The Crashworthiness Performance of the Energy-Absorbing Composite Structure—A Review

Irshad Ahamad Khilji, Siti Nadiah Mohd Saffe, Chaitanya Reddy Chilakamarry, and Siti Aishah Rusdan

Abstract The improved energy absorption capacity of composite materials will upgrade people's safety in accidents. Several parameters affect energy absorption such as fibre type, matrix type, fibre architecture, specimen geometry, processing conditions, fibre volume fraction, and test speed. These parameters influence the composite material-specific energy absorption. The distinct characteristic properties of composites play an essential role in a variety of industries. Automotive applications have attracted worldwide attention due to their rapid use and are expected to increase. This review focuses on understanding the effect of a particular parameter on the energy absorption capability of composites, an analysis of the energy absorption properties of polymer composites. The data from the various researchers are collected and categorised in the field of energy absorption of composites. Many testing methods and refraction types for composites are described.

Keywords Crash assessment · Composite material · Energy absorption · Polymer · Testing

1 Introduction

The energy absorbed by metallic materials during an impact or crash of moving vehicles is converted into plastic deformation energy. However, composite structures also absorb energy to convert impact or kinetic energy into deformation-absorbed energy [1]. The energy absorption capacity (EAC) of composite structures is higher than metallic equivalents. Recently, composite materials gained popularity due to their ability to absorb energy from crushing objects. The daily usage of composite

I. A. Khilji · S. N. Mohd Saffe (✉) · S. A. Rusdan
Faculty of Manufacturing and Mechatronics Engineering Technology, Universiti Malaysia Pahang, Pekan, Malaysia
e-mail: sitinadiah@ump.edu.my

C. Reddy Chilakamarry
Faculty of Chemical and Process Engineering Technology, Universiti Malaysia Pahang, Gambang, Kuantan, Malaysia

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materials intended for crushing objects by energy absorption attracted human. Prominent investigators specialising in crash resistance have carried out of highly unique research undertakings. The word crashworthiness means the ability to secure stuff from accidents or damage or death of passengers, cargo, or valuables. The factor that impacts the adequate energy absorbed is determined by the material used to produce energy absorption equipment. Energy-absorbing metallic structures (EAMS) have increased in popularity for more than twenty years [2].

Further, researchers have increasingly embraced the utility of energy-absorbing composite structures (EACS) in crashworthiness applications [3]. The desire to apply EACS to aviation, automobiles, vessels, wind turbines and space exploration arises from their significant benefits over metals and alloys. One of the benefits of EACS over EAMS is its lightweight that results in low consumption of fuel, and making it environmentally friendly. Additional benefits include improved mechanical qualities like greater strength, greater specific rigidity, promising vibration regulators, lesser density, and lower noise potential [4].

The significant key role is to provide safety and protection during crash incidents. Thus, choosing the right combination of composite material and the best manufacturing process must be confirmed. A variety of composite materials are used with various syntheses approaches to construct and design composite energy absorbers. The ultimate strength and crash resilience performance of EACS life cycles depend on the material composition, process of production, and sustainability maintenance. As a result of the crash, composite crushed tubes or structures break through a complex microstructural mechanism. Their performance is determined through many parameters that include specific energy absorption (SEA), the ability for energy absorption (EA), crush strength efficiency (CSE), mean crushing force (MCF), and loss of sound transmission (STL) [5–7]. Additional performing indices comprise initial peak force (Fi), peak/critical crushing force (Fp), initial failure indicator (IFI), and energy absorption efficiency (EAE) [8]. Figure 1 depicts the formula with absorption indicators of major crashworthiness. Various research on composite structure claimed that SEA and EA parameters are most important for industry 4.0.

