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An overview of penetration mechanism and simulation techniques of steel sandwich structure under ballistic testing

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Abstract

This review reports on the current trends in steel-based sandwich structures subjected under high velocity impact. The review begins with a brief introduction on sandwich structures in general. It then delves into detail on some structural configuration parameters that affect sandwich performance. Light has been thrown on the energy absorption mechanisms of sandwich panels. The current global demand on energy necessitates the design of lightweight structures. Therefore, the review also elucidates on sandwich design optimization techniques mostly employed by researchers in meeting design constraints and objectives at the minimum weight and cost. Among these optimization techniques are the artificial neural network, fuzzy logic, Taguchi based method, response surface method, particle swarm optimization, genetic algorithm among others. The promising potential of auxetic materials with their negative Poisson's ratio in resisting impact penetration has been discussed. A comprehensive explanation on failure mechanisms that are encountered during projectile penetration has also been elaborated upon. Parameters such as projectile geometry, core design, core material and thickness of facesheets noted to have enormous influence on penetration resistance have also been addressed.

Keywords: Ballistic testing; Penetration mechanism; Finite element simulation; Sandwich structure.

1. Introduction

Sandwich structures for ballistic protection basically consist of two parts, hard thin face sheets interlayered or sandwiched by usually a bulk soft material [1,2]. Engineering applications of sandwich composite structures are enormous. Their applications expands through the aircraft industry, defense, civil, mechanical and other industries where high energy absorbing capabilities are required [3]. Ability of structures to withstand ballistic impact have now extended speedily from the force services and has gained much attention in the civilian domain. There are differs of disciplines where energy absorbing structures are required such as space equipment for the satellite industries, designing of nuclear reactors, transportation and storage of hazardous materials among others [4].With the increasing demand for producing lighter structures, a greater requirement is put on designers as most aspect of structures approach critical strength threshold when their weight is reduced [5]. Composite materials are preferred in several areas as they demonstrate great synergy between high strength-to-weight ratios [6]. The survival of security persons against projectile threats is very crucial, and as such series of thorough processes are employed in designing of appropriate personal ballistic protective shields [7]. Fatalities and injuries within the police forces and correctional services have reduced due to wearing of effective personal protective equipment [8]. When it comes to materials for ballistic impact applications, polymer matrix composite structures are very much attractive because of their light weight, strength, and stiffness compared to unreinforced polymer and conventional metals. They are also easy to be tailored into several design configurations at a relatively less cost. Large number of astounding new applications have thus erupted into the market providing creative solutions and proposing vast applications by use of polymer matrix composites [9]. Notwithstanding, steel has continued to dominate the market when it comes to materials for protecting against impact penetrations. Reasons being that steel with their absolute strength and hardness augmented with their high ductility and of course their comparatively cheap price places them on such competitive advantage. Furthermore, steel possesses excellent load bearing capability and has good formability this also explains their dominance. Considering the above reasons, ultra-high strength steel has become the choice for both civil and military application against ballistic impacts. The selection of a particular steel alloy mainly depends on safety, nature of application, specific weight and price [10].

Recently, the use of high-performance fibers such as aramid (Kevlar, Twaron), High performance polyethylene (Dyneema, Spectra), glass fires (S and R glass) as impact protective materials has surged up. This is attributed to their low density, high strength and high energy absorption capabilities [9]. Therefore, much attention has been devoted into investigating perforation characteristics of sandwich composites that incorporate lightweight materials [11] .

This paper presents 1) The current trends in materials that are being used for ballistic protections, 2) research advances in ultra-high strength steel sandwich structures in resisting high velocity impact, 3) numerical techniques in studying multi-physics phenomena that take place during impact events 4) energy absorption mechanisms of sandwich structures 5) optimization techniques employed in designing sandwich structures and 6) failure mechanisms that take control in collapse of sandwich structures during impact loading. The motivation of this review is to combine findings in areas where sandwich structures are used for energy absorbing applications. Special concentration would be on their applications to impact penetration problems. It will also strengthen research works orientated to such area by virtue of identifying possible research directions that may contribute to ballistic resistive structures.

2. Steel based sandwich structures

In defeating small arm projectiles, polymer matrix composites (PMCs) have widely been utilize as backing layer to steel and or ceramic sandwich plates. PMCs when utilized in such manner poses high capability to absorb and thus reduce projectile kinetic energy. High-performance fibers are characterized by their high elastic modulus and high specific strength compared to their metal counterparts in providing equivalent ballistic protections [12]. Most utilized PMCs for armour applications include, braided and woven composites, aramid fiber, fiberglass and polyethylene fiber composites [3]. The utilization of these high performance polymers has significantly contributed to the development of sandwich panels tracking from the 2000s until 2022 [13]. Investigation by Wu et al. reported the improvement in mechanical properties of laminated aramid fiber/ epoxy composite reinforced with graphene oxide[14]. Nguyen et al. [15] using a non-linear orthotropic composite model investigated the ballistic characteristics of monolithic composite structure of ultra-high molecular weight polyethylene (UHMWPE). Yan et al. [16] investigated ballistic characteristics of 3D- printed auxetic honeycomb sandwich panel consisting two facet sheets; front (Q345 Steel) and bottom (carbon fiber reinforced polymer). The auxetic honeycomb sandwich core improved the ballistic performance by reducing residual velocity as well as enhancing damage tolerance when compared to a controlled Aluminum foam core. Nyanor et al [17] investigated the effect of water layer in enhancing the ballistic performance of steel/polymer sandwich structure. The response of low yield steel (AH36) sandwich panel subjected to highly decaying pressure load has been investigated by [18]. Perforation resistance of double layered high strength steel plates against velocity impacts has been investigated by [19], the double layer consisted of a 6 mm perforated steel plate placed in front of a 9 mm thick monolithic steel plate. Numerical simulation on perforation resistance of weldox/polyurea sandwich panel has been studied by [20]. Fatt and Sirivolu [21] analytically and numerically investigated the mechanism by which wave travel through a woven polyester facesheets with PVC foam core sandwich structure under high velocity impact. Flores-Johnson et al [22] numerically investigated the performance of multi-layered sandwich panel consisting of both same and dissimilar metals subjected to high velocity impact. The influence of projectile angle of obliquity and nose angle on ballistic limit of thick monolithic steel subjected to high impact velocity has been studied by Iqbal et al [23]. The strength of braze joint formed from dissimilar metals

(AR 500 steel and AA 7075 aluminium alloy) subjected to low velocity impact has been studied by [24]. Computation investigation on the energy absorption of layered laminates of high strength steel and aluminium was studied by [11]. They concluded their study by indicating that, higher absorption energy could be obtained in a three-layered panel compared to its equivalent double layered panel. Numerical study on the ballistic performance of carbon/epoxy composite and mild steel laminate subjected to high velocity impact using the FEM explicit solver Abaqus® has been investigated by [25]. Coupling of steel with ceramics for structural applications against projectile impact has been considered by Ni et al [26] through both numerical and experimental investigation of ballistic performance of hybrid sandwich system consisting of stainless steel as facesheets and metallic truss core filled with ceramic prism. Protection of steel/concrete composite structure against hyper velocity projectiles has been investigated by [27]. Publication trend on steel/ polymer-based sandwich structures between 2010 to current and still counting from science direct source is illustrated in figure 1. This takes us to the next section elucidating on the major classifications for sandwich core designs and major factors relating to their resistance to penetration.

