu, G.B. Chai, Damage and failure mode maps of composite sandwich panel subjected to quasi-static indentation and low velocity impact, Compos. Struct. 101 (2013) 204–214, https://doi.org/10.1016/j.compstruct.2013.02.010.
[161] J. Wang, H. Wang, B. Chen, H. Huang, S. Liu, A failure mechanism based model for numerical modeling the compression-after-impact of foam-core sandwich panels, Compos. Sci. Technol. 151 (2017) 258–267, https://doi.org/10.1016/j.compscitech.2017.08.027.
[162] S. Dhar Malingam, F.A. Jumaat, L.F. Ng, K. Subramaniam, A.F. Ab Ghani, Tensile and impact properties of cost-effective hybrid fiber metal laminate sandwich structures, Adv. Polym. Technol. 37 (2018) 2385–2393, https://doi.org/10.1002/adv.21913.
[163] Y. Li, A. Xuefeng, Y. Xiaosu, Comparison with low-velocity impact and quasi-static indentation testing of foam core sandwich composites, Int. J. Appl. Phys. Math. 2 (2012) 58.
[164] M.S. Rosenfeld, L.W. Gause, Compression fatigue behaviour of graphite/epoxy in the presence of stress raisers, Fatigue Fibrous Compos. Mater. (1981) 174–196.
[165] V. Dey, G. Zani, M. Colombo, M. Di Prisco, B. Mobasher, Flexural impact response of textile-reinforced aerated concrete sandwich panels, Mater. Des. 86 (2015) 187–197, https://doi.org/10.1016/j.matdes.2015.07.004.
[166] A. Ahmed, Z. Bingjie, M.H. Ikbal, W. Qingtao, A. Obed, L. Wei, Experimental study on the effects of stacking sequence on low velocity impact and quasi-static response of foam sandwich composite structures, Adv. Struct. Eng. 18 (2015) 1789–1805, https://doi.org/10.1260/1369-4332.18.11.1789.
[167] C. Audibert, A.-S. Andréani, É. Lainé, J.-C. Grandidier, Discrete modelling of low-velocity impact on Nomex® honeycomb sandwich structures with CFRP skins, Compos. Struct. 207 (2019) 108–118, https://doi.org/10.1016/j.compstruct.2018.09.047.
[168] L. Jing, X. Su, D. Chen, F. Yang, L. Zhao, Experimental and numerical study of sandwich beams with layered-gradient foam cores under low-velocity impact, Thin-Walled Struct. 135 (2019) 227–244, https://doi.org/10.1016/j.tws.2018.11.011.
[169] H. Wang, K.R. Ramakrishnan, K. Shankar, Experimental study of the medium velocity impact response of sandwich panels with different cores, Mater. Des. 99 (2016) 68–82, https://doi.org/10.1016/j.matdes.2016.03.048.
[170] Y. Chen, S. Hou, K. Fu, X. Han, L. Ye, Low-velocity impact response of composite sandwich structures: modelling and experiment, Compos. Struct. 168 (2017) 322–334, https://doi.org/10.1016/j.compstruct.2017.02.064.
[171] F. Balıkoğlu, T.K. Demircioğlu, O. İnal, N. Arslan, A. Ataş, Compression after low velocity impact tests of marine sandwich composites: effect of intermediate wooden layers, Compos. Struct. 183 (2018) 636–642, https://doi.org/10.1016/j.compstruct.2017.08.003.
[172] Z. Cai, Z. Li, Y. Ding, J. Zheng, J. Liu, Z. Zhou, Preparation and impact resistance performance of bionic sandwich structure inspired from beetle forewing, Compos. Part B Eng. 161 (2019) 490–501, https://doi.org/10.1016/j.compositesb.2018.12.139.
[173] X. Xue, C. Zhang, W. Chen, M. Wu, J. Zhao, Study on the impact resistance of honeycomb sandwich structures under low-velocity/heavy mass, Compos. Struct. 226 (2019), 111223, https://doi.org/10.1016/j.compstruct.2019.111223.