The energy absorber exhibits an improved SEA, CFE, and EA and reduces the initial peak force through crushing or impacts. Increased early peak load and force lead to a decreased crashworthiness efficiency of the crushed tube. Once exposed to quasi-static or lower velocity the dynamic stress conditions, composite tubes, sections, and lattices were examined. Almost many surveys found failure mechanisms following crushing impact circumstances [9]. In technology, many investigators have focused on fracture processes while analysing the crashworthiness of the composite structure. Fibre breaking, delamination, cracking matrix, and debonding matrix are responsible for fracture processes. Figure 2a, b show a ply model schematic from different fracture mechanisms. Matrix cracking and fibre breakage are called an intralaminar breakdown mechanism caused by damage in the layer because of low resin and laminated structure tensile properties [10]. In this case, the stress-energy created on the surface during the fracture is more than the vital energy. Warrior et al. have thoroughly conveyed the influence of inter-luminary methods on the crushing implementation of EACS [11]. Many researchers reported the crushing failure due

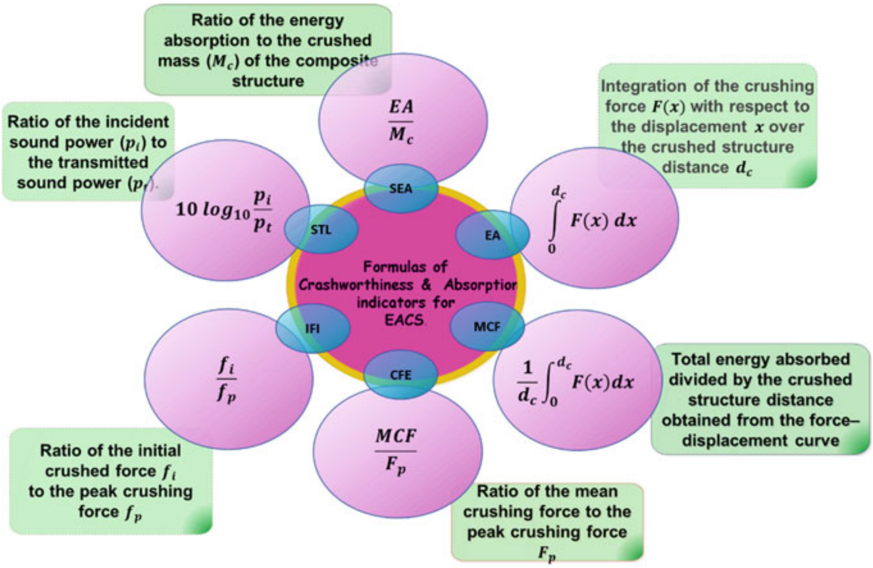

Fig. 1 Formulas for EACS

to lamina bending, brittle fracturing, splaying, and transverse disintegration [12]. Another purpose of this assessment is to investigate the various composite materials that researchers have utilised to create energy absorbers. These can be obtained in either a natural or artificial manner. Polymer composites can be formed using different fabrication procedures to make varied energy absorption composite structures due to fibre reinforcements and matrix resins [13].

Composites are materials created by combining existing materials that are made up of at least two materials. The first continuous component, the matrix, acts as a binder, while the secondary discontinuous component (particle, fibre, or layer distribution) is enforced [14]. Because of their excellent mechanical properties, they are used in a variety of industries. However, high prices and labour-intensive production primarily hamper composites. The automotive industry was the first to use composites in motorsport. Composite materials are now used in mass-produced cars as well as sports and luxury vehicles. Car manufacturers are working to reduce vehicle weight and emissions by improving vehicle safety and durability for long life. The composite materials manufacturers noticed the use of composites to develop an appropriate technology that will make composite parts easier, cheaper, and faster [15]. Composite structures are the most advanced in the automotive industry, and their use in the production of automotive components has a promising future. Automobile manufacturers make an attempt to lower the vehicles weight by enhancing their durability and safety. The number of cars driven and the amount of pollution emitted are consistently regulated [16]. Composite materials provide various advantages with a wide range of qualities that satisfy the needs of today's automobiles.