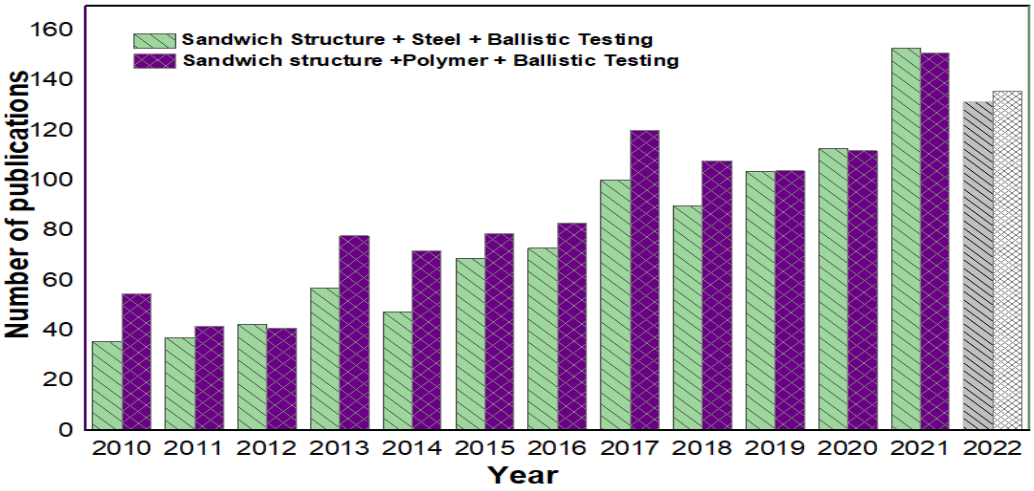

Fig.1 Science direct search on list of publications on steel and polymer-based sandwich structures under ballistic testing with the keywords (* ballistic testing, *sandwich structure OR panel, *steel, *polymer)

3. Effect of sandwich geometry design

3.1. Effect of sandwich core design on penetration resistance

According to literature, greater weight reduction in structure is attained in sandwich structures through the introduction of sandwich cores. However, the structural integrity of sandwich panel/structure could as well be jeopardized by wrong design in the core component. Several categories of sandwich structures available are basically due to the type of core structure. To the best of the authors' knowledge, the major classifications of typical sandwich structures are based on core types as illustrated in figure 2 below. The preference of a particular core topology is known to be dependent on the intended application. For instance sandwich structures with corrugated cores are preferred in the aerospace industry due to their light weight [28]. Mostly used sandwich core forms is the lattice/truss core type. They constitute but not limited to; corrugated cores, web core, hat core, round core, rectangular core, trapezoidal corrugated core, curvilinear core, pyramidal core, kagome core, X-type core, Z-type core, tetrahedral core, Y- type core [29] among others. Detail description on the mostly used sandwich cores with their advantages and disadvantages has been discussed by [13]. Extensive review on the various types of sandwich cores and their application has been done by [28].

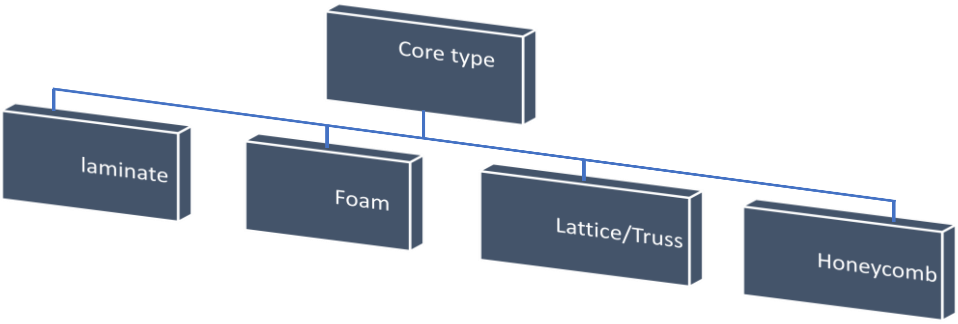

Fig. 2 Classification of typical sandwich structures based on core type

Abbasi and Nia investigated the effect of sandwich foam core structure between aluminum face-sheets (AL-1050). They experimentally and numerically studied how composite sequence of arrangement affect ballistic resistance of structures under high-velocity impact. In the same study, it was reported that for same core mass and total thickness, ballistic limit velocity increased for case with a greater number of core layers. And thus the ballistic limit velocity of the model configuration with four layers as core had about 5 to 8 percent improvement in its ballistic limit compared to configuration with single core layer [1]. Greater potential in load carrying capabilities of curved structures has been reported by Lan et al [30] in their investigation of novel cylindrical double arrowhead auxetic (DAA) core sandwich panel. Schematic diagram of the double arrow auxetic core structure is shown in figure 3. The promising qualities of such structures is anticipated to bring huge improvements in the quality of blasts curtains, bullet proof vest and helmets beside their potential economic benefits [31]. Yan et al. [16] investigation, three different cell configurations of aluminum honeycomb core structures namely, regular, re-entrant, and enhanced re-entrant hexagons. These configurations were then compared with a control foam core aluminum sandwich panel of identical areal density. Ballistic performances of auxetic honeycomb core configurations in enhancing damage tolerance and reducing residual velocity were reported to be better in comparison with foam core configurations. Enhanced auxetic core showing the best performance among the various core configurations which was then followed by auxetic core and lastly the regular hexagonal core [16]. Reason been that addition of the enhance rib greatly improved its resistance to impact. This interlocking of lattice structure of core materials has proven to exhibit enhance performance in sandwich panels (i.e. increasing the compressive and crushing strength of the core material) especially when subjected particularly to blast loading and high velocity impact [13,32–38].

