An Overview on Impact Behaviour and Energy Absorption of Collapsible Metallic and Non-Metallic Energy Absorbers used in Automotive Applications

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Abstract. Collapsible impact energy absorbers play an important role of protecting automotive components from damage during collision. Collision of the two objects results into the damage to one or both of them. Damage may be in the form of crack, fracture and scratch. Designers must know about how the material and object behave under impact event. Owing to above reasons different types of collapsible impact energy absorbers are developed. In the past different studies were undertaken to improve such collapsible impact energy absorbers. This article highlights such studies on common shapes of collapsible impact energy absorber and their impact behaviour under the axial compression. The literature based on studies and analyses of effects of different geometrical parameters on the crushing behaviour of impact energy absorbers is presented in detail. The energy absorber can be of different shape such as circular tube, square tube, and frustums of cone and pyramids. The crushing behaviour of energy absorbers includes studies on crushing mechanics, modes of deformation, energy absorbing capacity, effect on peak and mean crushing load. In this work efforts are made to cover major outcomes from past studies on such behavioural parameters. Even though the major literature reviewed is related to metallic energy absorbers, emphasis is also laid on covering literature on use of composite tube, fiber metal lamination (FML) member, honeycomb plate and functionally graded thickness (FGT) tube as a collapsible impact energy absorber.

1. Introduction
Automobiles are the basic needs in the human society nowadays, so safety of the passengers plays an important role in the automobile industries. Safety of the passengers is getting major concern which forces the automobile industry to improve automobile design. Advancement in automotive design and highways have succeeded in reducing the death and injuries in all countries but still the auto collision is the leading reason for the car accidents. As per the report of The National Highway Traffic Safety Administration (NHTSA), USA have published that 30,800 deaths and over 2,362,000 injuries recorded in year of 2012 due to vehicle crashes in the USA [1]. Road accidents are globally recognized as serious public health problem but the problem is more serious in India. As per the road accidents report for year 2014 and 2015, in India close to 5,00,000 road accident caused nearly 1,46,000 deaths and left thrice that injured. Detailed figures of comparative scenario for year 2014 and 2015 are given in table 1 which shows severity of the road accidents and required need of the attention to address this problem in India [2]. The main reason for the accident is frontal car collision hence...
more prominence needs to be given for developing vehicles with higher crashworthiness. Recent fatality analysis reporting system [1] data indicated that, despite refinements in seat belts and air bag technology, restrained occupant fatalities persist in frontal impacts. Therefore automobiles in India need to be designed and developed for higher crashworthiness. This requires use of some innovative technology for improving the efficiency of vehicle crash tubes with minimum weight to the structure of automobiles. This can be only achieved by use of proper material and some innovative design.

Table 1. Road accidents during year 2014 and 2015 in India [2].

| Parameter                        | 2014     | 2015     | % change over previous year |
|----------------------------------|----------|----------|-----------------------------|
| Total Accidents in the country   | 4,89,400 | 5,01,423 | 2.5                         |
| Total number of Persons death    | 1,39,671 | 1,46,133 | 4.6                         |
| Total number of Persons injured  | 4,93,474 | 5,00,279 | 1.4                         |
| Accident Severity*               | 28.5     | 29.1     | 2.1                         |

Steel is being used extensively in the energy absorber due to its lower price and high ductility properties. Reductions in vehicle weight is necessary to increase vehicle fuel economy and emission so there is continuously growing swing to substitute conventional steel by Aluminum (Al.) and Magnesium (Mg.) alloy due to their low weight and good mechanical properties [3]. There are some reports have published on substandard crashworthiness performance of light weight vehicle [4,5]. M. Ross and T. Wenzel [6] explored that how vehicle weight plays essential role in fatalities in road accidents and use of new technology to reduce weight without playing with the vehicle size for safety of occupant is the possibility to decrease rate of fatalities in accidents. Insurance Institute for Highway Safety had brought the attention on the poor crashworthiness of the light weight vehicle by publishing the result of head-on collision between a midsized Toyota Carmy and subcompact Yaris [7].

This paper describes the concept of crashworthiness and impact mechanics of the energy absorber in detail. Also, it covers the review of literature on the effect of different geometrical parameters on crushing mechanics, modes of deformation, energy absorbing capacity, effect on peak and mean crushing load of thin-walled tubes.