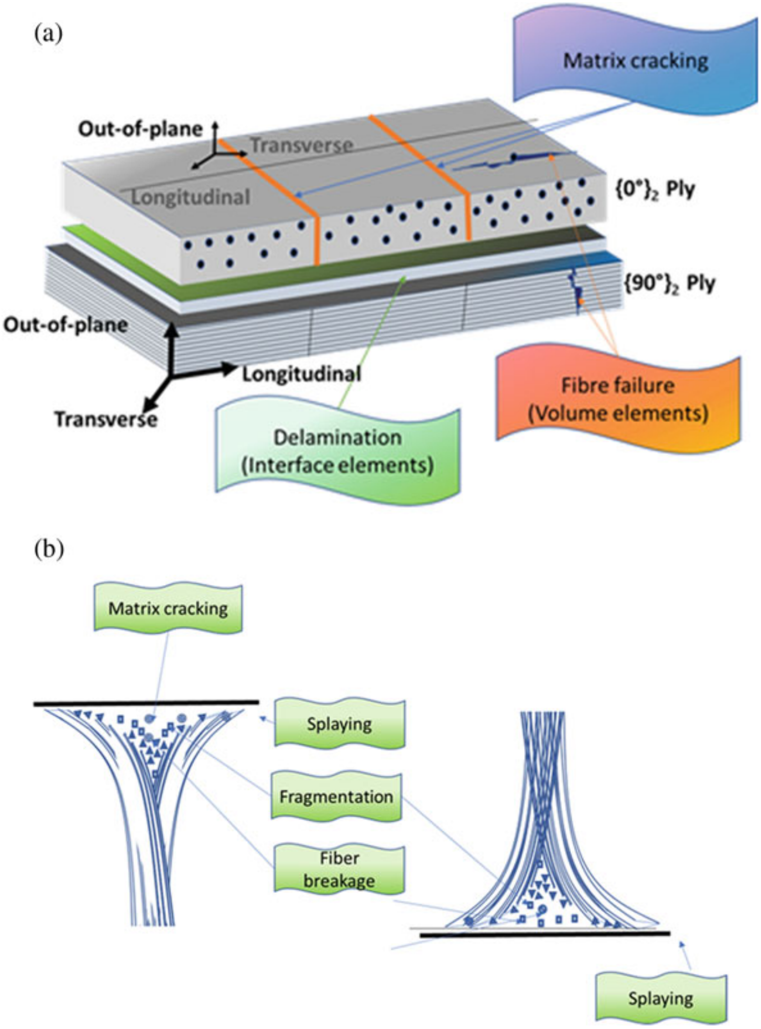

Fig. 2 **a** Ply model schematic different fracture mechanisms. **b** Schematic of fibre fracture mechanisms

Composites are primarily used in automobile manufacturing alternative to steel and other metal materials, to decrease weight, enhance strength and durability. The adoption of contemporary composite materials triggered a revolution in automobile technology worldwide at the beginning of the 1990s. In 1984, McLaren made carbon fibre from the monocoque of F1 vehicle [17]. The use of composites is currently more or less standard, particularly in sports vehicles. There are many advantages of composite material over conventional material, as shown in Fig. 3.

