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Design and materials development of automotive crash box: a review

N.S.B. Yusof[a,b], S.M. Sapuan[a,c,*], M.T.H. Sultan[d], M. Jawaid[a], M.A. Maleque[e]

[a]Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products (INTROP), University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

[b]Faculty of Information Sciences and Engineering, Management Science & University, Seksyen 13, 40100 Shah Alam, Selangor, Malaysia

[c]Department of Mechanical and Manufacturing Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

[d]Aerospace Manufacturing Research Centre (AMRC), Department of Aerospace Engineering, University Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia

[e]Faculty of Engineering, International Islamic University Malaysia, 53100 Jalan Gombak, Kuala Lumpur, Malaysia

Abstract

Recent interest by automotive manufacturing company is to develop a component, capable of enhancing safety features associated with lightweight materials such as using aluminum and composites. The use of aluminum metal matrix composites (MMC) and composite materials improve the performance of an automotive crash box due to their lightweight. Automotive crash box is a component, equipped at the front end of a car, and is one of the most important devices for crash energy absorption. The review is mainly divided by two topics, i.e. design of geometry profiles and the crash box material advancements, both geometry and material properties would influence the efficiency of kinetic energy absorption during collision. This review benefits both academics and corporate sector as it outlines major lines of research in the crash box design. It discusses the results from 3D simulations up to laboratory experiments of crash box specimen and the effect of material selection to the characteristic of crash box device. The information from this paper should stimulate more research and more crash box design solutions to reduce fatal damage during collision in automotive industry.

Keywords: automotive crash box; composites; energy absorption properties.

1. Introduction

Conventionally, the design of automotive related products or components is focused on achieving high operational performance as well as fulfills the safety regulations. For automotive crash box or generally known as frontal collision, numerous performance and safety regulation must be complied such as European regulation 33 revision 1 part 2 regarding uniform provision concerning the approval of vehicles with regard to the behavior of the structure of the impacted vehicle in a head on collision [1] and European regulation 42 regarding uniform provisions concerning the approval of vehicles with regards to their front and rear protective devices (bumper, crash box, etc.) [2].

For a few decades, the giant companies in this industry competed with each other to convince targeted market with proven quality in terms of performance and safety. Globalization was the highest factor contributing to the challenging automotive manufacturing environment [3]. Thus, it was resulted in a rapid pace in growing competition between international and domestic car manufacturer. Rapid increasing numbers of car produced by manufacturer make the automotive market saturated [4]. Therefore, automotive company recently looking for extra value added features such as sustainability [5]. Besides that, the increasing numbers of awareness regarding environmental impact and subsequently the needs towards sustainability encourage automotive company adhere to the environmental related requirements enforce by the government bodies such as European End-of-Life Legislation stipulated about recycling and

* Corresponding author.

E-mail address: nik_shamsul@msu.edu.my (S.M. Sapuan)

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recovery of heavy metal restriction as well as treatment for material break down directive 2000/53/EC criteria and International Organization for Standardization ISO, criteria 22628:2002 [6,7].

National Highway Traffic Safety Administration (NHTSA) recorded the first motor vehicle fatal accident occurred in 1889 in New York City [8]. An early period of safety awareness regards to the vehicle accidents initiate by United States government start from the turn of the century to year 1935 which is period of genesis, growth, and development to understanding the extremely complex process of vehicle collisions. The second period started from year 1936 to 1965, which was called as intermediate safety period with crash avoidance devices. After that period, the numerous researchers studied and investigated deeply crashworthiness in enhancing the crash box capability. Jacob et al. [9] studied crashworthiness of automotive using composite material systems, define crashworthiness as the ability of a vehicle to prevent fatal injuries to the occupants in the event of a crush, they also stated the most important concept in vehicle collision cases is crashworthiness. Witterman [10] mentioned that a vehicle's occupants are subjected to a various number of forces that can consequence in fatal injury and vehicle damage. It happened due to the rapid deceleration and rapid acceleration of vehicle during the event of crush, while the forces depend on the direction of impact in the collision. Liu [11] investigated the optimum design of crash box and crashworthiness analysis and mentioned that the design of crashworthiness device must be able to distribute the injurious forces by directing them to parts of the body, which was more capable of withstanding them. Bois et al. [12] stated that the crashworthiness is the ability of body structure include progressive crush zones to absorb part of the crash kinetic energy. The designers must consider the study of four crashworthiness parameters, which are accuracy, speed, robustness and development time to improve the crash box capabilities. Bathe et al. [13] explored advances of crush analysis specifically in crash box design. They concluded the effectiveness of complete analysis process can only be achieved by ensuring each of the solution procedures such as usage of consistent tangent and the precision of stress element calculation in elasto-plasticity is in an effective manner integrated into a complete solution scheme. Karim Hamza et al. [14] studied the crashworthiness, then they design vehicle structure by the use of equivalent mechanism predict the aggregated behaviors of structural members during crush. The proposed approach consists of two main phase which is exploration of the good crash mode and identical the design to the desired crash mode. Crashworthiness is a study focuses on occupant shield or protection to lessen the number of fatal injuries or major vehicle damage. Crashworthiness can be defined as research studies involves new or improved vehicle design, safety countermeasures and safety equipment such as crash box for automotive with main purpose to enhance occupant safety.

In this paper general information on automotive crash pox is presented where the overall review materials were obtained from the journal, books and internet resources. The review includes several important aspects of crash managements such as automotive crash box, front rail and crashworthiness. Furthermore, this paper also reviews crash box design criteria to attain high energy absorption such as crash box cross section, joining type during part assemble and typical materials used in designing the crash box.

2. General information on automotive crash box

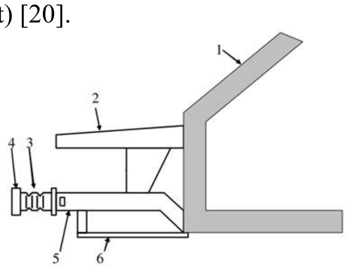
2.1. What is an automotive crash box?

Crash box is a deformation device, which is capable to be collapsed with absorbing crash energy to protect other body parts. The crash box is a structure assembled between the vehicle bumper and front rail as shown in Figure 1. The crash box is important to minimize the main cabin damage and to save occupant during collision at low speed crash. Meanwhile, during high speed collision, the crash box will crush first to reduce the crush impact before front rail absorbs most of the deformation energy.

2.2. Crash box in automobiles

Currently, safety in automotive industries is being widely studied due to the reason of road accidents assassinate people every day and large number of people are injuring or even dying during car crash. More than 1.2 million people are killed and 10 million injured every year in road traffic accident worldwide [15]. The statistic presents a major challenge for public health, trauma medicine and traffic safety authorities [16,17]. A lot of factors contribute to the accidents, as discussed in detail by Peden et al. [18] such as human factor, inappropriate speed, ignore the safety protective equipment such as seat belt, driving with drinking alcohol and drugs. All of the risk might create a brutality crash during frontal collisions. To protect occupant during collisions several approach selected to increase the safety level by using more safety devices such as air bag and anti-lock brake system.