2. Crashworthiness and Impact mechanics

2.1. Crashworthiness
Crashworthiness is the capability of the vehicle structure and its components to withstand and protect the occupants without any serious injury and death in case of crash. Nowadays it has become integral part of design of vehicles. In automobiles the structure should be capable of absorbing the maximum impact energy with less damage to structure, or injury to the passenger [8].

2.2. Mechanics of impact
The dynamic plastic deformation of the collapsible structure is more difficult to understand than the corresponding quasi-static deformation of the structure. The response of the structure which is subjected to dynamic loading is different from the structure under a quasi-static loading. It happens due to two basic physical phenomena known as inertia effect and strain rate effect. The dynamic plastic collapse. These two physical phenomena influence the energy absorption capacity and crush response of thin walled energy structure [9].

2.2.1. Inertia Effect
The thin-walled tube subjected to quasi-static loading, the rate of applied speed is sufficiently slow so that inertia effects have no influence on the crush response of structure whereas same tube is subjected to dynamic axial loading then inertia effect will influence the crush response. The final shape of the deformation depends on the loading of structure i.e. whether it is subjected to
quasi-static or dynamic axial loading. The deformation shape of the thin-walled circular tube under quasi-static and dynamic axial loading is shown in figure 1 [9]. Generally, quasi-static progressive buckling develops due to the low velocity impact whereas dynamic progressive buckling develops due to the high velocity impact [10].

![Deformation Shape of Thin-Walled Circular Tube](image1)

**Figure 1.** Final deformation shape of circular tube [9].

Calladine and English [11] studied two types of structure which absorb the energy through plastic deformation. They characterized these structure by the shape of their static load-deflection curve. Type I had a relatively "flat topped" static load-deflection curve, while Type II had a "steeply falling" curve with initial peak load as shown in figure 2. It was observed from their study that Type II structure is more sensitive to impact velocity than that of Type I structure.

![Types of Structures](image2)

**Figure 2.** Type of structures [11].

Reid and Reddy investigated experimentally [12] the inertia effect in one-dimensional arrays of laterally compressed tube. It was observed in their study that plastic deformation is concentrated at rings in the impacted side of the array. Furthermore, Initial buckling of the thin-walled tube is controlled by the axial stress wave propagation through the length of tube [13]. This stress wave was determined by the inertia characteristic and material properties of the tube. Karagiozova and Jones [13] also found that lateral inertia effect influences the energy absorption capacity and crush distance in square tubes. Harrigan *et al.* [14] studied the inertia effect of energy absorbing material like honeycomb and inversion tube structure experimentally and numerically. They found that inertia force tends to minimize crushing load with increase in inversion velocity.

### 2.2.2. Strain rate sensitivity

Material properties under dynamic loading are different from corresponding quasi-static property values [15]. The stress-strain behavior of material is sensitive to the loading rate [16]. According to Lu and Yu [8], plastic flow of various material is sensitive to strain rate so that yield stress may increase with increase in strain rate. The structure gets strengthen as increase in strain rate which is undesirable for energy absorbers used to enhance crashworthiness of vehicle [15]. It was noticed that influence of the material strain sensitivity exercises the important effect on the structure response so it should be taken into account for strain rate sensitive material [9]. Abramowicz and Jones [17] developed the equation of average strain rate which shown in table 2.
However, the Cowper-Symonds relation [18], which requires only two constants from experimental tests on given material. This equation is used extensively in theoretical and numerical studies [19].

**Table 2. Equation for average strain rate [17].**

| Mode of deformation | Equation | Equation No. |
|---------------------|----------|--------------|
| a Concertina mode   | $\varepsilon = \frac{V}{2D \left\{ 0.86 - 0.568 \frac{L}{D} \right\}}$ | (1) |
| b Diamond mode.     | $\varepsilon = \frac{0.74V}{D}$ | (2) |

(Where, $V$ is the impact velocity)

Equation (3) is known as Cowper-Symond's equation, which shows good agreement with available experimental values for various metal.

$$\varepsilon p = D \left\{ \frac{\sigma_d}{\sigma_s} \right\}^q - 1$$  \hspace{1cm} (3)

Where, $\sigma_d$ is dynamic flow stress, $\sigma_s$ is static flow stress, $D$ & $q$ are the material constant and to be determined experimentally.