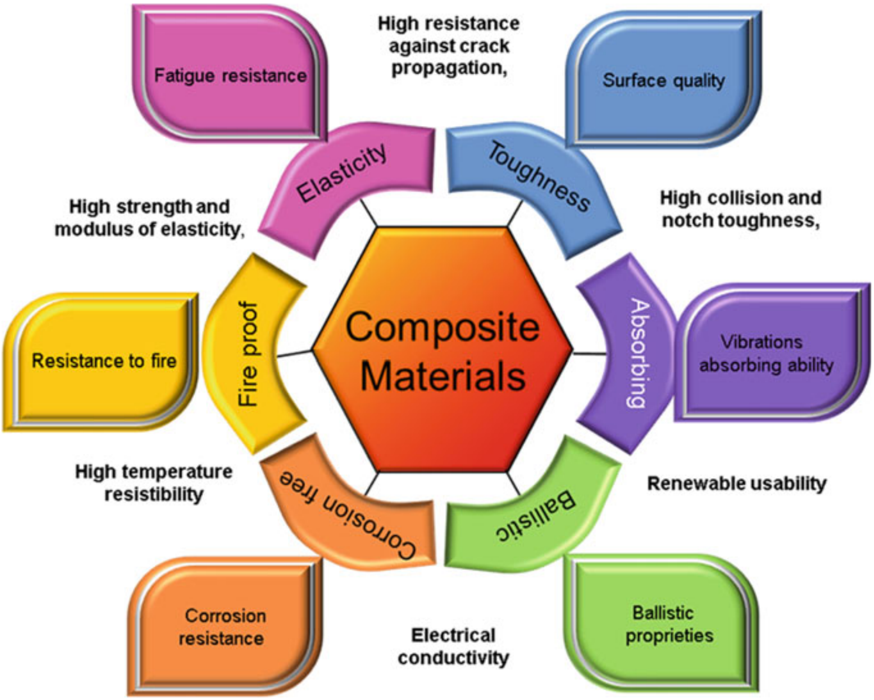

Fig. 3 Advantages of composite material

Using composite material, manufacturers can reduce vehicle weight by more than 30% by carbon fibre or other composite material [18]. Reducing vehicle weight lowers fuel consumption as fuel is an emerging issue for automobile engineers and vehicle manufacturers. The most substantial reason for using composite material is its high impact strength, making it more safe and secure against accident impact and saving human life [19]. However, we still need to improve the strength of this material. The fundamental reason for using composite material is shown and described in Fig. 4. Composite material is reusable, like steel and plastic. However, the composite material require unique manufacturing process and a high-skilled engineer for developing new material with high cost and time. This review focuses on types of composite material, energy absorption characteristics.

2 Material for Energy Absorber

Energy absorbers constructed using composite materials exhibit mechanical qualities that are not found in their metallic equivalents. These features include increased strength, decreased weight, increased specific stiffness, increased vibration and noise

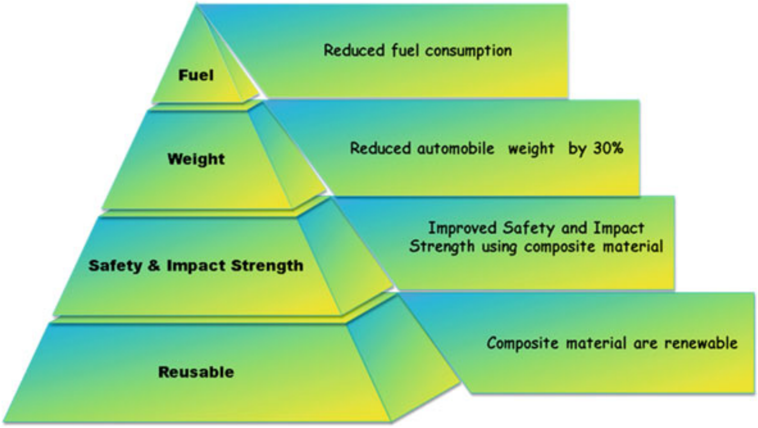

Fig. 4 Composite material strength

control capability. Composite materials are employed to construct the structures thatcombine fibre reinforcement with a polymer matrix. Fibre/matrix composites combined with suitable amounts of hardener/curing materials for faster curing and strengthening of polymer materials depending on developing processes [20]. The two types of polymer matrices are thermosetting and thermoplastic, while fibre reinforcement can be natural or synthetic origin [21]. Sandwich and nanostructure as advanced materials used in the automobiles sector. However, hybrid structures used for the front bumper and windshield. Synthetic compound structures like carbon GRP and glass GRP are used for high speed and armed class vehicles.

3 Polymeric Matrices and Foams

Usually, thermoplastics or thermosets are used as polymeric matrices in crashworthiness applications. All thermoplastics have a rigid molecular structure that reform on heating. Polyamide [22], polypropylene, polystyrene [23], polyvinyl chloride, polyether ether ketone are thermoplastics. Whereas, thermosets have a low molecular weight and are incapable of reforming. The standard type of thermosets is epoxy resin, vinyl ester resins [24].