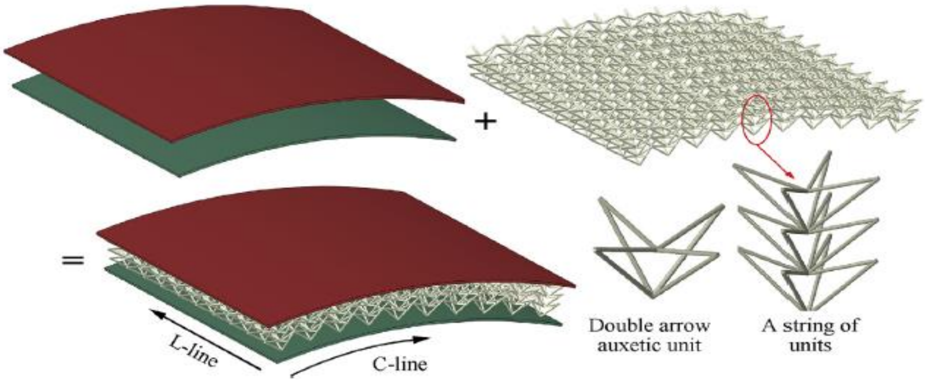

Fig.3 Schematic diagram of novel cylindrical sandwich panel with DAA core structure article under CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/) [30].

Dahiwale et al. investigated the impact performance of empty triangular corrugated core sandwich structure [39]. For same areal density, ballistic performance of monolithic plate is better compared to empty triangular corrugated sandwich. They reported that design parameters such as web angle, thickness, and core thickness are crucial. And that, optimal ballistic performance at effective cost to weight ratio could be obtained by increasing web thickness for corrugated cores. Formula used in calculating aerial density ρa of corrugated core is given as [39];

$$\rho a = (hf + hb + c\acute{\rho})\rho \tag{1}$$

where $\acute{\rho}$ is the density ratio between the core and solid metal and ρ is the density of solid metal. Geometry of sandwich panel with corrugated triangular core structure is shown in figure 4.

Relation between relative core density, web thickness, core thickness and angle of web is given as.

$$\acute{\rho} = \frac{t}{t + cCos\alpha}. \tag{2}$$

Recent review [40] shows the effect of filling material on honeycomb sandwich structure. Ni et al. [26] numerically and experimentally investigated the ballistic resistance of hybrid sandwich cores. Three different core types were considered in their investigation, namely, type –A: metallic pyramidal lattice, type – B: pyramidal lattice with ceramic insertion and type – C: consisting of type B together with epoxy filling resin.

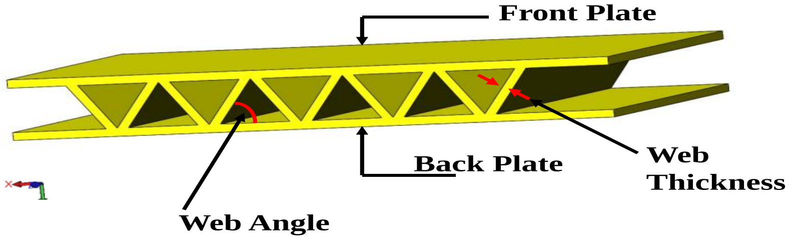

Fig.4 Geometry of a typical corrugated metallic plates with triangular hollow cores.

Figure 5 shows sandwich configurations for the various types. These sandwich panel configurations had earlier been investigated by [41] where massive ballistic resistance against spherical steel projectile compared to monolithic plates of equal masses were achieved. Ballistic resistance was improved by the insertion of ceramic prism due to projectile erosion during projectile – ceramic interaction. The energy absorption was enhanced after type-B was filed with epoxy resin (type–C) as the fluid eliminated any small gaps [41,42] that existed between the core components. Also, bonding facesheets and core was enhanced by the filling of epoxy resin. Study by Adachi et al. investigating effect of filling hollow cylinder with silicone rubber showed improved energy absorption [43]. We conclude this section with this remarks that, it is obvious constraints on weight limit could be achieved through hollow core structures, filling of hollow crevices with filler materials is noted to increase energy absorption, impact resistance and reduction in delamination between layers of sandwich structures [24,44].

3.2 Effect of sandwich skin sheet thickness on penetration performance

Geometry of skin sheets of sandwich panels have been proven by several researchers to have major effect on its ballistic performance. For a given laminated sandwich structure with same areal density, energy absorption can be improved by adopting a thinner faceplate and thicker backboard [45]. Flores – Johnson et al. numerically investigated penetration resistance offered by double-layered plates of aluminum and steel. In their findings, thin plate aluminum as a front sheet when backed by thick steel plate showed greater resistance than multi-layered steel plates of equivalent areal density [22]. Energy absorption by sandwich configuration is enhanced when thick plate is used as back face sheet for configurations of same mass [26].

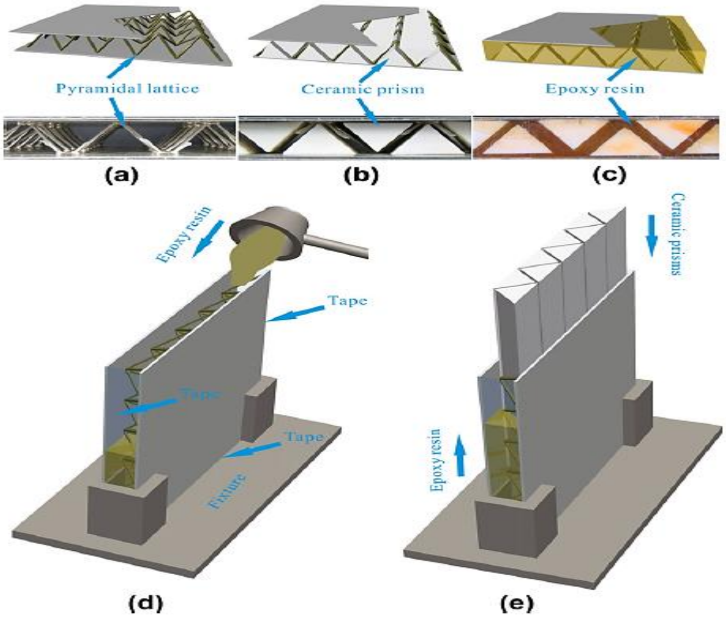

Fig.5 Sandwich plates with various core configurations; (a) Type A (b) Type B (C) Type C (d) filling of lattice core with epoxy resin and (e) insertion of ceramic prisms into epoxy filled pyramidal lattice core adapted with permission from [26].