**3. Deformation modes in thin-walled tubes:**

3.1. *Thin circular tubes*

A thin circular walled tube having mean radius '$R$' and height '$h$', when subjected to an axial compressive load, may buckle axisymmetrically (concertina pattern) or non-axisymmetrically (diamond pattern) as shown in figure 3. Various theoretical methods indicated that the thicker tubes with $R/h < 45$, deform axi symmetric manner whereas the thinner tubes having larger value of $R/h$ ratio buckle non-axisymmetric manner [9]. Alexander [20], Pugsley and Macaulay [21] proposed static theoretical form of the mean axial crushing load for axisymmetric and non-axisymmetric behaviour of circular tubes as shown in the table 3. In Alexander's theoretical model, the material was assumed to be rigid and perfectly plastic. With some combination of $R/h$, the tube may show the ring mode (concertina pattern) and then it switches to the diamond mode, hence tubes show the mixed mode of deformation. It was also seen that the tube having length '$L$' to thickness '$h$' ratio i.e. $L/h$ ratio significantly affect the deformation modes of the circular tubes. If the $L/h$ ratio is less than 2 then ring or concertina pattern may form where as diamond pattern is present when $L/h$ ratio is more than 2. The Euler-type buckling can also be seen in long length tube [8].

![Figure 3](image_url)

(a) Axisymmetric (concertina pattern)  
(b) Non-axisymmetric (diamond pattern)

*Figure 3. Deformation modes of thin-walled circular tube [9].*
Table 3. Theoretical equations for mean crushing load.

| Mode of deformation | Theoretical estimate form | Equation No. |
|---------------------|---------------------------|--------------|
| a Axisymmetric [20]  | \( F_m = CYh^{1.5}\sqrt{D} \) | (4)          |
| b Non-axisymmetric [21] | \( F_m = Yh(10.5h + 0.38D) \) | (5)          |

(Where, \( Y \) = yield strength, \( h \) and \( D \) are the thickness and diameter of the tube respectively, \( C \) constant to be calculated through experimental data)

3.2. Thin square tubes

Wierzbicki and Abramowicz [22] proposed the first theoretical model for static buckling of square tubes. They identified the two basic collapse elements as shown in figure 4. They used this model to examine the static progressive buckling in square tubes. Later on, Abramowicz and Jones [23] used the same basic collapse elements to study the dynamic progressive buckling in square tubes. From two collapse elements, they predicted four deformation modes one symmetric mode, one extensional mode and two asymmetric mixed mode and estimated theoretical equation for the mean crushing load with prediction criteria. Table 4 gives the short review for theoretical equation.

![Basic collapse element](image)

**Figure 4.** Basic collapse element [23].

Table 4. Theoretical equation for mean crushing load [23].

| Deformation          | Prediction criteria | Equation | Equation No. |
|----------------------|---------------------|----------|--------------|
| a Symmetric          | \( C/H > 40.08 \)   | \( \frac{F_m}{M_o} = 38.12(C/H)^{3/4} \) | (6)          |
| b Extensional        | \( C/H < 40.08 \)   | \( \frac{F_m}{M_o} = 32.64(C/H)^{3/4} + 8.16 \) | (7)          |
| c Asymmetric mixed A | -                   | \( \frac{F_m}{M_o} = 33.58(C/H)^{3/4} + 2.92(C/H)^{3/2} + 2 \) | (8)          |
| d Asymmetric mixed B | \( 7.5 \leq C/H \leq 40.08 \) | \( \frac{F_m}{M_o} = 35.54(C/H)^{3/4} + 1.65(C/H)^{3/2} + 1 \) | (9)          |

(Where, \( C \) = mean width, \( H \) = mean thickness, \( M_o \) = plastic moment of the wall per unit length)
4. Energy Absorbers

The energy absorber is a system which converts kinetic energy into another form of energy. Converted energy can be either reversible like elastic strain energy in solids and pressure energy in fluids or irreversible like plastic deformation in solids [25]. Collapsible energy absorber is connected to the vehicle bumpers as crash boxes also a connecting member between a bumper and front cross member of the chassis. There are many collapsible energy absorbers that are studied in open literature. Some common types of energy absorbers are overviewed in following section.