Another improvement to enhance the safety level is to improve design structure, the structure was expected to be able endure shock load impact during accident. In order to ensure the passengers' safety, the common way to minimize mortality and property damage in a collision is to install energy absorption device in the vehicle structure called "crash box" [19]. Essentially crash box design reduces the force transferred to occupant and the structure would be able to absorb most of the impact energy with progressive folding deformation. A typical automotive crash box is denoted in (3) in Figure 1 equipped at the front end of a car which is assembled at front side frame. The illustrated crash box is created to absorb kinetic energy during collision hence reducing the damage to the front rail, (denoted in (5) in Figure 1) and the engine. The initial impact during collision was absorbed by crash box, and then it transmitted force to the front rail. Hence, it minimizes the damage caused by major accidents. However, bumper cross member represented by (4) in Figure 1 absorbs impact energy for a minor collision (no damage of functionally relevant parts, and no plastic deformation of any other component) [20].



(1) Undeformable cockpit, (2) upper front rails, (3) crash box, (4) bumper cross member, (5) main front rails, (6) mechanics frame.

Fig. 1. Front structure configuration [20].

Nakawaza et al. [21] reported that crash box must have the ability to collapse preceding to other body part in order to absorb crash energy during collision, minimize the damage of the main cabin frame and save passenger live. The study concentrated upon discovery an optimum cross sectional shape of a crash box to certify high capability for energy absorption without several ditches on crash box body called crash bead. The actual part and cross sectional shape are illustrated in Figure 2. They created new design of crash box consisted of four grooves with 24 ridge line which are able to obtain high buckling load caused by impact load in axial direction

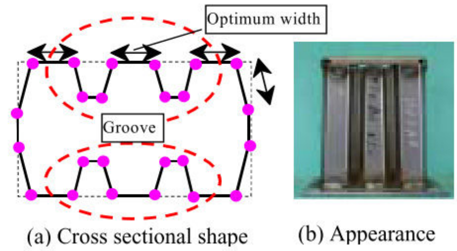


Fig. 2. Crash box design with groove by Nakawaza et al.[21]

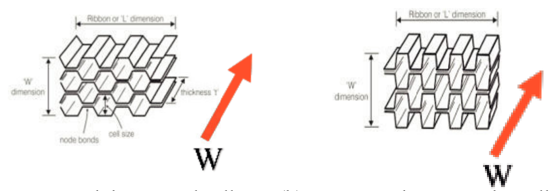
They concluded that the width of plane between ridge lines on crash distortion was quantitatively clarified as most important design parameter which influence to achieve high crash energy absorption.

Peroni et al. [22] stated that crash box is a deformable device, which is able to dissipate kinetic energy. The efficiency of devices depends on the thin wall prismatic column, geometry of device at front rail, material thickness, dimensions of the cross section, structural material used in fabrication as well as the application of joining system used. The research concluded that high capacity of energy absorption can be obtained using adhesive bonding and continuous welding in structures subjected to crash.

From the above review of the literature, it is concluded that crash box must have the ability to absorb energy during collision. The crash box must undergo plastic deformation prior to other parts to minimize the vehicle damage. Researchers had come up with new design to improve the energy absorption capability. The parameters often determined to improve crash box performance included thickness, cross section dimensions, types of material and the ditches on the crash box, called crash bead.

3. Typical materials (honeycomb/composites) used in automotive crash boxes

Honeycomb aluminum sandwich concept structure was introduced to investigate the energy capabilities of a thin walled crash box through experiment and numerical method approach as reported in Zenkert [23]. Figure 3 (a) depicts honeycomb hexagonal cell which can provide low density to the crash box materials. Figure 3 (b) shows honeycomb rectangular cell with less anticlastic curvature which can easier forming in "W" direction. During the collision, the position of crash box honeycomb structure is as shown in Figure 3 and the load impact comes from the "W" direction. Conclusions were made from the studies that, the shear forces normal to the panel is supported by the honeycomb core during the collisions.



(a) Honeycomb hexagonal cell (b) Honeycomb rectangular cell

Fig. 3. Honeycomb cell shape [23].

When the span of the panel is large compared to its thickness, the shear deflection is negligible.

Boria and Forasassi [24] studied aluminum sandwich structure focused on energy absorption capabilities of a thin wall crash box as well as the benefits of honeycomb structure, materials selection and sandwich design. They concluded that, a shell-solid-shell modelling approach is the best design base on the capability to represent the failure modes of the impact absorbing structure. Figure 4 shows a shell solid shell modelling with 2D elements for the faces and 3D elements for the core are characterized the best compromise design.

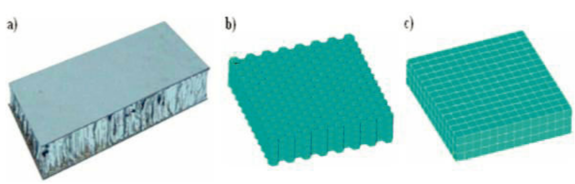


Fig. 4. Different models for the cellular core: a) real 2D face and 3D core, b) detailed cell wall modelling, and c) modelling with solid elements [24]

A research was conducted on characteristics of a car crash box by using finite element method and shape optimization design of thin-walled tubes [25]. Six types of thin-walled tubes were considered and compared as shown in Figure 5. It was found that the peak impact loads of tubes decreased at different degree when the different grooves are adopted. Among them, the best one was proposed to maximize frontal crash energy absorption is double concave and bulgy grooves.

Pereira et al. [26] presented a study on the improvement of aluminum tubular properties structure using initiator through localized heating during the production. The purpose of the study was to improve material properties and enhance the capability to absorb impact energy in a progressive and controlled manner by local adaptation. The study reveals that by using a thermal trigger, a reduction in the initial crushing force is achievable.

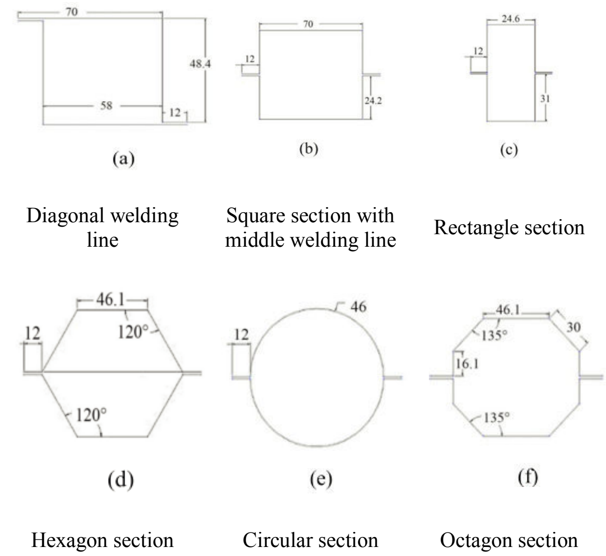


Fig. 5. Geometries of different tubes for crash box [25].