4. Sandwich structure optimization techniques

Sometimes the design specifications for a sandwich structure requires meeting several objectives which may be composite weight reduction, improvement in mechanical properties, cost reduction, resistance to fire etc. Such criteria may be met by employing any of the several multi criteria analysis techniques [46]. Among the several objectives, weight reduction of the sandwich structure is the prominent objective mostly sort after. In view of this some researchers have tried to optimize the performance of sandwich structures through manual manipulation of its geometric parameters through sandwich core designs. However, the alteration in sandwich geometric parameters should not be without constraints, because it has been revealed that, the safety of sandwich structures can be greatly jeopardized when their areal density is reduced by 30% below their total weight [11,13]. Literature has reported on several of these optimization techniques that ensure designing safe, economical, low weight and optimum performing sandwich structures. Among these optimization techniques are Taguchi-Based Method, Fuzzy Logic Method, Artificial Neural Network (ANN), Genetic Algorithm and Response Surface Method (RSM), [13,47–50]. Lan et. al. [30] optimized the design of auxetic core structure based on Latin Hypercube Sampling method (LHD), Artificial Neural Network (ANN) Meta Model and the Non-Dominated Sorting Genetic Algorithm (NSGA-II). Optimization of wire rods as core material in sandwich panel has been studied by Alavi et al. [51] in their study, observed that ballistic limit of sandwich panels increases with reducing wire diameter and inter distance between them. Parametric investigation on the influence of honeycomb type, unit cell angle and face-sheet type on the ballistic performance of honeycomb sandwich has been studied by [16].

A new genetic algorithm [52] has been developed to optimize the weight and cost through web design of a steel based polyurethane foam core sandwich structure. Mehdi et al [53] optimized the strength of carbon/epoxy sandwich structure against ballistic impact through orientation of its ply. Stress bearing capacity of sandwich panel under loading has been optimized by [54] using particle swarm algorithm which was firstly developed by Jalkanen [55] to be used in MATLAB environment. Energy absorption of fibre reinforce polymer laminate composite was optimized using a Taguchi based design of experiment method [56]. Benzo et al. [52] optimized the performance of sandwich structure for its mechanical, thermal and acoustic properties using genetic algorithm with a minimum mass objective function. Karen et al [57] optimized energy absorption of a filled corrugated core sandwich panel subjected to blast loading. The study utilized a hybrid evolutionary optimization technique which involved the Multi-Island Genetic algorithm and the Hooke Jeeves Algorithm. Cost and weight of composite floor panel has been optimized by Awad et al [58] using a multi-objective simulated annealing approach. Brief description on some of these optimization approaches are discussed in the next section. This section on sandwich optimization is finally summarized by the optimization trend on steel based sandwiched panels, specifying core material type and application areas between the years 2010 and 2022 as shown in table 1.

4.1. Application of artificial neural network in ballistic impact

Neural networks are made up of layers of neurons that serve as processing cores for data exploration and analysis. The architecture of ANN is such that layers are linked together by mapping of connectors between them. These connectors are basically modelled by simple functions that pass a given set of values from the input layer to the output layer. Input layer receives data, and the output layer predicts the outcome, in between them is the hidden layer(s) where most of the computations required by the network is performed. Over the past 30 years, within the field of material mechanics several neural architectures have successfully been employed in predicting material failure. Among those networks are the Perceptron, Hebbian, Kohonen, and Hopfield [59]. Within ballistic applications, the multiple layer perceptron (MLP) and the generalized feed forward (GFF) architecture are the most widely used due to their simplicity [59–63]. Review on the network type, learning algorithm, data sampling method, and cost error function has been reported by Gonzalez et al. [59]. Kilic et al. [60] employed both MLP and GFF neural architecture in combination with the momentum, Levenberg-Marq and back propagation learning algorithms to investigate the depth of penetration within steel target with input variables as impact velocity and material thickness. The MLP works by assigning adaptive weights to the hidden layers. It has been reported by some researchers that the MLP predicts very well even with few hidden layers [61]. A schematic diagram of an MLP network architecture is as shown in figure 6 below.

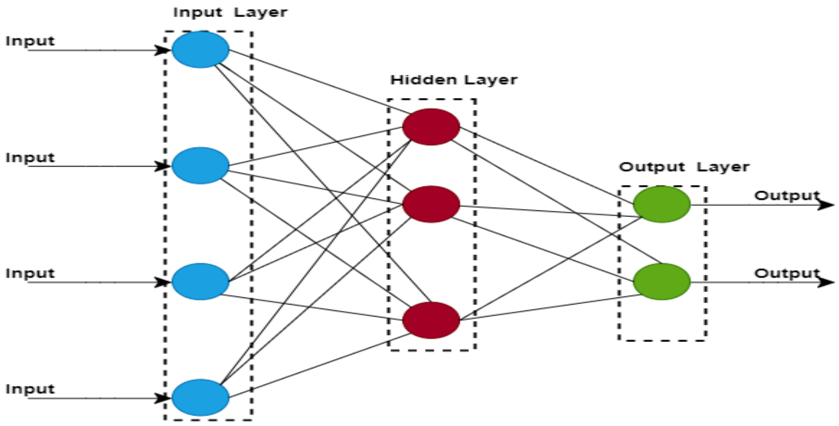

Fig.6 A Multiple layer perceptron network architecture

4.2. Application fuzzy logic in impact ballistic

Fuzzy logic works like the vagueness which is often related to human decision making rather than the usual yes or no approach. The structure of fuzzy logic consists of fuzzifier, membership function, fuzzy inference system, fuzzy rule and defuzzifier. Layout of a typical fuzzy system is illustrated in figure 7. The fuzzifier convert crisp input data into fuzzy variables which are linguistic in nature using the membership functions. For example, weightiness is a precise input data which can be converted to imprecise variables such as light, heavy, very heavy. Membership functions associate the degree by which elements of a given input data set belongs to all the input membership functions. Their assigned values range between 0 and 1. This makes it obvious that without the intermediate values between 0 and 1, the concept of fuzzy set will not be different from a crisp set. The generated fuzzy set are then carried to the fuzzy inference system where fuzzy reasoning takes place by applying the fuzzy set rules to generate fuzzy values. There are several inference systems in fuzzy logic with the Mamdani fuzzy method being the most widely used [64]. The generated fuzzy values are finally converted back into crisp form by use of the defuzzifier. The most used defuzzification approach is the centroid method. There are several membership functions available namely, trapezoidal, s-shape, monotonic and triangular. The selection of any of the membership functions are not governed by any rules. However, the triangular membership function happens to be the popular one [65] . Triangular membership function is expressed as;

$$\mu_A(x) = \begin{cases} \mathbf{0} & x \le a \\ \frac{x-a}{c-a} & a \le x \le c \\ \frac{b-x}{b-c} & c \le x \le b \\ \mathbf{0} & x \ge b \end{cases} \tag{3}$$

where is the membership function of the fuzzy set, x is a variable, and a, b, c are parameters

fuzzy rules used by the fuzzy inference system consist of IF, THEN rules involving multiple input and one multi-response output y, the rules can be expressed as.