3.1 Synthetics Composite

EACS has been formed by combining a variety of synthetic materials with their polymers. Carbon, glass, and aramid fibres are synthetic fibres used in EACS are listed in Fig. 5, the caron/graphite and glass two fibre types are often used due

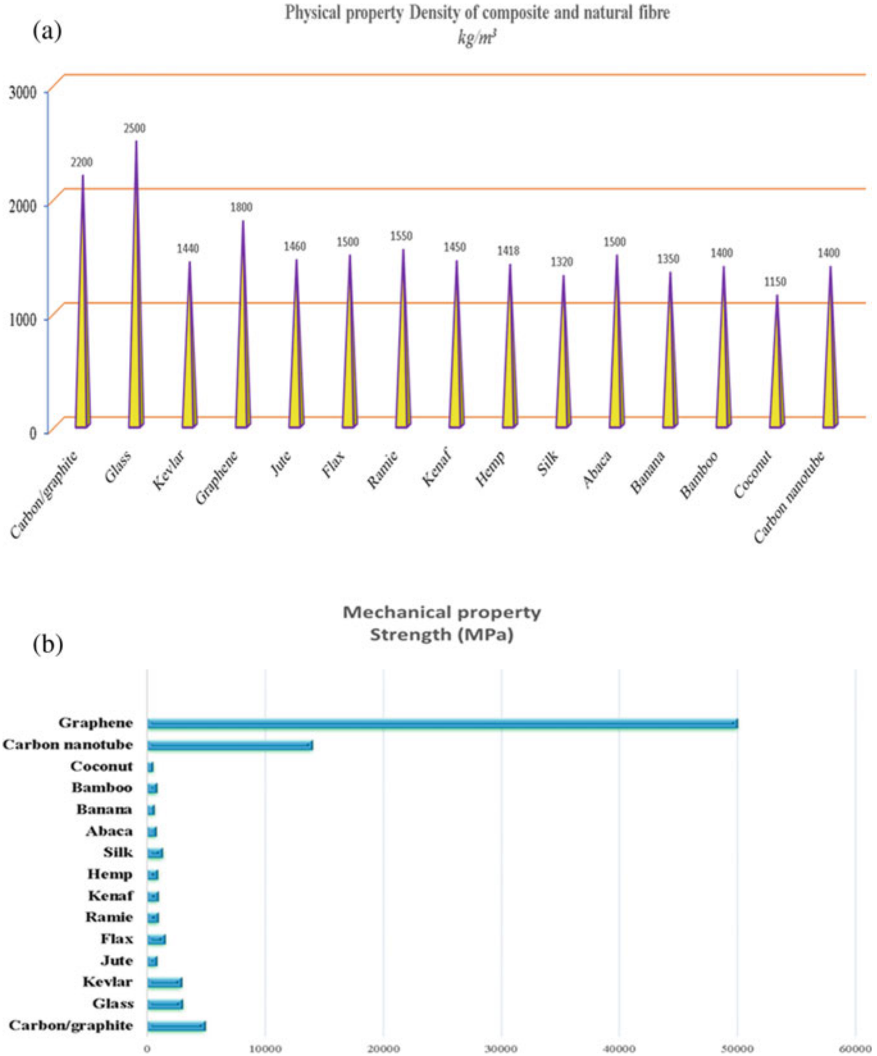

Fig. 5 **a** Physical property of energy-absorbing composite and natural fibre. **b** Mechanical property of energy-absorbing composite and natural fibre

to greater mechanical strength than the Kevlar fibre. Many aspects of the energy absorption capability of reinforced polymer of glass fibre and carbon were reported by Ochelski and Gotowicki [25]. They observed 20% greater specific energy absorption for the epoxy composite of carbon than glass. To enhance the mechanical strength of synthetic fibres, graphene nanoparticles blended with EACS structure as shown in Fig. 5a, b (Graph). Glass fibre has the most robust physical property than natural and synthetic composite. The combination of synthetic composites with nanoparticles functions as good reinforcing elements to improve the energy absorbers of crushing characteristics. The model for the crash box's mechanical behaviour was developed by Elmarakba et al. [26]. The composite comprised of three materials like glass fibres, with graphene nanoparticles (round shape) placed in a polymer matrix. The mass of more than 1673 Pond is used for crushing the box to calculate values by finite element and mean field homogenization (MFH). The finding determines graphene composite has better compactibility then glass fibre reinforces composite in terms of SEA value.