[174] A.A. Prakash, B. Mohan, A. Rajadurai, A. Jaswin, Low velocity impact behaviour of glass fabric/epoxy honeycomb core sandwich composites, Sci. Eng. Compos. Mater. 22 (2015) 525–538, https://doi.org/10.1515/secm-2013-0069.
[175] R.A.W. Mines, C.M. Worrall, A.G. Gibson, The static and impact behaviour of polymer composite sandwich beams, Composites 25 (1994) 95–110, https://doi.org/10.1016/0010-4361(94)90003-5.
[176] R.A.W. Mines, C.M. Worrall, A.G. Gibson, Low velocity perforation behaviour of polymer composite sandwich panels, Int. J. Impact Eng. 21 (1998) 855–879, https://doi.org/10.1016/S0734-743X(98)00037-2.
[177] F. Cucinotta, A. Paoli, G. Risitano, F. Sfravara, Optical measurements and experimental investigations in repeated low-energy impacts in powerboat sandwich composites, Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ. 232 (2018) 234–244, https://doi.org/10.1177/1475090217720619.
[178] R. Abdullah, A.B.H. Kueh, I.S. Ibrahim, W.S. Easterling, Characterization of shear bond stress for design of composite slabs using an improved partial shear connection method, J. Civ. Eng. Manag. 21 (2015) 720–732, https://doi.org/10.3846/13923730.2014.893919.
[179] Triantafillou, T.C. Failure Mode Maps and Minimum Weight Design for Structural Sandwich Beams with Rigid Foam Cores 1987.
[180] T.C. Triantafillou, L.J. Gibson, Failure mode maps for foam core sandwich beams, Mater. Sci. Eng. 95 (1987) 37–53, https://doi.org/10.1016/0025-5416(87)90496-4.
[181] T.C. Triantafillou, L.J. Gibson, Minimum weight design of foam core sandwich panels for a given strength, Mater. Sci. Eng. 95 (1987) 55–62, https://doi.org/10.1016/0025-5416(87)90497-6.
[182] T.M. McCormack, R. Miller, O. Kesler, L.J. Gibson, Failure of sandwich beams with metallic foam cores, Int. J. Solids Struct. 38 (2001) 4901–4920, https://doi.org/10.1016/S0020-7683(00)00327-9.
[183] M.F. Ashby, T. Evans, N.A. Fleck, J.W. Hutchinson, H.N.G. Wadley, L.J. Gibson, Metal Foams: A Design Guide, Elsevier, 2000. ISBN 0080511465.
[184] J. Yu, E. Wang, J. Li, Z. Zheng, Static and low-velocity impact behavior of sandwich beams with closed-cell aluminum-foam core in three-point bending, Int. J. Impact Eng. 35 (2008) 885–894, https://doi.org/10.1016/j.ijimpeng.2008.01.006.
[185] X. Huo, H. Liu, Q. Luo, G. Sun, Q. Li, On low-velocity impact response of foam-core sandwich panels, Int. J. Mech. Sci. (2020) *181*, https://doi.org/10.1016/j.ijmecsci.2020.105681.

[186] S.N. Mokhatar, Y. Sonoda, A.B.H. Kueh, Z.M. Jaini, Quantitative impact response analysis of reinforced concrete beam using the smoothed particle hydrodynamics (SPH) method, Struct. Eng. Mech. 56 (2015) 917–938, https://doi.org/10.12989/sem.2015.56.6.917.
[187] S.N. Mokhatar, R. Abdullah, A.B.H. Kueh, Computational impact responses of reinforced concrete slabs, Comput. Concr. 12 (2013) 37–51, https://doi.org/10.12989/cac.2013.12.1.037.
[188] P.R. Prem, M. Verma, A.R. Murthy, J. Rajasankar, B. Bharatkumar, Numerical and theoretical modelling of low velocity impact on UHPC panels, Struct. Eng. Mech. 63 (2017) 207–215, https://doi.org/10.12989/sem.2017.63.2.207.