Rule 1: IF x_1 is A_1 and x_2 is B_1 and x_3 is C_1 THEN y is E_1
ELSE
Rule 2: IF x_1 is A_2 and x_2 is B_2 and x_3 is C_2 THEN y is E_2
ELSE
…….
Rule n: IF x_1 is A_n and x_2 is B_n and x_3 is C_n THEN y is E_n

with A_n, B_n, C_n, E_n being fuzzy subset models with their respective membership functions as μ_{An}, μ_{Bn}, μ_{Cn}, μ_{En}. The multi response output value, y is computed as.

$$\boldsymbol{\mu_{C0}(y) = (\mu_{A1}(x_1) \wedge \mu_{B1}(x_2) \wedge \mu_{C1}(x_3) \ldots\ldots \mu_{E1}(y)) \vee \ldots (\mu_{An}(x_1) \wedge \mu_{Bn}(x_2) \wedge \mu_{Cn}(x_3) \wedge \mu_{En}(y))} \tag{4}$$

where ∧ and ∨ are minimum and maximum pointers. The minimum and maximum operators are the means by which intersection and union are respectively estimated in fuzzy logic systems. Other methods such as the product operator are available as well. The non-fuzzy response value which is also known as the Multiple Performance Characteristic Index (MPCI) is computed as.

$$\boldsymbol{y_0} = \frac{\sum y\mu_{C0}(y)}{\mu_{C0}(y)} \tag{5}$$

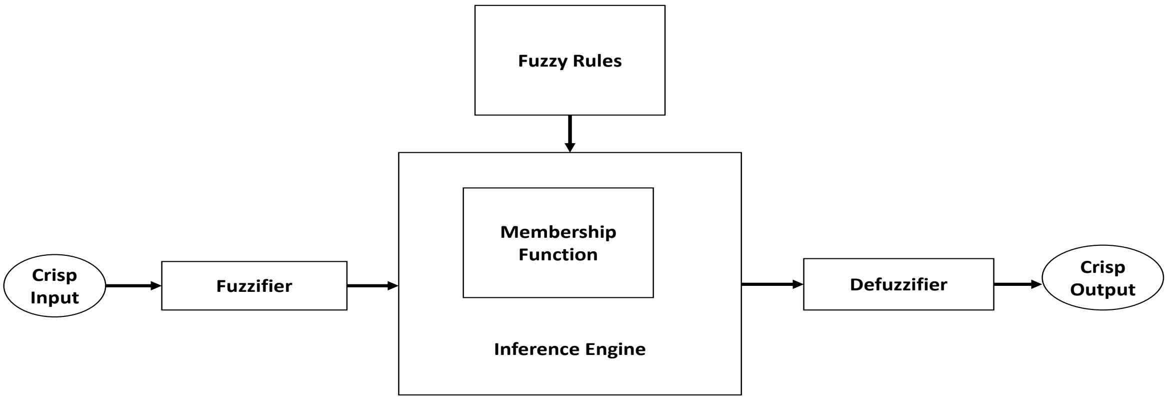

Fig.7 Layout of a typical fuzzy logic system

4.3. Taguchi method in ballistic impact applications

The Taguchi method provides an efficient means for product design and improvement by setting up optimum plan for experimentation. Smaller design of experiment DOE is created from the combination of design parameters and their corresponding levels through orthogonal arrays OA. The signal to noise ratios (S/N) of the output responses from all DOE cases are then computed for further analysis. There are three main criteria in estimating the S/N ratios; smaller-the-better, nominal-the-best and larger-the-better [66]

S/N ratio n_{ij} for smaller-the-better characteristics is calculated as.

$$n_{ij} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} {y_{ij}}^2\right) \quad (6)$$

S/N ratio for nominal-the-best characteristics is calculated as.

$$n_{ij} = 10\log\left(\frac{{\bar{y}_{ij}}^2}{s^2}\right) \quad (7)$$

S/N ratio for larger-the-better characteristics is calculated as.

$$n_{ij} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_{ij}}^2}\right) \quad (8)$$

where y_{ij} is the response value of the i^{th} experiment at the j^{th} run, s^2 is the variance of y_{ij} and $\bar{y}_{ij}$ is the mean response value of the i^{th} experiment at the j^{th} run

Table 1 Trend on optimization techniques for sandwich panels and their applications between 2010 to 2022

Year	Core Material(s)	Core Type	Optimization Technique	Application	Ref.
2010	Carbon/Epoxy	laminate	GA	Structure	[53]
2011	Phenolic	laminate	Multi-Objective Simulated Annealing	Building	[58]
2012	PET/PVC/HDPE	Foam	Artificial neural network	Automobile (trailer)	[46]
2013	Aluminum	Pyramidal lattice trusses	Response surface method	Automobile	[67]
2014	steel	laminate	Particle swarm optimization	Structure	[54]
2015	Polypropylene	laminate	Taguchi design of experiment	Structure	[56]
2016	Polyurethane foam	corrugated	Hybrid evolutionary optimization algorithm	structure	[57]
2017	aluminum	laminate	GA	Automobile	[68]
2018	aluminum	Corrugated	Response Surface Method	Automobile	[69]
2019	Polyisocyanurate	foam	Evolutionary Algorithm	structure	[70]
2020	Continuous carbon fiber/epoxy	laminate	GA	Automobile	[71]
2021	steel	Corrugated	BP Neural network / GA	structure	[63]
2022	Steel/Polyurethane	web	GA	structure	[52]

NB: GA – Genetic Algorithm, BP – Back Propagation

5. Energy absorption in Sandwich Structures

5.1. Energy absorbing capabilities of sandwich against ballistic impacts

During impact, structures absorb energy due to high dynamic loading for example high strain rates events as seen in impact situations as a result of collision or blast. For such applications, the energy absorbing materials are designed to dissipate the impending kinetic energy of projectile by way of converting them into strain energy which is subsequently used to deform the target absorber [72]. Energy absorption applications has become a constituent part among many sectors in industrial setting to name a few; construction industry, power generation, packaging industry, transport among others [73]. Their nature of applications defers with areas requiring higher safety precedence - finished products for packaging industry or humans as end users in cases of transport and defense. Another form of variation may be in the nature in which they dissipate energy. There is irreversible transformation and dissipation of energy from the impactor unto the absorber which is attributed to permanent deformation sustained within an elastoplastic material and its damage [74]. The main energy absorbed or dissipated by material is illustrated under a typical stress strain curve in figure 8. The performance of sandwich panels against blast loading is shown to be greatly enhanced for fluid structure interaction scenarios compared to loading conditions involving solid to solid interactions for sandwich plates of equivalent mass [18,75].