3.2 Carbon Fibre Based Reinforced Polymer (CFRP)

Many researchers worked on the crash resilience of CFRP nano-composite structures. Zhu et al. recently developed single-cell with multi-cell CFRP forms to evaluate the overall absorbance of energy throughout the distinct dual configurations and concluded that the multi-cell structure generated a greater EAC than the single-cell design [27]. The CFRP presented by Xin et al. shows the effect of the cut angle on the crushed tubes of SEA. The investigator also examined the energy absorbing of the crushed structure enhanced by adjustment of the cuts [28]. For instance, Boria et al. examined the CFRP wall thickness, conical structures angle, and internal diameter of minor conical structure as a significant EA parameter. Based on the results, the inclination angle greatly influences the failure of a structural model [29].

Though, the EAC was improved by increasing the CFRP laminate thickness and the average diameter and by lowering the wall thickness. Energy absorbers created by combining graphite, a carbon fibre, with matrix resin. EAC of circular graphite/epoxy tubes impact was examined experimentally by Siromani et al. [30]. According to their findings, the effect of the trigger mechanism results in a substantial drop in peak load and simultaneous increase in SEA.

3.3 Glass Fibre Reinforced Polymer (GFRP)

Glass Fibre Reinforced Polymer has received considerable attention, similar to carbon fibre reinforced nano-composite tubes the glass fibres with their matrices is used as energy absorbers. Glass Fibre Reinforced Polymer is available in various forms A-GFRP, C-GFRP, D-GFRP, E-GFRP, and S-GFRP. The E-GFRP and S-GFRP are primar energy absorption forms. The amount of fibre and staking series affect the implementation of the composite. Solaimurugan et al. investigated the effect of fibre orientation and stacking sequence with GFRP tube shown SEA enhancement upon axial impact by the increasing axial fibre content [31].

3.4 Composite Sandwich Structures

Sandwich structure form is designed by composite energy absorbers. The inspiration for this design style is to create a lightweight and strong structure. Use of such design in automobiles and other commercial vehicles reduce vehicle weight by improving fuel efficiency. Sandwich composite structures are constructed from two adjacent lightweight plates of any size that joined by a core. To further enhance the energy absorption sandwich device's crushing ability, the core is also structurally aided by polymer or metallic foams. For instance, Sun et al. used closed-cell Al foam substrate and different panels to support metallic foams to examine their dynamic impact resistance [32]. In collaboration with other scientists, a few researchers have previously investigated the absorption and impact architecture of aluminium-based graded core sandwich structures for low-speed impact; their findings indicate the deformation and failure characteristics of the impact panel are significantly affected by the density gradients of the graded foam core. Metallic foams were recently structured as honeycombs for providing better safety in addition to superior structural strength [33].

4 Functionally Graded Crash-Resistant Composites

Functionally graded crash-resistant composites emerge with great potential to provide more excellent, effective energy absorption patterns. Crushing tubes are also manufactured via integrating various composites' features in one energy-absorbing graded component. The graduated design has lightweight qualities, strong bonding, and reduced stress due to smooth interface changes [34]. The progressive change in the Unit Cell increases the connecting force, guarantees that the mechanism of failure is progressive during a crash and improves the energy absorber's crash resistance. Therefore, functionally graded crash-resistant composites are an excellent technique to reduce fracture in composite constructions [35]. It is also highly efficient for isolating noise and vibration and can be an alternative material for the equipment's casing to reduce vibration and noise in the crash. But the use of graded materials for energy absorbents is not studied well. One of the probable reasons for this may be the task to form a single material type by combining a composite material with two or more incompatible features. Therefore, most research has recommended metallic materials with functionally graded thickness (FGT) and functionally graded foams (FGF). FGT metal alloys are a unique type of composite materials produced by infiltration of molten metals, resulting in graded preforms of varied shapes. FGT metal alloys are categorized as a unique composite material produced when molten metals are melted infiltration to generate preforms of varied forms [36].