[189] S. Gopinath, C.K. Madheswaran, A.R.C. Murthy, R. Chandra, N.R. Iyer, T. Barkavi, Low and high velocity impact studies on fabric reinforced concrete panels, Comput. Model. Eng. Sci. 92 (2013) 151–172, https://doi.org/10.3970/cmes.2013.092.151.
[190] M.Q. Nguyen, S.S. Jacombs, R.S. Thomson, D. Hachenberg, M.L. Scott, Simulation of impact on sandwich structures, Compos. Struct. 67 (2005) 217–227, https://doi.org/10.1016/j.compstruct.2004.09.018.
[191] X. Fan, I. Verpoest, D. Vandepitte, Finite element analysis of out-of-plane compressive properties of thermoplastic honeycomb, J. Sandw. Struct. Mater. 8 (2006) 437–458, https://doi.org/10.1177/1099636206065862.
[192] A.R. Murthy, G.S. Palani, N.R. Iyer, S. Gopinath, V.R. Kumar, Impact failure analysis of reinforced concrete structural components by using finite element method, Comput. Model. Eng. Sci. 86 (2012) 409–434, https://doi.org/10.3970/cmes.2012.086.409.
[193] A.R. Murthy, G.S. Palani, S. Gopinath, V.R. Kumar, N.R. Iyer, An improved concrete damage model for impact analysis of concrete structural components by using finite element method, Comput. Mater. Contin. 37 (2013) 77–96, https://doi.org/10.3970/cmc.2013.037.077.
[194] A. Ramachandra Murthy, G.S. Palani, N.R. Iyer, A simple analytical model for evaluation of penetration depth and resistant strength of concrete targets, Int. J. Struct. Stab. Dyn. 13 (2013), 1250061, https://doi.org/10.1142/S0219455412500617.
[195] E. Talebi, M. Md Tahir, F. Zahmatkesh, A.B.H. Kueh, Comparative study on the behaviour of buckling restrained braced frames at fire, J. Constr. Steel Res. 102 (2014) 1–12, https://doi.org/10.1016/j.jcsr.2014.06.003.
[196] V.N. Burlayenko, T. Sadowski, A numerical study of the dynamic response of sandwich plates initially damaged by low-velocity impact, Comput. Mater. Sci. 52 (2012) 212–216, https://doi.org/10.1016/j.commatsci.2011.01.009.
[197] C. Santiuste, S. Sánchez-Sáez, E. Barbero, A comparison of progressive-failure criteria in the prediction of the dynamic bending failure of composite laminated beams, Compos. Struct. 92 (2010) 2406–2414, https://doi.org/10.1016/j.compstruct.2010.03.004.
[198] I. Ivañez, S. Sanchez-Saez, Numerical modelling of the low-velocity impact response of composite sandwich beams with honeycomb core, Compos. Struct. 106 (2013) 716–723, https://doi.org/10.1016/j.compstruct.2013.07.025.
[199] P. Griškevičius, D. Zeleniakienė, V. Leišis, M. Ostrowski, Experimental and numerical study of impact energy absorption of safety important honeycomb core sandwich structures, Mater. Sci. 16 (2010) 119–123, https://doi.org/10.1016/j.ijimpeng.2016.01.012.
[200] T. Boonkong, Y.O. Shen, Z.W. Guan, W.J. Cantwell, The low velocity impact response of curvilinear-core sandwich structures, Int. J. Impact Eng. 93 (2016) 28–38, https://doi.org/10.1016/j.ijimpeng.2016.01.012.
[201] M. Xu, G. Huang, S. Feng, X. Qin, G.J. McShane, W.J. Stronge, Perforation resistance of aluminum/polyethylene sandwich structure, Mater. Des. 100 (2016) 92–101, https://doi.org/10.1016/j.matdes.2016.03.090.
[202] Dimassi, M.A.; Herrmann, A.S. Numerical Simulation of Low Velocity Impact on Pin-Reinforced Foam Core Sandwich Panel. In Proceedings of the Key Engineering Materials; Trans Tech Publ, 2017; Vol. 742, pp. 673–680.