In addition, this thermal trigger can reduce the initial maximum force as well as ensure stable and uniform absorbed energy at smartest models.

Frank et al. [27] conducted a study particularly on weight reduction of crush box structure by using thermoplastic advance composite. The purpose of the research was to study composite crush tube in unidirectional energy absorption and how to design crush device to achieve an optimum performance. The specimen for composite crush device made from high performance material such as carbon fiber with epoxy resin, polyetheretherketone (PEEK), which is high performance thermoplastics and glass fiber reinforced thermoplastics or thermoset, the part model depicted in Figure 6. They concluded that E-glass reinforced polyethylene terephthalate and thermoplastics polyurethane composites had the maximum lap shear strength without conditioning whereas specimen for material E-glass reinforced polyamide composites reached maximum lap shear strength after the bonding procedure. From the above review of literature, it is found that experimental and numerical method approaches were performed to enhance the crash box capabilities. To achieve an optimum energy absorption, honeycomb crash boxes with single layer and multiple layer (sandwich) design structures were introduced. In addition, different types of geometry profiles made with welding and joining had undergone laboratory testing to determine their performances. Finally, composites were used to replace the metal counterparts in order to achieve an optimum performance.

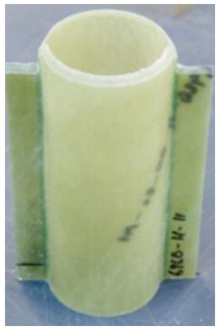


Fig. 6. Final tube specimen for crush device [27].

4. Review of previous research on crashworthiness of automotive crash boxes

Ma et al. [28] carried out a research on vehicle collision via finite element analysis method. This study aimed to provide the reference for bumper impact study. The research will start by building the CAE model as shown in Figure 7, the model used to evaluate and predict the best performance of collision resistance for crash box structure. The simulation performed by using LS-Dyna and Hypermesh software. They made four conclusions after analyzing the simulation results, which is a better safety performance acquires from small acceleration of bumper collision. The second conclusion is that the maximum safety is obtained if crash box able to absorb maximum energy during collision. Next conclusion based on the simulation result which is, the heavier and thicker the structure, the better performance of crash box in term of energy absorption. Final conclusion is, improving the balance point, improves the performance safety.

An initiative had been taken to focus on optimum cross sectional shape of a crash box [29]. New crash box design as shown in Figure 8 was proposed after clarifying the influence of cross sectional profile on the energy absorption during the collision.

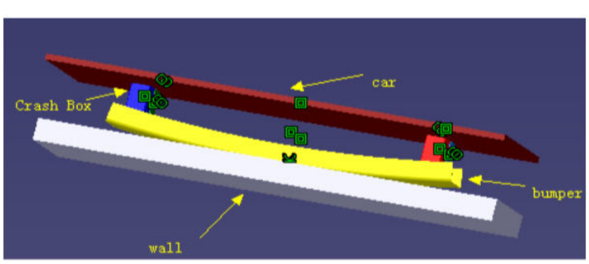


Fig. 7. 3D models for collision system [28].

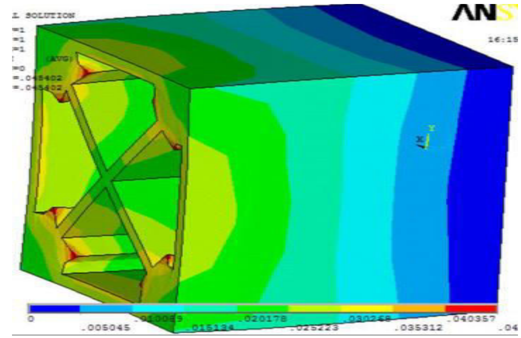


Fig. 8. Proposed new crash box profile [29].

This design ensures high capability for energy absorption without crash bead. This studies applied finite element method to clarify which body part absorbs crash energy in axial collapse. Then, the impact of cross sectional profile of the part on energy absorption was quantitatively discovered. A few materials selected to develop the crash box structure such as combination of (aluminum + magnesium + silicon) and (aluminum + zinc + magnesium).

The comparison of results of absorbed energy value during the impact between deformation and stress for three models of crash box is shown in Figure 9. The researcher employed mathematical optimization by altering the geometry, material and structural properties of the bumper beam and crash box to improve safety performance at lower speed during impact [30]. Profile and dimensions of the crash box were obtained from repeated simulations and continuous enhancements. Figure 9 shows three models (labels by M1, M2 and M3) geometric solutions for impact energy management system. They concluded that a better behavior of the structure is possible when it is subjected to similar stress to those that occur in a frontal impact. The model enhancement in this stage was obtained by selecting the measure to increase the cross-section of the front frame rail of crash boxes, by the relative disposition of the vehicle body block so that its center of gravity to be at a usual distance above the assembly and by choosing the front frame rail's curvature radius from the frontal part to the cockpit.

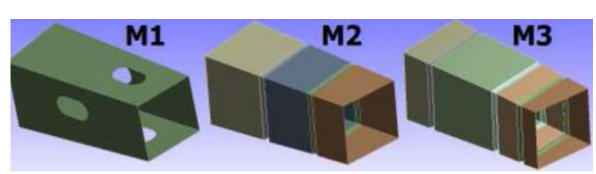


Fig. 9. Isometric view of the three model geometric solutions for impact energy management system [30].

They also concluded that, the model labeled by M2 has the higher strain in shortest deformation time, resulting minimum transmitted energy to other body parts or passenger compartment.
A study is concerned with the performance of rectangular cross-section crash box in the vehicle crash worthiness applications, the behavior of the crash box at various velocities and how absorption energy varies by increasing crash box wall thickness [31]. Figure 10 illustrates crash box profile component design by CATIA and rigid wall created using Hypermesh. They carried out study for three cases, each case has three different material models, different velocities and different wall thickness. They found that the total kinetic energy absorption during collision is directly proportional to the product of force and deformation.

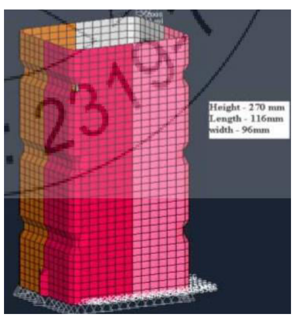


Fig. 10. Geometric model and meshed model of a crash box [31].

From the values presented in Table 1, the data depicted increasing of wall thickness will rise the capability of crash box to absorb energy by using equal force at loading point.

Table 1. Tabulated values of wall thickness against energy absorbed [31].