5 Solutions to the Problems, for the Sustainable Development of Energy Absorber Crash Assessment

This review has demonstrated that EACS performs better in a crash than metallic counterpart if crushed under axial or oblique stress conditions. However, several problems in the synthetic structure and its manufacturing methods remain challenging. Practical solutions to some of these difficulties have been provided with probable progress in manufacturing highly efficient energy absorbers. EACS damage evaluations are also revealed with potential composite fixes. Figure 6 pie chart demonstrates the future need for crash assessment regarding the material used for future-ready vehicles, advanced manufacturing process with better adhesive material that last longer, and low cost for repair and sustainability.

5.1 Material Comparison

The comparison of different metallic and composite materials is shown in Fig. 7. Among the various materials, IM carbon is excellent for composite material in specific strength, tensile strength, and elasticity, followed by HM carbon and fiberglass.

Weight reduction and vehicle usage decrease

Automobile makers are employing new, ultra-light polymers to reduce carbon dioxide emissions. The composite material is the main advantage of making vehicles lightweight and more secure against accidental impact and fuel efficiency. Still,

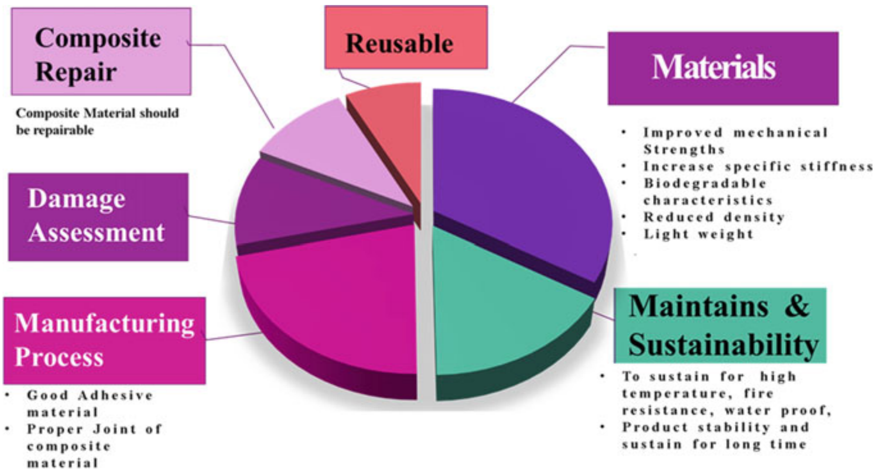

Fig. 6 Crashworthiness assessment for industry 4.0 ready vehicles

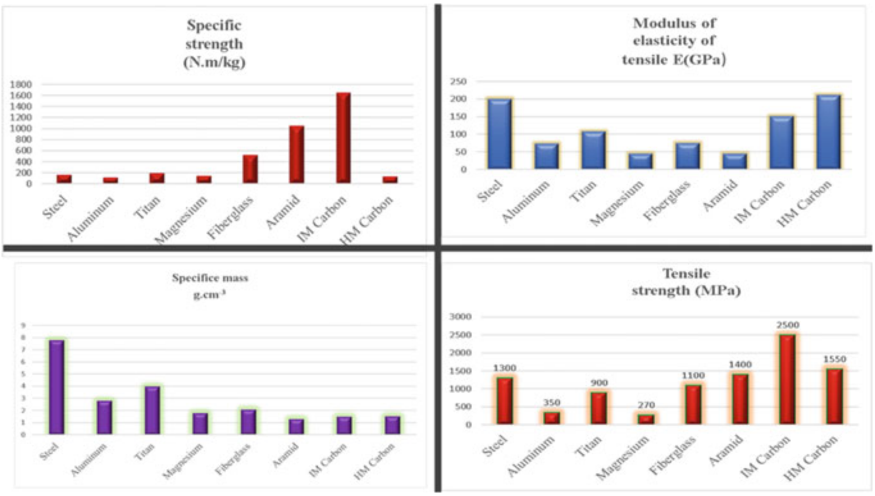

Fig. 7 Comparative chart for different metal and composite material

the only obstacle to use such materials is their high price and complex production process. Figure 8 show the comparison of carbon composite with other essential material used for vehicle body manufacturing. The lower vehicle weight by 30%, resulted in fuel efficiency of 7% and is helpful for reducing CO_2 to build eco-friendly and EURO 7 standard vehicles [37]. Also, a comparison with an engine that provides higher efficiency than a diesel engine.

The tensile strengths are the material structure's capacity to absorb energy via a controllable approach. The requirements for the durability of automobiles are:

- Reconfigurable vehicle end part that protects the integrity of the rear passenger area and protects the gas tank [38].

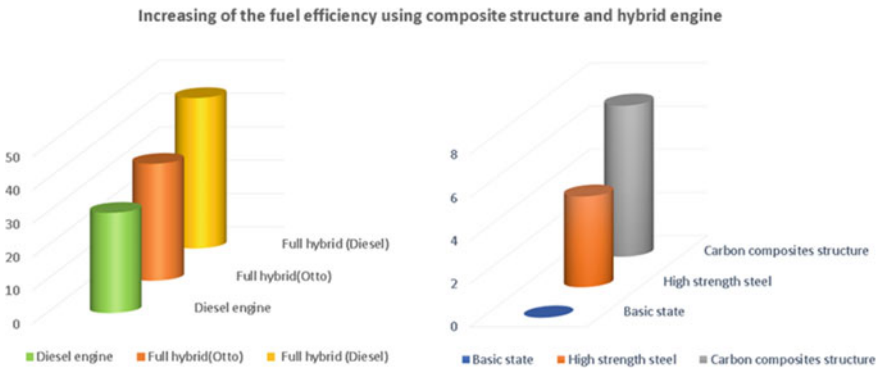

Fig. 8 Fuel efficiency comparison with composite material and primary material