4.1. Thin metallic absorber

Thin tubes are most common and oldest shape of collapsible energy absorbers. These type of energy absorbers are designed to buckle progressively to absorb maximum impact energy in controlled manner [8]. The conversion of kinetic energy into the plastic strain energy depends on some factor like tube geometry, material properties and deformation pattern [26]. Jones [9] observed that the thin tubes are more suitable and desirable as energy absorber due to their low cost, simplicity and high energy absorption capacity. A thin walled tube may develop either concertina (axi-symmetric buckle) or diamond (non-axisymmetric buckle) when they are subjected to axial compressive load. Jones [9] showed that concertina deformation mode is most efficient energy absorbing mode. Alghamdi [25] discussed the different modes of deformation of different types of energy absorbing structures. Al-hassani et al. [27] investigated the crashworthiness characteristics of different inversion tubes. His analytical model predicts constant inverting load for uniform tubes. Ramsey [28] evaluated the experimental axi-symmetric buckling of truncated conical shells under axial compression. From experimental study, it was concluded that there is no minimum load required to initiate buckling in the specimens. Andrews et al.[29] presented experimental investigation of axial crushing modes and energy absorbing properties of Aluminium alloy tubes under quasi-static compression. In their study, they investigated the influence of the tube length on collapse mode.

Mamalis et al. [30] studied the axial compression behaviour of aluminium circular cylinder and truncated cone having semi-apical angle $5^\circ - 20^\circ$ under the quai-static loading. They noticed that peak load and mean collapse load is increased with increase in slenderness ratio. Mamalis et al. [31] carried out the same experimental study using the mild steel at elevated strain rate (2.5 m/min) and noticed that both the peak crushing load and mean collapse load increases as in increase slenderness ratio. Wlodzimierz and Jones [24] carried out the dynamic test on the square tube of various length with $c/h=30.25$ and $c/h=32.18$ (where, 'c' is mean width and 'h' is mean thickness of the square tubes) and used kinematical method of analysis to propose theoretical model. Good agreement between the analytical and experimental study was shown. Langseth and Hopperstad [32] carried out the quasi-static and dynamic testing on square Aluminium extruded alloy AA6060 with different thickness and temper. In static test, they marked that a progressive symmetric deformation is independent of wall thickness and temper. In dynamic testing, linear behaviour between impact energy and deformed length of temper T4 was observed.
Singace and El-sobky [33] studied the energy absorption characteristics of corrugated tube. The main aim of their study was to control formation of plastic hinges and plastic stretching work. From their experimental study, they noticed that energy absorption can be controlled by suitable depth of corrugation. Singace et al. [34] performed the dynamic axial load test on circular frusta to investigate the different mode of deformation and energy absorbing performance. It was concluded that constraining the end of structure enhances energy absorbing capacity. From their results, they evaluated that inertia effect plays key role to increase the energy absorbing capability of frusta in dynamic testing. They also noticed the mixed mode of deformation. The deformation begins with concertina and ending up with multi lobe. Alghamdi [35] reported the new mode of deformation called folding crumpling mode which can be seen in only within limited range of angle. He observed that frusta with semi-apical angle 75° and free fixed boundary condition undergoes in the folding crumpling mode.

Shakeri et al. [36] proposed new mechanism in which the energy dissipation takes place due to deformation of deformable tube by rigid tube. In this proposed mechanism, plastic deformation of the tubes and friction at the contacts play key role for energy absorption. From the studies, they concluded that mean crushing force can be mainly affected by thickness and material of deformable tube, clearance between the tubes and value of friction coefficient. The main advantage of this proposed mechanism is that the mean crush load can be controlled by varying the friction coefficient at the contact of the two tubes. Nagel and Thambiratnam [19] investigated the energy absorption response of straight and taper tube by using finite element techniques (Tool- ABAQUS). Simulation results were validated with the past literature results [37]. From the simulation result, they noticed that taper tubes have highest energy absorption capacity than straight tubes and also crush force efficiency increases with increase in a wall thickness. Gramarian and Zarei [38] carried the crashworthiness investigation of conical and cylindrical end capped tubes under the quasi-static axial loading and validated experimental readings with numerical results (ABAQUS). Good agreements were found between experimental and numerical results.

4.2. Composite Energy Absorber
Price and Hull [39] performed an experimental study on the glass fibre–polyester (GFRP) composite cones. It was noticed that the Composite cones with wall thickness more than 2 mm were failed by progressive crushing. They found that the specific energy absorption and absorbed energy of specimen increase with the increase in wall thickness and diameter of the composite specimens but decrease with the increase semi apical angle of the cone. Mamalis et al. [40] studied analytically the behavior of fiberglass composite conical shells with semi apical angle 5° – 20° under static and dynamic axial loading and reported that the circular frusta having semi-apical angle 5° shows the best crashworthy capability. Mamalis et al.[41] reported the behaviour and crashworthiness characteristic of the square tubes made of two different types of composite material. They studied the effect of the specimen geometry i.e. thickness and axial length on the energy absorbing capability under the static and dynamic axial compression.