[203] X. Wu, Y. Li, W. Cai, K. Guo, L. Zhu, Dynamic responses and energy absorption of sandwich panel with aluminium honeycomb core under ice wedge impact, Int. J. Impact Eng. 162 (2022), 104137, https://doi.org/10.1016/j.ijimpeng.2021.104137.
[204] D.P.W. Horrigan, R.R. Aitken, G. Moltschaniwskyj, Modelling of crushing due to impact in honeycomb sandwiches, J. Sandw. Struct. Mater. 2 (2000) 131–151, https://doi.org/10.1177/109963620000200203.
[205] Aktay, L.; Johnson, A.F.; Kröplin, B.-H. Semi-Adaptive Coupling Technique for the Prediction of Impact Damage. In Proceedings of the 8th International Conference on Plasticity (COMPLAS); CIMNE, Barcelona, 2005; Vol. 1, pp. 523–526.
[206] L. Aktay, A.F. Johnson, M. Holzapfel, Prediction of impact damage on sandwich composite panels, Comput. Mater. Sci. 32 (2005) 252–260, https://doi.org/10.1016/j.commatsci.2004.09.044.
[207] L. Aktay, A.F. Johnson, B.-H. Kröplin, Numerical modelling of honeycomb core crush behaviour, Eng. Fract. Mech. 75 (2008) 2616–2630, https://doi.org/10.1016/j.engfracmech.2007.03.008.
[208] N. Rasin, A.B.H. Kueh, M.N.H. Mahat, A.Y.M. Yassin, Stability of triaxially woven fabric composites employing geometrically nonlinear plate model with volume segmentation ABD constitution, J. Compos. Mater. 50 (2016) 2719–2735, https://doi.org/10.1177/0021998315612538.
[209] Kueh, A.B.H.; Pellegrino, S. ABD Matrix of Single-Ply Triaxial Weave Fabric Composites. In Proceedings of the Collection of Technical Papers - AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference; 2007; Vol. 6, p. 2161.
[210] S. Bargmann, B. Klusemann, J. Markmann, J.E. Schnabel, K. Schneider, C. Soyarslan, J. Wilmers, Generation of 3D representative volume elements for heterogeneous materials: a review, Prog. Mater. Sci. 96 (2018) 322–384, https://doi.org/10.1016/j.pmatsci.2018.02.003.
[211] S. Sorohan, D.M. Constantinescu, M. Sandu, A.G. Sandu, In-plane homogenization of commercial hexagonal honeycombs considering the cell wall curvature and adhesive layer influence, Int. J. Solids Struct. 156 (2019) 87–106, https://doi.org/10.1016/j.ijsolstr.2018.08.007.
[212] A.B.H. Kueh, Fitting-free hyperelastic strain energy formulation for triaxial weave fabric composites, Mech. Mater. 47 (2012) 11–23, https://doi.org/10.1016/j.mechmat.2012.01.001.
[213] M. Hanifehzadeh, M.M.R. Mousavi, Predicting the structural performance of sandwich concrete panels subjected to blast load considering dynamic increase factor, J. Civ. Eng. Sci. Technol. 10 (2019) 45–58, https://doi.org/10.33736/jcest.1067.2019.
[214] W. Xiao, M. Andrae, N. Gebbeken, Air blast TNT equivalence concept for blast-resistant design, Int. J. Mech. Sci. 185 (2020), 105871, https://doi.org/10.1016/j.ijmecsci.2020.105871.
[215] K. Das, R.C. Batra, Local water slamming impact on sandwich composite hulls, J. Fluids Struct. 27 (2011) 523–551, https://doi.org/10.1016/j.jfluidstructs.2011.02.001.
[216] J. Xiao, R.C. Batra, Delamination in sandwich panels due to local water slamming loads, J. Fluids Struct. 48 (2014) 122–155, https://doi.org/10.1016/j.jfluidstructs.2014.02.008.
[217] Ashby, M.F.; Shercliff, H.; Cebon, D. Materials: Engineering, Science, Processing and Design; Fourth Edi.; Butterworth-Heinemann: Oxford, UK, 2019; ISBN 0081023774.