Wall thickness (mm)	Energy absorbed (Nm)	Energy at loading point (Nm)
2	9000	27775
4	25000	27775

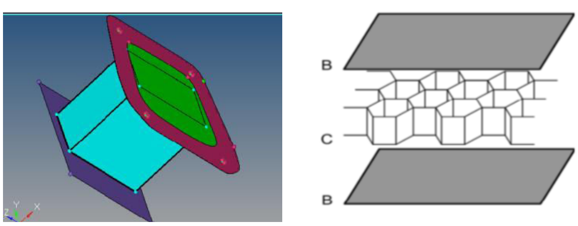
Finally, they concluded that the higher the velocity, the higher will be the energy absorption and the energy transferred at faster rates to other parts of the car. Moreover, Biradar and Babu [31] mentioned on the aluminum foam used in this study is a versatile and cost effective material. Furthermore, aluminum have high mechanical energy absorption in all direction, excellent strength and stiffness to weight ratio, constant properties over temperature and moisture range and recyclable. However, they also proposed fiber reinforced composite as an excellent alternative material with tremendous performance such as high stiffness to weigh ratio, corrosion resistance, fatigue resistance and strength to weigh ratio which is very attractive in crashworthiness.
Tanlak and Sonmez [32] conducted a study on crash box shape optimization under axial impact load to maximize crashworthiness. Design variables such as parameters defining the cross-sectional profile of the tube as well as parameters defining the longitudinal profile like the depths and lengths of the circumferential ribs and the taper angle are used. Unacceptable low specific energy value obtain since the deformation variance is minimized. They concluded to minimize the jerk effect, the profile must be larger taper angle and deeper circumferential ribs. Another conclusion is, different optimal shape is obtained by choosing different value for the factor of weighting, and the variance of crash box thickness will improve the crashworthiness.
In the above review of the literature, few types of computer-aided engineering (CAE) software packages were used to validate the models of crash box in order to investigate the crashworthiness behavior. Design parameters needed to acquire high mechanical energy absorption was also discussed.

5. Review of previous research on energy absorption capabilities of automotive crash boxes

Work published by Kumar and Vitala [33] was conducted with the aims to review all related literature works about energy absorbing structure and energy absorbers analysis. The study discussed specific energy absorption, measured mean crush load as an indicator of absorbing energy capability, and introduced the polymeric foam as a material in the energy absorption and impact application. Figure 11 shows four experimental specimens of empty and filled concentric tubes consisted of 2 materials, aluminum 6063 T6 and polyurethane foam. They concluded that the main finding from the past research on energy absorption was that FEA was a common tool for the researchers to study the structural responses. In addition, most of the information relates to axial quasi static or dynamic impact loading with circular tube and rectangular geometry was selected as geometry for crash box.
Another study was done to discover optimum cross sectional shape of a crash box to ensure high capability for energy absorption with the use of finite element analysis (FEA) [34].

Fig. 11. Experimental specimen of empty and filled concentric tubes [33].

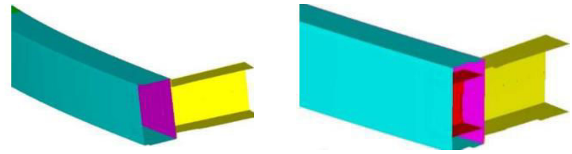
Two designs were proposed and analyzed. Figure 12 (a) shows a crash box rectangular model and Figure 12 (b) shows a honeycomb model. Referring to the analysis results, it was concluded the optimized profile for crash box was honeycomb structure. The benefit of honeycomb structure profile compared to rectangular cross sectional was that honeycomb structure offers a compressed panel with minimal weight and excellent rigidity. Moreover, the comportment of the structure is orthotropic. Therefore, the panels were acting differently in different orientations. Finally, they reached optimization by using very low amount of material. Hence, they provide lightweight structure with minimum cost.



(a) Rectangular model (b) Honeycomb model

Fig. 12. Two proposed CAD model for crash box [34].

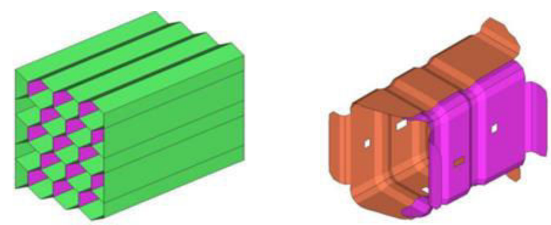
Furthermore, another study focused on design enhancements in vehicle frontal protection by various techniques that can absorb more kinetic energy during collision [35]. Finding from this study was that, bumper beam was improved by implementing axial tube inside it, exactly in front of the crash box and overall length of crash box was increased as shown in Figure 13. Therefore, it absorbs more crash energy and lesser the damage to the occupant and vehicle. The researchers suggested the use of honeycomb model structure for the crash box to replace the conventional structure. Hussain [36] investigated how to increase the energy absorption during collision as well as to reduce the weight. Aluminum honeycomb structure as shown in Figure 14 (a) was selected as a design for crash box and the results obtained from this study was compared with the conventional steel crash box as shown in Figure 14 (b).



(a) Original section of bumper beam (b) Cut section of axial tube results

Fig. 13. Comparison of original and enhancement of bumper beam [35].

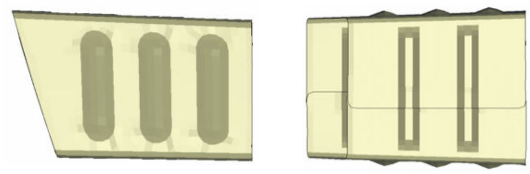
Finding from this study was that the amount of energy absorbed for crash box using aluminum honeycomb was increased by 28% if compared with conventional steel crash box. Another conclusion was that, during low speed crash test, less amount of component failure occurred due to permanent damage for crash box using honeycomb aluminum structure compared with conventional steel crash box.



(a) Honeycomb crash box (b) Steel crash box

Fig. 14. Conventional steel crash box and honeycomb crash box [36].

Furthermore, a study was conducted to investigate the optimize geometry of crash box due to impact at low velocity collision [37]. The aim for this study was to minimize the weight of the crash-box subjected to double deformation constraints and the supreme plastic strain constraint in the crash-rail behind the crash-box was inadequate. This study was using Finite element simulator in LS-OPT software to figure out the best geometry based on variables such as material thickness, length of crash box, width of crash box and height of the front of crash box. The 12 FE simulations were run to complete five major iterations using LS-OPT interface. Throughout the optimization procedure, the crash-rail had to be reinforced using an additional part in the weak section of the crash structure. Hence no solution fulfilled all the constraints was established. Nevertheless, LS-OPT reduced the weight of the component for 20 % as well as reduced the sum time of all constraint violations with 50 %. After five iterations, only crash box plastic strains were violated, and the optimal crash box geometry solution is shown in Figure 15.



(a) Top view (b) Left view

Fig. 15. The geometry of the crash-box in the optimal design point. Top and left views [37].

Ahmet et al. [38] studied another method in improving the performance of energy absorption for crash box. The study used of aluminum foam as a main material for telescopic crash box geometry design as shown in Figure 16. They concluded, telescopic crash box geometry aluminum foam filled will absorb kinetic energy 47% higher than empty geometry. Another conclusion was, filling the box with aluminum foam can be preferable to thickening the wall.