Alkateb et al. [42] investigated the energy absorption capability of elliptical cones under quasi-static axial compression. They performed a series of experiments on the composite elliptical cones with the same ellipticity ratio with vertex angles ranging from 0° to 24°. From the results, they concluded that the average crushing load increases as increase in vertex angle with decrease in first peak crushing load. Mamalis et al. [43] investigated the study of collapse modes, crash behavior and crashworthiness characteristics of carbon fibre reinforced plastic (CFRP) tubes under axial compression. They reported that the peak compressive load increases remarkably as the number of fibre layers, fibre volume ratio and increase in thickness of the tube and it is independent of mode of deformation of tubes. Morthorst and Horst [44] presented an experimental and numerical analysis of the crushing response of truncated conical shells. The experimental results showed a dependency of the stability of the crushing response and the specific energy absorption on the loading, the geometry of specimen and the material composition.
Ochelski and Gotowicki [45] performed an experimental assessment of energy absorption capability between CFRP and GFRP composites. The crush failure load and first peak load in the composite testing increases remarkably with the increase in the number of layers, content of fibres, composite thickness and bending stiffness. Shadmeirhi et al.[46] proposed a semi-analytical approach to get the linear buckling response of conical composite shells under axial compression load. The results showed that the critical buckling load decreases with increase in the semi-apical angle and it is more prominent as the semi-cone angle exceeds 20°. The critical buckling load decreases as fibre-orientation angle increases.

4.3. Metal -Composite (Hybrid) Type Energy Absorber

The structural member which are made with fibre metal lamination technique (FML) having good crashworthiness behavior than the metallic member. FML members takes advantages of the fibre-resin composite and the metals together along with stable ductile plastic collapse mechanism at the time of the impact.

Hanefi and Wierzbiicki [47] considered the simplified analytical model for their study. In analytical model, they modified the classical Alexander [20] solution to check additional resistance by the composite wall during impact loading. From the analytical results, they derived mean crushing load and crushed length which showed good agreements with experimental results and proved that compound metal/composite tube gives much higher specific energy absorption as compared to conventional metal tubes. Song et al. [48] studied the behavior under axial impact and energy absorption efficiency for glass/epoxy composite having externally wrapped circular metal tubes. In their study, they identified four types of collapse modes. They also studied the effect of strain rate, composite wall thickness, fibre ply orientation and mechanical properties of metal on energy absorption efficiency. Shin et al. [49] investigated study on bending collapse and axial crush of GFRP wrapped Aluminum square hybrid tubes. They considered the modified plastic hinge collapse model and the modified Keeman’s model [50] for hybrid tube for investigation of axial crush and bending collapse of composite wrapped tube. They also proposed two models for hybrid tubes which showed good agreements with experimental results.

Bouchet et al. [51] conducted experimental investigation on crushing behavior and CFRP/GFRP composite-wrapped Aluminum alloy circular tube under dynamic loading. The different chemical treatments like chemical itching, anodizing and degreasing were conducted prior to bonding. From result, they observed that specific energy absorption is increased by 60% in chemically etched specimens. Babbage and Mallick [52] carried out experimental investigation for the static axial crush performance of Aluminum–composite hybrid tubes. From the experimental result, they observed that static axial crush performance of square and round tube can be improved by using E-glass fiber composite and desired crush performance can be obtained by varying some parameter like fiber orientation angle, the number of composite layers and thickness of Aluminum tubes.

Bambach et al. [53] carried out axial crush test on different range of steel square hollow section (SHS) geometries strengthened with externally wrapped carbon fibre reinforced polymer (CFRP) and presented empirical expression to check the effect of CFRP strengthening. Results showed good agreement, particularly in case of compact and non-compact sections. Bambach et al. [54,55] performed experimental studies on axially compressed SHS. It was reported that CFRP provides restraints to the development of elastic buckling deflection which results into delay in local buckling of the material. Guden et al. [56] conducted an experimental investigation to check the effect of Al closed-cell foam filling on the quasi-static crushing behavior of an E-glass woven fabric composite and Al metal/composite hybrid tubes. They observed two types of crushing mode, namely progressive and catastrophic. The progressive crushing mode resulted in higher SEA.