Experimental work done by Taylor and Farren in estimating plastic dissipation energy of metals proved that large part of input mechanical energy is converted into heat energy with the remaining non-recoverable going into plastic work which is also known as stored energy of cold work [76]. An energy absorber may be defined as “a system that can totally or partially convert the directed kinetic energy to any other form. Energy converted is either reversible, like pressure energy in compressible fluids and elastic strain energy in solids, or irreversible, like plastic deformation energy” [5].

Several parameters come to play in terms of energy absorption of polymer, for instance study of stacking sequence of composite layers in a hybridized carbon-fiber reinforced polymer composite consisting of Kevlar and glass fiber under ballistic impact was investigated by [77]. In their investigation, different layers of carbon fibres, Kevlar, and glass fibres were combined which showed that replacing four layers of monolithic sheet carbon fibres in the back with Kevlar resulted 135% improvement in the absorbed energy with only 9% increase in the weight of the carbon fibre - Kevlar laminate compared to the pure carbon fibre laminate.

Current absorptive systems are designed to maximize energy dissipations by utilizing both reversible and irreversible modes of energy conversions [73]. Weight sensitivity continues to pose limiting constraints on energy absorbing structures, as in most applications, it is required that they are less weight, rigid, ensuring good stability with strength as well as portable to carry.

For low velocity impact, strain-rate effect on yield stress may be estimated by using an approximate factor which is based on the average strain-rate in the critical plastic zones. However, by such estimation, the inertia effects within the body itself are not accounted for and thus the kinetic energy is assumed to be converted into plastic work like a quasi-static deformation mode [5].

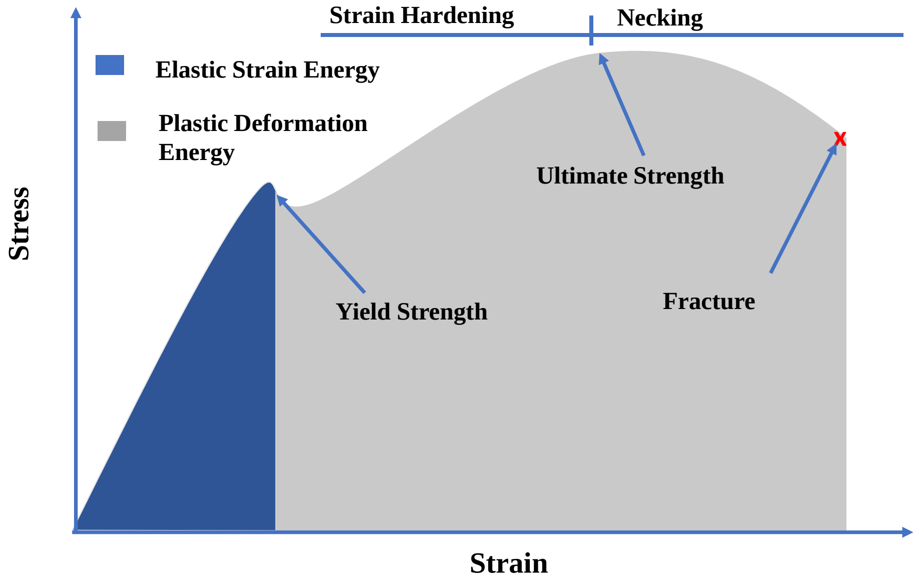

Fig.8 Illustration of elastic and plastic energy regions under a typical stress- strain curve.

5.2. Energy absorption during projectile penetration mechanisms

Problems associated with projectile penetrations through solid armor is very complex and involves complex material behavior for both the projectile and armor. Hence, it is imperative that we understood the complex nature in which projectile and target materials deform under impact situations. During the perforation of target material, the loss of the kinetic energy of the projectile are in two parts. First part constituting the absorption of the kinetic energy of the projectile to global target deformation, elastic work and local plastic flow and failure [78]. Absorbed energy during the penetration process leads to retarding the kinetic energy of the projectile. The remaining projectile kinetic energy comes out as its residual energy [17]. Depending on the projectile type, additional energy may be lost due to the type of failure that occurs, for example hemispherical and blunt projectiles loose extra energy during perforation through ejecting of plug [78]. Kpenyigba et al. showed that target subjected to blunt and conical projectiles absorb approximately same energy before failure which is comparatively lower than that obtained by hemispherical projectile [78]. This observation seems reasonable because for hemispherical projectiles there is a notable plastic flow of material during its perforation process. However, for a given initial impact velocity, relative to the value of the ballistic limit, the energy loss depends on the projectile shape. A similar experimental results was reported by Landkof and Goldsmith [79] who reported that, at velocity slightly higher than the ballistic limit, the influence of projectile nose shape on energy absorbed is negligible.

5.3. Damping efficiency of sandwich core structures

Structures subjected to high velocity impact are liable to undergo several vibration motions which significantly contributes to their collapse. The ballistic resistance of structures can be improved by introducing structures which are capable of increasing damping effect. Damping capacity is improved in structures with high loss tangent, as well as high storage modulus [80]. An important parameter which is essential for any structure to mitigate vibration is the loss modulus – energy dissipation which constitutes the product of loss tangent and storage modulus [81].

Typically, energy dissipation in sandwich structure is based on the constrained layer damping (CLD) approach where the top layer limits the tensile deformation of the middle layer (most preferably viscoelastic material). By so doing, shear deformation in the middle layer increases significantly which results in higher energy dissipation in the structure

[82]**.** Investigating energy absorption between fiber metal layer (FML) skins and polyurethane foam core sandwich structure under high-velocity impact showed high energy absorption by the skins as the specific energy absorbed by the panel decreases with increasing foam density [83]. Ma et al. [84] investigated the damping efficiency of a double arrowhead corrugated auxetic structure core made from carbon fiber composite. Their investigation was based on the combination of finite element and modal strain energy (MSE) approaches. Their finding revealed that high damping energy for such system could be obtained at an optimized corrugated inclination angle. Zhu et al. [85] optimized the topology of sandwich structure for satellite adapter application using a concurrent approach. The 3D FEM module of the sandwich configuration consisting of a host layer, lattice core and a damping layer is as shown in Fig. 9.