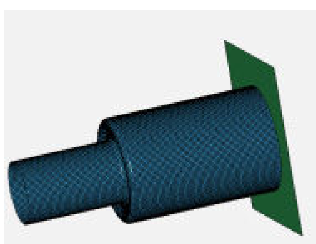


Fig. 16: Telescopic crash box geometry [38].

Choiron et al. [39] studied the crush box with multi segments design as well as the deformation behavior and crash energy absorption. Cylindrical profile was selected as crash box structure with multi segment design and the model was performed by finite element analysis. Three major segments in this study were crash box with two segment design, crash box with sequence diameter of three segment and three segment crash box with alternating diameter as shown in Figure 17.

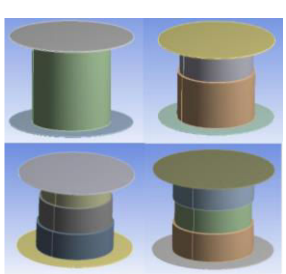


Fig. 17. Crash box model: 1 segment, 2 segments, 3 segments (type 1) and 3 segments (type 2) [39].

This crash box designs were made by using aluminum alloy as a material which box length of 100 mm and velocity speed for the crash test was 16 km/h. Crash box was designed as bilinear isotropic hardening. Test results found that crash box with two segment and three segments have minor increasing of energy absorbed. The supreme increasing in energy absorbed was happened in central of crash for multi segments model. Distortion has begun at the first segment, then extend penetrated to the second segment with identical deformation pattern. The conclusion made for this study is, the deformation of crash box in multi-segments crash box design with alternating diameter has better ability to absorb energy. Buckling phenomenon was arisen in three segments crash box design with sequence diameter model and has translated the cause of decreasing of energy absorbed.

Meanwhile a study was conducted to address a general review or summary in the field of energy absorbers for the crash box device that are used to lessen impact during collisions [40]. This paper highlighted the outcome related to tubular structure as energy absorber over the years published by researchers and engineers. Finding from this study is, comparison made for two materials, which is aluminum and steel, the results shows that the aluminum effectively absorbs more energy per unit weight. Another finding is, only the rectangular profile significantly less sensitive for variations in the load direction particularly in a lying orientation. To increase the absorption of energy, the width and thickness of the tube must be increase accordingly, but the study related to varying thickness rectangular tube are very less done by the researchers. The tubes folding during the impact shows in the Figure 18, the folding pattern during the crush defines efficiency of energy absorption used in crashworthiness design. The conclusions made for this review paper is, multi cell thin walled have better performance in energy absorption during collision as compared with single thin walled crash box.

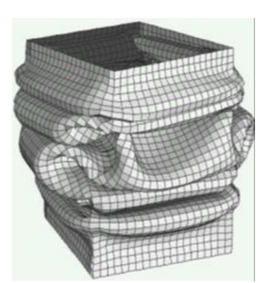


Fig. 18. Folding of tubes during impact [40].

Most of the researcher study crash box based on an axial loading and uniform thickness cross section but very less researcher investigate and published the results for oblique load directions. Subsequently, a study was conducted by Hassin et al. [41] to investigate the characteristics of the reverted joints of automotive crash box numerically and experimentally. This study was divided into two step which is developed initial finite elements model of the reverted joints structure and simulate using ABAQUS. Figure 19 shows the reverted meshing model used to setup the crush simulation. Thin aluminum metal sheet was fabricated as crash box structure with two hat shape components. The reference point on the top plate area received impact load during crush test simulation. For this model, five reverted joints were used to assemble the crash box, while other parameters were used as a boundary condition for this simulation. Finding from this study is, all aspects starting from modeling the components and correctly keying in the data improved the Finite elements analysis data accuracy compared with experimental data. They concluded, both experiment and crush simulation produced good agreements. Nevertheless, in order to minimize errors between finite element and measured data the model updating method must applied.

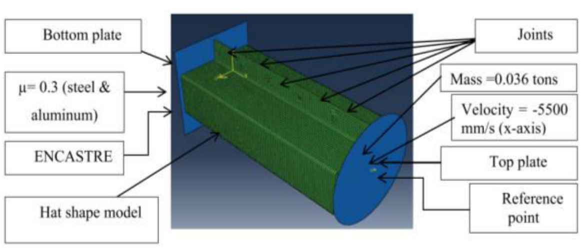


Fig. 19. Assemble of hat shape crash [41].

Another research carried out for crash box discussed the energy absorption for crash box [42]. Performances for crash box were studied based on design of experiments using Minitab 17. Width, thickness and taper area are variables used to analyze the characteristics of crash box crushing behavior.

Figure 20 presents four proposed design models used to find the optimization of energy absorption. Design A1 came with beads on one pair of opposite faces, design B1 had a continuous bead along parameter, design D1 have all small beads inside and design G1, all small beads inside with eight sides. Table 2 depicts results of crush test, the highest mean crushing load obtained by G1 design while D1 design offered lowest mean crushing load.

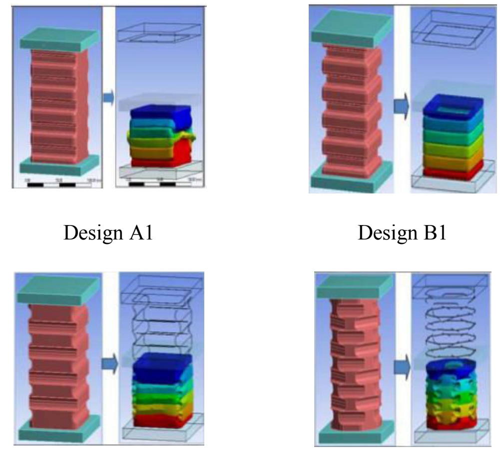


Fig. 20. Analysis of crash box design using various beads [42].

Table 2. Crush test results for Design A1, Design B1, Design D1 and Design G1.

Design	Mean crushing load (kN)	Energy absorbed (J)	Critical Buckling load (kN)	Lowest crushing load (kN)
A1	37.1292	2505.36	59.025	18.266
B1	37.178	2430.57	62.026	18.025
D1	36.009	2402.615	42.125	30.125
G1	37.442	2537.93	40.489	33.265

Design G1 has highest energy absorption while D1 design is the lowest followed by design B1 and A1. Design G1 had 35% less buckling effect compared with the highest buckling effect design which is B1. They concluded, design G1 is the best design in all circumstance. Another conclusion is, numerous bead positions applied showed a very good influence on the energy absorption. Increasing the thickness and reducing the taper angle will increase the absorb energy in crash box. Guillon et al. [43] designed a cone shape crash box with total axial symmetry using carbon fiber reinforced polymer (CFRP) composite materials as shown in Figure 21. This part went through reactive resin transfer moulding RTM process which established for years as state of the art production process for high quality and performance parts. This process used highly reactive epoxy resin systems allowing 2 to 5 minutes total cycle with opening and loading/removing of parts. Besides producing high performance crash box with high energy absorption, this process is recognized as an economical process which can produce more than one thousand parts for each cycle.