Kathiresan et al.[57,58] studied the axial crushing behaviour and energy absorption capacity of conical frustum made-up of Aluminium (AC) and E-glass fibre/epoxy resin composite wrapped Aluminium (CWAC) under quasi-static and dynamic compression loading. They found good agreement between experimental and numerical study (Tool-ABaqus) and reported that CWAC
showed 3–5 times more energy absorption capability than Aluminum and specific energy absorption capacity of CWAC specimens was increased to the maximum of 14.9% over that of AC type specimens.

4.4. Honeycomb Plate
Metal honeycombs are well known for excellent light weight structural material due to their strength and energy absorbing properties. The development of bio-inspired honeycomb structure is also offering good opportunity and new challenges in the field of crashworthiness [59]. Wierzbicki [60] studied the crushing behavior of metal honeycombs and proposed mathematical model to predict the average axial force. The average crushing force is given below,

\[ P_{avg} = 8.61\sigma_o^{5/2}C^{1/2} \]  

(10)

Where, \( \sigma_o \) = Average flow strength, \( t \) = core thickness, \( C \) = width of the basic panel element.

Wu and Jiang [61] carried out the experimental investigation on Aluminium honeycomb structure under quasi-static and dynamic loading. It was found that the crushing strength increased by 60-74 % in dynamic case than quasi-static case. Finally they concluded that honeycomb structure of small cell size and core height with high strength are best suitable for static and dynamic loading. Zhao and Gray [62] reported crushing strength percentage difference up to 40% between dynamic and static conditions.

Crupi et al. [63] presented the detail of impact responses of aluminum foam and honeycomb sandwiches under the static and low-velocity load. They concluded that the collapse of honeycomb sandwiches is influenced by the cell size during low-velocity impact. Foo et al.[64] evaluated numerically the impact response of aluminium honeycomb filled sandwich panels. They noticed that denser the core greater the peak load. It was concluded that energy absorption capacity is independent of core density of the honeycomb cell. Wu et al.[59] carried out dynamic investigation of bio-inspired aluminium honeycomb sandwich with CFRP panels. From their study, they reported the improvement in crashworthiness parameters like peak load of panels decreased by 21 % to 45.2% and energy absorption increased by 25.8% to 43.1%.

4.5. Functionally Graded thickness (FGT) Tubes
In practice, use of large tapered angle tubes is not possible due to the space restriction. This limitation can be eliminated using functionally graded thickness tubes (FGT) [65]. FGT tubes give the variable stiffness throughout the length of the tubes, hence deformation of structure and crashworthiness parameter can be controlled in efficient manner at the time of the impact. Sun et al. [66] carried out the numerical study (Tool-LS-DYNA) to evaluate the effect of thickness gradient pattern on crashworthiness properties and reported that FGT tubes show good crashworthiness properties than that of uniform thickness (UT) tubes.

Baykasoglu and Cetin [67] investigated the effect of thickness gradient pattern on energy absorption of Aluminium FGT tubes. They reported that FGT tubes have overall better energy absorption capacity than UT tubes due to the progressive crush behaviour. The comparative study on crush behaviour of the FGT and UT tubes was done by Li et al.[68]. In their study, they evaluated that FGT structure reduces the initial peak force more effectively than that of UT.

5. Summary
The aim of this comprehensive review was to present the research information on collapsible metallic energy absorbers. Initially, the paper overviewed how the production of lighter vehicle is compromising the safety of the human at the time of impact event and importance of crashworthiness in automotive. The article highlights on the common shapes of collapsible impact energy absorber and their impact behaviour under the static and dynamic axial compression. Also, the effects of different geometrical parameters such as thickness, cross-sectional dimensions, length and semi-apical angle (for cones and pyramid) on crushing mechanics, modes of deformation, energy absorbing capacity,
effect on peak and mean crushing load were studied. Literature shows that non-linearity and large
deformation make the design more challenging in thin-walled energy absorber.

While designing the collapsible energy absorber structures, following forces play an important role,
(a) Mean crushing force: In all above literature study, authors were mainly concerned with the
average crushing force as this is the most important parameter during evaluation of the energy
absorbing capacity.
(b) First peak force: The peak force is also important aspect. Ideally, it should be closed to mean
force. From literature, it was seen that peak force can be minimized with the use of composite
material, honeycomb cell and FGT tubes.

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