[218] C. Sergi, F. Sarasini, P. Russo, L. Vitiello, E. Barbero, S. Sanchez-Saez, J. Tirillò, Effect of temperature on the low-velocity impact response of environmentally friendly cork sandwich structures, J. Sandw. Struct. Mater. 24 (2022) 1099–1121, https://doi.org/10.1177/10996362211035421.
[219] J. Zhang, A. Koubaa, D. Xing, H. Wang, Y. Tao, X.-M. Wang, P. Li, Fire behavior and failure model of multilayered wood Flour/HDPE/polycarbonate composites with a sandwich structure, Polymers 14 (2022) 2833, https://doi.org/10.3390/polym14142833.
[220] E. Kandare, P. Luangtriratana, B.K. Kandola, Fire reaction properties of flax/epoxy laminates and their balsa-core sandwich composites with or without fire protection, Compos. Part B Eng. 56 (2014) 602–610, https://doi.org/10.1016/j.compositesb.2013.08.090.
[221] A. Hörold, B. Schartel, V. Trappe, M. Korzen, J. Bünker, Fire stability of glass-fibre sandwich panels: the influence of core materials and flame retardants, Compos. Struct. 160 (2017) 1310–1318, https://doi.org/10.1016/j.compstruct.2016.11.027.
[222] M. Khanzadeh, P. Rao, R. Jafari-Marandi, B.K. Smith, M.A. Tschopp, L. Bian, Quantifying geometric accuracy with unsupervised machine learning: using self-organizing map on fused filament fabrication additive manufacturing parts, J. Manuf. Sci. Eng. (2018) *140*, https://doi.org/10.1115/1.4038598.
[223] F. Li, X. Peng, Z. Wang, Y. Zhou, Y. Wu, M. Jiang, M. Xu, Machine learning (ML)-assisted design and fabrication for solar cells, Energy Environ. Mater. 2 (2019) 280–291, https://doi.org/10.1002/eem2.12049.
[224] M. Ramsgaard Thomsen, P. Nicholas, M. Tamke, S. Gatz, Y. Sinke, G. Rossi, Towards machine learning for architectural fabrication in the age of industry 4.0, Int. J. Archit. Comput. 18 (2020) 335–352, https://doi.org/10.1177/1478077120948000.

[225] A.B.H. Kueh, Artificial neural network and regressed beam-column connection explicit mathematical moment-rotation expressions, J. Build. Eng. 43 (2021), 103195, https://doi.org/10.1016/j.jobe.2021.103195.
[226] Y.X. Tang, Y.H. Lee, M. Amran, R. Fediuk, N. Vatin, A.B.H. Kueh, Y.Y. Lee, Artificial neural network-forecasted compression strength of alkaline-activated slag concretes, Sustainability 14 (2022) 5214, https://doi.org/10.3390/su14095214.
[227] I. Yakub, A.B.H. Kueh, E. Andres Pineda De La O, M.R. Rahman, M.H. Barawi, M.O. Abdullah, M. Amran, R. Fediuk, N.I. Vatin, Employing an artificial neural network in correlating a hydrogen-selective catalytic reduction performance with crystallite sizes of a biomass-derived bimetallic catalyst, Catalysts 12 (2022) 779, https://doi.org/10.3390/catal12070779.
[228] Kueh, A.B.H.; Soykasap, O.; Pellegrino, S. Thermo-Mechanical Behaviour of Single-Ply Triaxial Weave Carbon Fibre Reinforced Plastic. In Proceedings of the European Space Agency, (Special Publication) ESA SP); 2005.
[229] M.Y. Al-Fasih, A.B.H. Kueh, S.H. Abo Sabah, M.Y. Yahya, Influence of tows waviness and anisotropy on effective mode I fracture toughness of triaxially woven fabric composites, Eng. Fract. Mech. 182 (2017) 521–536, https://doi.org/10.1016/j.engfracmech.2017.03.051.
[230] M.Y. Al-Fasih, A.B.H. Kueh, S.H. Abo Sabah, M.Y. Yahya, Tow waviness and anisotropy effects on mode II fracture of triaxially woven composite, Steel Compos. Struct. 26 (2018) 241–253, https://doi.org/10.12989/scs.2018.26.2.241.