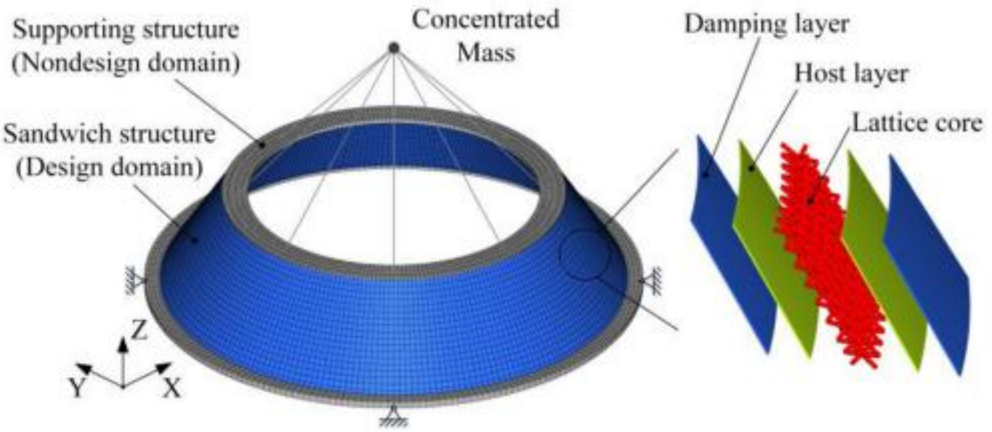

Fig.9 3D FEM model of sandwich panel for satellite adapter application adapted with permission from [85].

6. Ballistic failure in Sandwich Structures

6.1. Penetration mechanism in ballistic testing

Several parameters may influence the projectile penetration mechanisms. Major penetration mechanisms are plugging, spall, enlargement of crater diameter, and petaling [86]. The occurrence of these mechanisms may act at different stages during the penetration process.

Understanding the failure conditions for both target and projectile during perforation is very important as they are necessary for designing target against impactors. In designing, optimization could be achieved with target having minimum areal density as well as less expenditure of energy.

When a projectile impacts a target, compressive waves begin to develop at the impacted area. This wave then transverse through the thickness of the target medium [87]. Upon reaching the free end of the target material this wave is reflected in the opposite direction. The interception of the returning wave with subsequent waves which is following thereafter, generates high tensile stress waves which may cause failure by spalling [21]. Spall failure condition is achieved if the original compressive wave is large enough.

Petal failure is initiated as a result of large tensile and hoop stresses generated on the surface of the opposite side of the impacted plate. This initiated failure then begins to propagate along the axis of the through thickness towards the impact point. This failure is characterized by radial triangular petals. For initiation of failure by petaling, the critical stress is perpendicular to the direction of impact. This failure mode is known to be a function of the geometry of the impactor and the velocity which determines the magnitude of the stress levels. Petal failure by conical shaped impactor occurs by inducing radial necking during the penetration process. Conical impactors easily perforate targets through localized plastic straining at the impactor ends by forming petals [78,88].

During plug failure, chunk of the target material right in contact with the penetrator is kept firmly attached to it. As this stacked chunk is pushed on by the projectile, high tensile stress forms on the opposite side of the target material. Plug failure is formed due to generated tensile stress in the target material [89]. Plug failure are also termed as adiabatic plugging as temperature may contribute to this failure. Temperature effect comes to play when heat generation during plastic deformation is greater than as dissipated through conduction. The flow stress of target material experiencing adiabatic heating keeps reducing until failure is initiated by plugging.

In literature, failure by petaling is often with thin plates whiles plugging with thick plates. Structures subjected to impact penetrations may be termed as either thin or thick based on their ratio values between target through thickness and projectile radius. The ratio value may either be less than or greater than unity and is expresses as [90] ;

$$Thick\ plate = \frac{Target\ thicknes}{Projectile\ radius} > 1\ (Plugging) \quad (9)$$

$$Thin\ plate = \frac{Target\ thickness}{Projectile\ radius} < 1\ (\ Petaling) \quad (10)$$

6.2. Failure modes during ballistic impact process

Mechanisms of failure in sandwich panels under ballistic impact are dictated by several factors: design of core, type and configuration of face sheets materials, type of adhesive material, shock intensity, projectile velocity, relative density of core in sandwich configuration [13,18]. Failure modes mostly developed in sandwich structures subjected to dynamic loading, impact and blast loading are noticeable for showing skin sheet and core wrinkling, buckling and indentation [13]. In addition, failure modes such as crack growth, dishing, delamination, rearward petaling, plugging, frontal petaling are experienced in high velocity projectile penetrations [91]. Nature of fracture is reported to be a function of how projectile makes trajectory within the composite structure [92]. Study by Kilic et al. [19] estimated the resistance offered by perforated target under ballistic testing indicated two major defeating mechanisms as deviation of projectile trajectory which is caused by the perforated target and subsequent breaking of projectile due to significant shear stresses developed within the projectile. Failure mechanism of projectile for perforated steel target in relation to projectile angle of obliquity has been reported by [93] as projectile breaking was found at angles between 20° and 30° and total projectile shattering occurring at incident angles exceeding 45°.

Material strength and geometry also play important role in failure of sandwich structures under impact load. A minimum impact velocity on structure with thickness to projectile radius ratio approaching unity is likely to fail by either plugging or petaling. Petal failure is prominent in low strength targets due to reduced resistance to deflection. However, for configuration with equal target thickness to projection radius ratios, failure by plugging may occur for high strength targets [94]. The geometric configuration of the impactor together with the angle at which it hits a target also influence the nature of failure. Numerical study by [23] showed that a projectile with nose angle of 33.4^0 demonstrated the formation of circular crater which enlarged for a normal impact angle. However, the nature of crater formed changed from circular to ellipse for oblique impact.