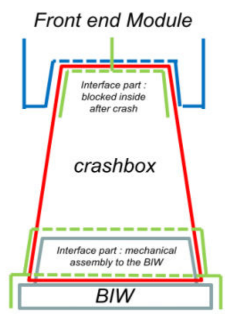


Fig. 21. Cone shape crash box [43].

To validate the design performances, crushing tests were carried out by using a drop-weight tower. A 319 kg mass fall from a height up to 3.4 m for a maximum energy of 10650 J. Conical crash box is fitted on a fixture representative of the patented automotive solution. They conclude that selection of CFRP materials is a right decision based on two reasons. First, it's allowing fast industrial implementation with braiding and RTM are proven process. Besides that, fast cure RTM epoxy systems are suitable for mass production. In addition, crash performance of composite has been proven for years in sport car design.

Zarei and Kroege [44] investigated energy absorption capabilities by using composite crash absorber elements. Square and hexagonal profile crash boxes performed axial impact test to examine the energy absorption. The rapid crash load is analogous to the instantaneous crash displacement. Therefore, area under the crash load-displacement curve provided the value of crash absorb energy for square composite tubes as shown in Figure 22 and hexagonal composite tubes as shown in Figure 23. Both specimen profiles were created using similar dimensions and similar material which is aluminum and composite. Referring to the results test and comparison between data experiments and simulations in Figures 22 and 23, they concluded that aluminum crash boxes which are crushed in a progressive buckling manner, whereas the composite tubes are crushed in a progressive destructive manner. In addition, comparison made for crushing behavior between composite and aluminum crash box indicated that the composite crash box able to absorbs 17 percent more impact energy than aluminum equal to 27 percent higher specific energy absorption SEA.

Maddever and Guinehut [45] conducted a study to design crash box using aluminum foam, the main objective is to investigate potential of aluminum foam to absorb kinetic energy during collision.

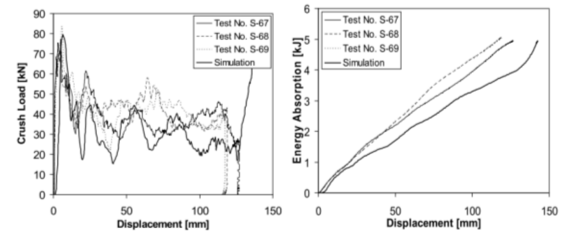


Fig. 22. Comparison between experimental and numerical crush load- displacement curves (left) and energy absorption-displacement curves (right) of square composite tubes [44].

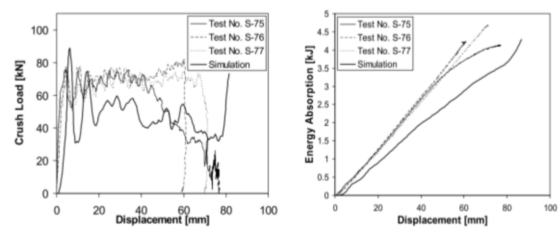


Fig. 23: Comparison between experimental and numerical crush load-displacement curves (left) and energy absorption-displacement curves (right) of hexagonal composite tubes [44].

The automotive designers show interest on this material due to its extreme lightweight properties approximately from 0.3 g/cm^3 to 0.5 g/cm^3 only. This paper also described how the aluminum foam use as stabilized produced by the melt method obtain from metal matrix composite (MMC). This crash box performance was compared with same extrusion existing hollow aluminum crash box. The data recorded including energy absorption per unit mass and per unit length. The results specified significant improvement in energy absorption using aluminum form with reducing crash box length at the front-end of crash box applications.

Davoodi et al. [46] carried out research on how car bumper beam can improve structural energy absorption. The study goals to select the best geometrical bumper beam profile to fulfill the safety parameters of the defined product design specification (PDS). TOPSIS method was implemented to select the best car bumper beam design concept. The study found that high strength sheet molding compound material (SMC) able to replace common bumper beam from glass mat reinforced thermoplastics material (GMT). They are also removing strengthen rib and reduce 2.5 mm of material thickness in order to increase flexibility of 5% deflection and meet the cost reduction criteria. They concluded, SMC material properties did not completely fulfill the common bumper beam material GMT. Therefore, the geometric concept evaluation is examined to improve structural energy absorption and deformation besides other criteria in the car bumper beam development.

Yang [47] developed a new method in designing a crash box which is put forward coupling design under the constraint of styling. In this approach, crash box section force target to reduce its energy absorption ratio while the design parameters were also deduced. Hence, the compatibility between the aesthetics outlook and crash box performance can be evaluated during the early phase of the car's development. The work also presented the results verification of effectiveness and feasibility study for this method. Table 3 illustrates the crush force of the gauge with 2.2 mm thickness. Table 4 describes the types of material listed on Table 3.

Table 3. The crush force of the gauge with 2.2 mm thickness [47].

No	t /mm	a /mm	d /mm	Material	Area (mm)²	F /KN
1	2.2	50	100	H220BD	640.64	54.32
2	2.2	55	105		684.64	55.21
3	2.2	60	110		728.64	56.05
4	2.2	65	115		772.64	56.86
5	2.2	50	100	SPHD	640.64	56.1
6	2.2	55	105		684.64	57.01
7	2.2	60	110		728.64	57.88
8	2.2	65	115		772.64	58.72
9	2.2	50	100	H340LAD	640.64	76.71
10	2.2	55	105		684.64	77.96
11	2.2	60	110		728.64	79.15
12	2.2	65	115		772.64	80.29
13	2.2	50	100	HC420LA	640.64	93.98
14	2.2	55	105		684.64	95.5
15	2.2	60	110		728.64	96.96
16	2.2	65	115		772.64	98.36

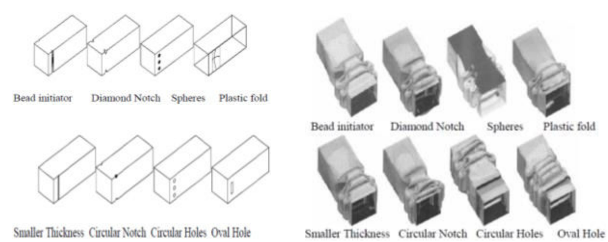
t – thickness; a – width; d – length; F – crush force.

Table 4. Material description [47].

Material	Description
H220BD	Hot Dipped Galvanized steel under the standard; Q/BQB 420-2003 and it is a kind of bake hardening of high strength steel
SPHD	Steel plate/sheet as stamping and cold forming steels Under standard JIS G3131
H340LAD	Hot dipped galvanized steel under the standard Q/BQB 420-2003 and it is a kind of high strength cold-rolled steel.
HC420LA	Micro-alloyed steel grades with high yield strength for cold forming

Results indicated the crush force increase parallel with increasing of crash box length. Based on CAE results, crash force must be greater than 54.1 kN for the crash box to achieve 45% to 50% energy absorption. Therefore, they concluded that this method is effective in absorbing force energy during impact by comparing CAE and test results.