- The side framework and doors of vehicle were design in ergonomics standerds [39].
- Rooftop structure should protects passenger when vehicle turnover [40].
- Proper utilisation of available space using the latest ergonomics [41].

5.2 Manufacturing Technique

In producing energy-absorbing materials, the hybrid components are generally inadequately connected, resulting in increased structure weight and less energy absorption during impact. A good adhesion material can provide an actual answer to increasing hybrid structure's stability. More studies focused on the testing and production of materials can increase hybrid structure adhesion quality [42].

5.3 Assessment of Damage

Residual pre-impact crashworthiness could arise through production, maintenance, and handling of the energy absorber. These numerous tiny impacts may result in the formation of early cracks. The energy absorber suffers from metal fatigue and pre-damage, lowering its entire crashworthiness [43].

5.4 Composite Material Repairing

The most challenging issue of composite repair is composite constructions includes detecting fractures, riveting, and bolting. Because they enhance tensile stress and increase structure weight, other repair techniques like scarfing and injection repair techniques need depth research, or apart from repair, composite structures need to develop to replace a particular part. It is a common practice called scarf patches; it provides the best stress transfer and effectiveness.

6 Conclusion

This review summarises investigations on the crash behaviour of EACS. The increasing amount of fatalities, injuries, and damage to precious objects in the previous decades during the disaster crash has raised academics' interest in finding more effective means of detaining the situation. Structures or gadgets built of composite materials absorb energy exhibit more integrity and crash resilience than metallic equivalents. They are unmatched to other materials because of their low weight, environmental friendliness, low densities, more incredible strengths, higher specific rigidity, and excellent possibilities for noise reduction. However, this research has demonstrated that choosing composite materials and manufacturing processes may significantly impact their more effective energy absorption capacity. Finally, there have been several ideas and plans for future progress.

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