[231] C. Yang, W. Ma, Z. Zhang, J. Zhong, Low-velocity impact behavior of sandwich plates with FG-CNTRC face sheets and negative poisson's ratio auxetic honeycombs core, Polym. (Basel) 14 (2022) 2938, https://doi.org/10.3390/polym14142938.
[232] N. San Ha, G. Lu, A review of recent research on bio-inspired structures and materials for energy absorption applications, Compos. Part B Eng. 181 (2020), 107496.
[233] H. Jiang, Y. Ren, Z. Liu, S. Zhang, Z. Lin, Low-velocity impact resistance behaviors of bio-inspired helicoidal composite laminates with non-linear rotation angle based layups, Compos. Struct. 214 (2019) 463–475.
[234] K.S. Mu, A.B.H. Kueh, P.N. Shek, M.R. Mohd Haniffah, B.C. Tan, Flow responses alteration by geometrical effects of tubercles on plates under the maximal angle of attack, Proc. Inst. Mech. Eng. Part C. J. Mech. Eng. Sci. 235 (2021) 3975–3987, https://doi.org/10.1177/0954406220975434.
[235] K.S. Mu, A.B.H. Kueh, P.N. Shek, Hydroelastic responses of plates with sinusoidal tubercles under perpendicularly loaded flow, Ocean Eng. 219 (2021), 108301.
[236] J.-H. Cha, Y. Kim, S.K.S. Kumar, C. Choi, C.-G. Kim, Ultra-high-molecular-weight polyethylene as a hypervelocity impact shielding material for space structures, Acta Astronaut 168 (2020) 182–190, https://doi.org/10.1016/j.actaastro.2019.12.008.
[237] K. Wen, X. Chen, Y. Lu, Research and development on hypervelocity impact protection using whipple shield: an overview, Def. Technol. 17 (2021) 1864–1886, https://doi.org/10.1016/j.dt.2020.11.005.
[238] S.A. Hambric, M.R. Shepherd, N.H. Schiller, R. Snider, C. May, Quieting a rib-framed honeycomb core sandwich panel for a rotorcraft roof, J. Am. Helicopter Soc. 62 (2017) 1–10, https://doi.org/10.4050/JAHS.62.012009.
[239] L. Yang, H. Fan, J. Liu, Y. Ma, Q. Zheng, Hybrid lattice-core sandwich composites designed for microwave absorption, Mater. Des. 50 (2013) 863–871, https://doi.org/10.1016/j.matdes.2013.03.032.
[240] P. Shahmohamadi, A.I. Che-Ani, K.N.A. Maulud, N.M. Tawil, N.A.G. Abdullah, The impact of anthropogenic heat on formation of Urban heat island and energy consumption balance, Urban Stud. Res. (2011) *2011*.
[241] M.A. Khan, A.K. Syed, H. Ijaz, R. Shah, Experimental and numerical analysis of flexural and impact behaviour of glass/Pp sandwich panel for automotive structural applications, Adv. Compos. Mater. 27 (2018) 367–386, https://doi.org/10.1080/09243046.2017.1396199.
[242] W. Shen, B. Luo, R. Yan, H. Zeng, L. Xu, The mechanical behavior of sandwich composite joints for ship structures, Ocean Eng. 144 (2017) 78–89, https://doi.org/10.1016/j.oceaneng.2017.08.039.
[243] M.S.H. Fatt, D. Sirivolu, Marine composite sandwich plates under air and water blasts, Mar. Struct. 56 (2017) 163–185, https://doi.org/10.1016/j.marstruc.2017.08.004.
[244] J. Chróścielewski, M. Miśkiewicz, Ł. Pyrzowski, B. Sobczyk, K. Wilde, A novel sandwich footbridge-practical application of laminated composites in bridge design and in situ measurements of static response, Compos. Part B Eng. 126 (2017) 153–161, https://doi.org/10.1016/j.compositesb.2017.06.009.