Kumar et al. [48] carried out investigation for crash box using simulations for different segment car using LS-DYNA. In this study, development process to improve the energy absorption is proposed in two steps. Its start with study the crash box behavior using numerical analysis and experimental test. Then, the study continues with adding reinforcement to the crash box at the critical area to acquire the best crash box design. Figure 24 illustrates the results of impact test for this study. The picture clearly indicate crash box with notches on the corner, the circular hole and the oval hole profiles are not stable. This design produces weak corner area with reduce the stiffness then produce rotation and translation of the whole cross section. They concluded that the bead initiator is the most stable and preferable design which produce the most effective energy absorption device with axial collapse behavior.



(a) (b)

Fig. 24. (a) Crash box concept design and (b) impact test results for the specimen of the crash box concept design [48].

Boria and Forasassi [49] presented the results of a study on a frontal energy absorber for racing car prototype made of fiber reinforced composite materials. Figure 25 presents the crash box profile design, the pyramidal shape provided more stability to the device structure during the progressive crushing, while the bass employed by the rectangular section with rounded edges to avoid stress concentrations. They concluded, this design profile with 15 mm thickness and [0°/45°] 5s orientation is the best design configuration as energy absorbers.

Ghasemnejad et al. [50] investigated the performances of thin wall aluminum alloy (6060 temper T4) tube used as crash boxes.

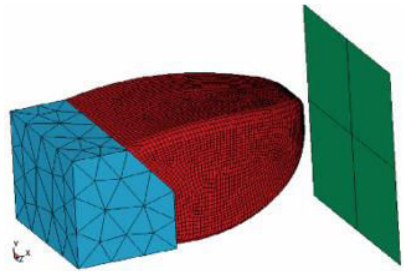


Fig. 25: Detail of the crash box finite element model [49].

At the end, the optimized energy absorbers were produced from numerous cross section of crash box and the model specimen has been tested under dynamic impact test. From the results collected, graph plotted base on dynamic crushing load against crushing distance to investigate the crush force efficiency and the specific energy absorption to various crash boxes. The comparison results between experimental and numerical method leads them to produce the most efficient square profile crash box design.

Stein et al. [51] used three various formulations at the preliminary phase of the product development process to predict the best crash box configuration structure. The device was designed to enhance the automotive passive safety requirements. All three structures for frontal impact are using similar modelling approach in order to define an implicit parameter before enhance the crash box design. At the end, all three simplified model was combined to become one common full implicit parametric crash box model. They concluded, this research successfully optimized the designed crash management systems and the models shows a good correlation with existing crash box model.

The procedure how to enhance the energy absorber for crash boxes was propose by Lee at el. [52]. The proposed procedures consist of two steps which is parameters study using discrete design with orthogonal array to select the best cross sectional dimensions. The second procedure is using topology optimization to maximize the absorbed strain energy. Figure 26 illustrates the Model M1, M2 and M3 profiles before and after the crash. Figure 26 (a) specifies the side rail and crash box. The model on the left shows the crash box before collision while the right side illustrates the deformation shapes of Model M1, M2 and M3 after the collision. The side rail is isolated for clarity of the deformed shape in Figure 26(b) and 26(c). They concluded, by using discrete design with orthogonal array method, three cross sectional model M1, M2 and M3 have high energy absorption capability and light mass.

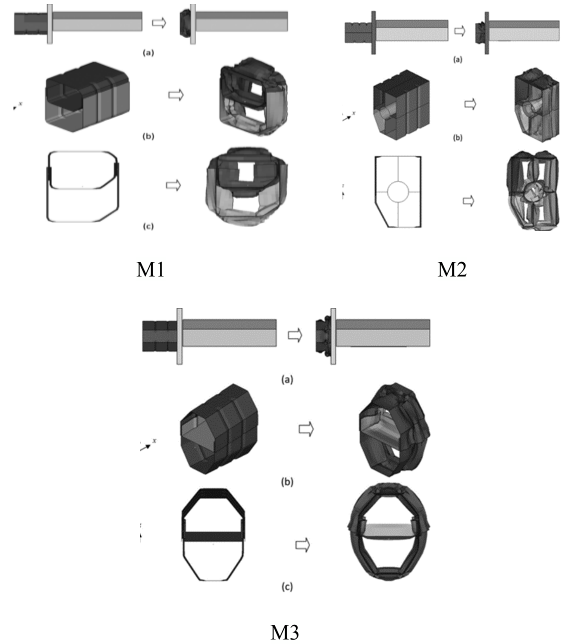


Fig. 26. The deformation shapes of Models M1, M2 and M3 before and after the crash: (a) side view, (b) isometric view, (c) front view [52].

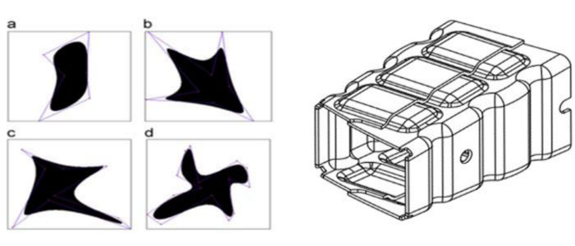
Kim et al. [53] used basic cross section profile such as rectangle, hexagon and octagon to investigate the crashworthiness of an aluminum crash box. The examined profile was simulated using numerical software to predict the energy absorption capacity and mean load value. Then, the sample profile was fabricated to perform the simple axial crush tested. From the data results collected, they found that the hexagon profile absorbs higher energy capacity and the mean load. Finally, the simple crush system consist of crash box specimen was assemble with bumper, front side members and a sub frame to representing a full car crush protection. From the analysis results, they concluded the best performance crash box come from rectangular cross section profile which collapse preceding to the front side member, and the verification test results from numerical simulations shows the close tendency deformation shape with experimental results.

Kim [54] used aluminum carbon fiber reinforced polymer Al/CFRP square hollow cross section profile to investigate crashworthiness and axial collapse with destruction dissemination behavior under dynamic axial crushing load for crash box application. Two different laminate thickness of crash box coat with five different lay-up sequences was tested under low speed impact test referred to The Resource Conservation and Recovery Act (RCRA) regulation.

Results analysis shows that the specific energy absorbed SEA and crush force efficiency were improved instantaneously in rage of 30% to 38% for material hybrid casting joining technology which is aluminum carbon fiber reinforced polymer (Al/CFRP) hybrid square hollow section SHS beam. The second lay-up sequence [0°/90°] were marginally improved by increase the thickness of the aluminum carbon fiber reinforced polymer laminate.