6.3. Influence of projectile geometry and incident angle on target failure

This section highlights on the relation that exist between projectiles geometry and their angle of incident on target performance. Iqbal et al [23] investigated how projectile nose angle and their incident angle affect the ballistic limit of a monolithic plate. In their findings, they noticed a general decrease in target deforming with increasing projectile nose angle. They also reported on the fact that, the ballistic limit of target material increases with increasing incident angle. Shape of impactor greatly influences failure mode when ratio of target thickness to projectile radius approaches unity [94]. Ogive-shaped projectiles are likely to cause petal failure in target structures just as blunt projectiles would favor failure by plugging [95]. During the process when a blunt projectile is penetrating a given target, high stresses and strains develop in the target material surrounding the projectile peripheral which accelerates plug failure within the target. Hemispherical shape projectiles also cause plug failure in target materials. However, the initiation of plug failure by hemispherical projectiles is delayed due to localization of plastic strain. The localized plastic strain induces high circumferential necking around the impacted area of front plate interacting with hemispherical projectile [78]. Both blunt and hemispherical projectiles are sensitive to localized strain hardening during perforation [96]. A typical composite target consisting of ceramic face sheet placed on top of metallic sub layer subjected by both sharp and blunt projectiles with same impacting velocities would demonstrate the following characteristics. Penetration into the front ceramic plate by the sharp projectile is less probable than would be for the blunt projectile. Explanation to this is that for a given impacting velocity, larger stress levels are developed for a one - dimensional non-steady state impact compared to a two-dimensional steady state impact [90]. Furthermore, the blunt cylinder provides one-dimensional, higher impact stress over a large area and for a longer time than does the sharp cylinder. In sharp projectiles, material flow quickly becomes two-dimensional as the tip point get destroyed leading to deceleration of cylindrical portion of the projectile. Figure 10 below shows different failure modes observed by blunt, hemispherical and conical projectiles impacting steel targets.

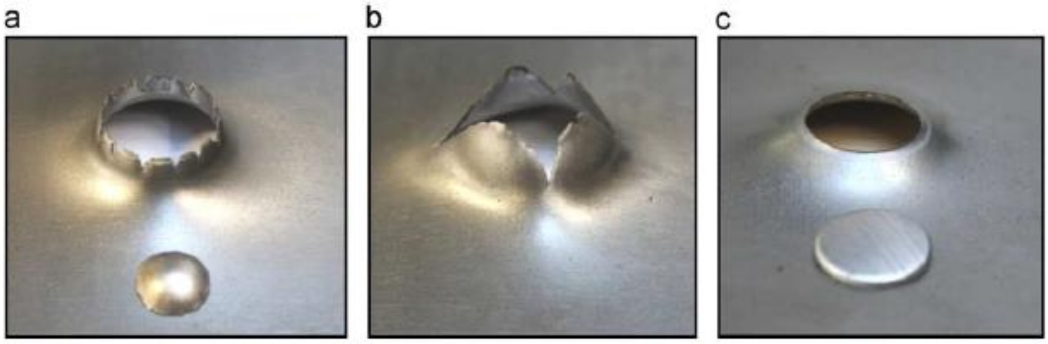

Fig.10 Experimental observed failure patterns of (a) Hemispherical (b) Conical and (c) Blunt projectiles impacting steel target adopted with permission from [78].

Relationship between projectile nose angle and the failure mode has been analyzed by [78]. Analytical model which estimates the number of petals to form when thin metal sheet is impacted by conical and spherical projectiles is given as [88];

$$N = \frac{\pi \sigma_y}{f}\left\{2nr_0 + \frac{[\exp(n) - \sin(\phi)]}{(dt/dr)}\left[\frac{1}{\exp(2n)} - \frac{1}{\exp(2\varepsilon_f)}\right] \cdot t_0\right\} \tag{11}$$

where σ_y is material yield, f is the fracture thickness, r_0 is initial hole radius in the target, dt/dr is the thickness distribution where necking is propagated, ε_f is the failure strain level, n is strain at neck and t_0 is the thickness of the plate. Expression for the expansion of hole radius is related to sheet thickness t_0 and projectile angle ϕ as.

$$r_0 = \frac{t_0}{2} \cdot \tan(\phi) \tag{12}$$

Sheet thickness between 0.6 - 1.5, the fracture thickness may be assumed as below

$$f = \frac{Y \cdot t_0}{0.8} \tag{13}$$

Analytical model above keeps all parameters as constant except dt/dr. In which case according to [88] the value varies between 0.07 - 0.09.

Nature of crater formed during projectile penetration can also be approximated by material properties such as density ρ, hydrodynamic sound speed C, and dynamic yield strength in shear Y. A non-dimensional crater depth that relates penetration depth and diameter of projectile is expressed as [90] ;

$$\frac{p}{d} = K\left(\frac{\rho_P}{\rho_T}\right)^{\alpha_1}\left(\frac{V}{C_T}\right)^{\alpha_2}\left(\frac{Y_T}{\rho_T {C_T}^2}\right)^{\alpha_3} \tag{14}$$

p is the penetration depth, d is the projectile diameter, and the subscripts P and T referring to projectile and target material, respectively. Material constants K, α_1, α_2 and α_3 can be obtained from the cratering calculations.

7. Discussions

The demand for low weight, high strength, high stiffness and less bulky structures for engineering applications has always been sort for, most especially in the recent surging global demand for energy. Such requirements are inarguable for ballistic protective materials also. Composite materials with their synergetic advantages have been exploited over the years, most especially, in areas where light weight and high energy absorption are required such as ballistic impact applications. This current review reveals the appealing demand for high performance polymer metal sandwich structures. Energy absorption capacity of sandwich structures, which is very crucial in high impact velocity has been noticed to be dependent on core design, nature of projectile and density of core material. With low density cores proving to have high performance in energy absorption. Recent emerging auxetic core structures – which contracts upon impact have shown outstanding resistance to projectile penetrations. With the advancement in 3D printing technologies, complex sandwich cores could be designed to harness the full potential of auxetic structures for energy absorption applications. Sandwich structures of multi-materials happen to have better energy absorption compared to their equivalent monolithic solid counterparts. Filling of voids within sandwich core with fluid has indicated to exhibit improvement in ballistic resistance as it ensures effective energy transfer due to effective bonding conditions introduced by the fluid. Design optimization methods such as ANN, RSM and fuzzy logic which have recently been employed in obtaining optimum design by some researchers is noted to facilitate and expand research work in the current area. Such optimization approaches still need to be explored further in designing sandwich topologies for higher performance at their minimum weight.

8. Summary and Conclusions

In this review, we have outlined extensively based on previews works some of the underlying factors that contribute to the integrity of sandwich structures for ballistic protection which include but not limited to core designing, different type of failure mechanisms, energy absorption capabilities and mechanical properties of sandwich panels. The review has also shown that the core material type and its design specifications have significant effect on sandwich performance. Summary of this work is outlined below.

1. Effect of sandwich geometry design in enabling energy absorption.
2. Exposure to current numerical optimization techniques in designing sandwich structures.
3. Current materials such as auxetic structures which show outstanding performance under ballistic impact.
4. The relationship that exists between projectile type and failure modes in monolithic and sandwich structures.
5. Effect of core design such as interlocking grid, thickness and bonding layers between core and face sheet in absorbing energy during impact.
6. Damping efficiency of sandwich core structures in ballistic applications
7. The effect of skin thickness of sandwich structures in absorbing energy has also been highlighted.

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