Yaghoubi et al. [55] studied on steel front bumper crush can (FBCC), they present the experiment procedure for frontal impact assembly subjected to a rigid full and 40% offset impact. All the equipment and standard operation procedures explicitly explain to evaluate the crash box performances. Based on the data collected, they compare the results between the deformation of velocities time histories from video tracking with accelerometers. Both of the data shows a good agreement and have a good correlation. Heat was created and dissipated at the can tip and additional heating was detected as the can continue to fold.

Ambrozinski et al. [56] studied multiscale simulations of the crash box to improve safety features for passengers, used in automotive industry. They are applied statistically similar representative volume element (SSRVE) together with conventional representative volume element (RVE) in order to shortage iteration computational time. The qualitative results were analyzed and safety solutions proposed offers better properties for the final product with rational computational time.



(a) (b)

Fig. 27. (a) Similar representative volume element (SSRVE); (b) crash box profile from stamping process [56].

Figure 27(a) illustrates similar representative volume element (SSRVE) segmentation used to proposed final crash box design while Figure 27(b) shows a final product design for crash box produced using stamping process. The device fabricated using multi-phase steel and it composed two asymmetric part joined together, which able to absorb high kinetics energy during collision. Hence, to ensure the occupant safety inside a car frame.

Kavi et al. [57] studied energy absorption in a foam filled thin walled circular aluminum tube as shown in Figure 28. The specimen was tested experimentally to determine the strength coefficient of structure filling using aluminum polystyrene closed cell foam with three different densities. Regardless the foam type and density used, foam filling was found to change the deformation mode of tube from diamond (empty tube) into concertina. From the experimental data results analysis, the foam filling has higher energy absorption if compared with tube or foam alone. In addition, they said that it was not effective to increase the device wall thickness to acquire high energy absorption. The proper approach is, an appropriate tube foam combine must be selected by considering the amount of strengthening coefficient of foam filling and the plateau load of foam filler.

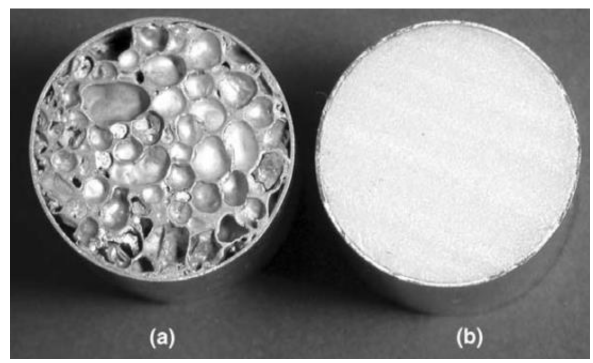


Fig. 28. Specimen of (a) aluminum and (b) polystyrene foam filled aluminum tubes [57].

Toksoy and Güden [58] studied energy absorption characteristics for partially aluminum closed-cell foam filled commercial 1050H14. Two different sizes and three different thickness of crash box profile which is determined at quasi-static and dynamic deformation velocities was simulated using the LS-DYNA software to clarify the deformation process. Then, the specimen was test under dynamic crush test to validate the specific energy absorption SEA values of empty, partially and fully foam filled crash boxes as shown in Figure 29. The results in Figure 29 depicts that empty boxes were actively more efficient than fully and partially foam filled boxes until almost reaching critical foam relative density. However partial foam filling was the most efficient at increasing box wall thicknesses at relatively high foam filler densities. In compare with fully foam filling, the critical foam density for efficient partial foam filling decreased with increase in box wall thickness.

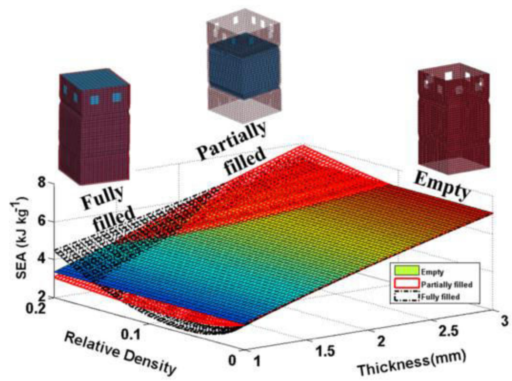


Fig. 29. Partially aluminum closed-cell foam filled commercial 1050H14 [58].

Zarei et al. [59] investigated the thermoplastics composite crash box behavior. Thermoforming and welding are selected as an approach method to fabricate the crash box specimen. They are using method of multi design optimization MDO to create an optimum composite crash box to absorb most kinetics energy and produce lightweight device. LS DYNA software choose to simulate the crush process, data collected were analyzed to understand more regards to the crush test behavior. Then, the research process followed by dynamic crush test to verified the prediction performance. They concluded, the tubes are crushed in progressive manner initiate from one end of the tubes, then continued by delamination which is mode of failure for composite materials between the layers.

From the above review of the literature, it is postulated that different types of materials were selected in a crash box structures and several testing related to this process such as impact testing, and testing related to the mean crush load were used as indicators to measure the energy absorbing capability. Moreover, comparison of the results of simulation of the impact test results, using honeycomb with other profiles, the lightweight honeycomb structure absorbed more kinetic energy during collision compared with other profiles. Besides, enhancement of bumper beam in front of crash box also improved the crash box performances. Furthermore, this section also reviews the comparison of aluminum and steel in cylindrical profiles and it is observed aluminum profiles effectively absorbed more energy per unit weight compared with steel counterpart. Another researcher presented that composite materials was the best choice for a crash box. Another review shows that the percentage of energy absorption for composite crash box is higher than crash box with aluminum.

6. Conclusions

Based on previous research, the important findings are:

1. In the past, many researchers used FEA method with different software packages to analyze the impact behavior during crash and how the device responded to the energy absorption. Moreover, various types of materials had been used in crash box structures in order to obtain high energy absorption. Composite materials such as PEEK based composites, E-glass reinforced polyethylene terephthalate composites carbon fiber reinforced composites as depicted in this paper are potential options to replace the traditional crash box structures materials notably aluminum and steel. The comparison of impact test results illustrated that crash boxes made from composites were able to absorb more impact energy compared to aluminum. However, so far, none of the previous researchers used natural fiber reinforced polymer composites as materials for crash box structures. It is strongly believed that the selection of natural fiber composites in a crash box structures can offer several advantages such as low density, lower manufacturing cost, lower pollution level during production comparable specific tensile and flexural properties to carbon fiber composites and they could provide more values to the crash boxes in addition to better energy absorption performance.
2. Researchers had used different methods to determine the optimum or the highest energy absorption during quasi statics and dynamic impact tests via variety of geometric profiles and material types. Honeycomb profile was proposed as the best energy absorption structure and aluminum was the best material to absorb energy during collision. However, honeycomb composite profile structure only went through simulation analysis but it was still not proven experimentally. There was still no solid laboratory testing data to support the simulation work. In addition, no evidence from any manufacturers all around the world that prefers to replace the current shape of crash box to honeycomb profile structure.

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