CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter reviews the background literature, which is relevant to the research conducted in this work. Since the study focuses on the crashworthiness behaviour of conical frusta, all the established experimental and theoretical research works relevant to quasi-static, impact crush behaviour of conical shell structure are identified from the literature. The information related to the influence of material properties, effect of semi-apical angle, boundary conditions and shape are reviewed.

The crush behaviours and energy-absorption characteristics of conical shells made by metal, Fibre Reinforced Plastic (FRP), and FRP over-wrapped metallic materials, i.e. hybrid, are highlighted in the following sections. The key concept of numerical investigations related to the study also highlighted in this chapter. Further, the limitations of the existing literatures and objectives of the present research are also presented at the end of this chapter.

2.2 STUDIES ON METALLIC CONICAL FRUSTA

Ramsey (1977) investigated the plastic axi-symmetric buckling of steep, truncated conical shells under axial compression. The conical test specimens were machined from aluminium material of 6061-T6 and stainless
steel 416 grades. It was found that the buckling modes of geometrically similar conical frusta are identical irrespective of the material considered for the study as shown in Figure 2.1.

![Cross-section of buckled conical frusta made by (a) steel and (b) aluminium material (Ramsey 1977)](image)

**Figure 2.1** Cross-section of buckled conical frusta made by (a) steel and (b) aluminium material (Ramsey 1977)

Mamalis & Johnson (1983) investigated experimentally the quasi-static crumpling of thin-walled circular cylinders and frusta made out of aluminium alloy under static axial compression to compare the collapse behaviour of circulars cylinders and frusta. From the study, it was found that the thick tubes failed by axi-symmetric buckling by generating circumferential rings whereas the thin walled members exhibited progressive folds of diamond-shaped lobes after assuming an initially axi-symmetric ring mode of deformation. As the loading progressed, the ring type pattern was transferred into non-symmetric elliptic, triangular and square and diamond patterns as shown in Figure 2.2. The study also proved that the buckling loads for both cylinders and frusta were increased with increasing slenderness ratio. Further, the mean load of the conical frusta decreased with the increasing in the value of mean diameter to thickness ratio. The post-buckling load and peak load were found to be increasing in a parabolic manner with the increase in slenderness ratio.
El-Sobky & Singace (1999) conducted experiments on conical frusta of aluminium alloy having 20° semi-apical angle. The elastic stress profiles along the generator of various diameters of the frustum were analysed under axial compressive load. The magnitude and location of the highest stresses, the regions of severe stress gradient, and the anticipated mode of failure in a frustum subjected to axial loading for different end conditions were also studied. The study concluded that the cone will buckle at top end in all cases considered, and the position of the buckling was shifted downwards (i.e. away from the top) as the cone apex angle increases. Further, it was apparent that a combination of the mean diameter to thickness ratio and the apical angle of the frustum decided the transition from one mode to the other.

Gupta & Abbas (2000) presented a mathematical model for the axi-symmetric axial crushing of thin frusta having semi-apical angle less than 10°. The study considered the outside straight folds and the variation of circumferential strain during the formation of a convolution. Based on the experimental results of cylinders as well as frusta, the mathematical model is developed by considering the first limb of the first fold as straight, and the other folds are considered as curved. The developed mathematical model proved that the flexural energy-absorption in the first fold is less, and the consideration of first fold brings the calculated results closer to the experimental results.
El-Sobky et al. (2001) investigated the energy-absorption characteristics or performance of right circular aluminium frusta subjected to quasi-static loading. Aluminium alloy (1200-soft) right-angled frusta with different vertex angles 30°, 37°, 41°, 51° and 90° were axially crushed at the rate of 5 mm/min and the results were analysed. The experimental observations indicated that the effects of the end constraints on the energy-absorption were qualitatively similar to those observed under quasi-static testing. The study proved that constraining the ends of the frusta enhanced the overall SEA capacity of frusta. Further, the choice of length to thickness ratio is found to be influencing more on energy-absorption characteristics than on the diameter to wall thickness ratio. Finally, the study concluded that the top-constrained frusta exhibited the highest increase in the magnitude of the specific energy compared with free ends, followed by the fully constrained frusta. The study also proved that the heat-treated, the top constrained frusta resulted in a maximum SEA.

Singace et al. (2001) studied the energy-absorption characteristics of right circular frusta subjected to dynamic axial load and the results were compared with quasi-static test results. In this study, frusta made out of aluminium alloy (AL 1200-soft) with different apex angles (30°, 37°, 41°, 51° and 60°) were axially crushed by means of a drop hammer setup. The initial velocity of the drop hammer with the mass of 47.5 kg was chosen in the range of 2-5 m/s to study the optimum conditions of highest specific energy absorption by the frusta. The study concluded that fully constrained frusta absorbed more specific energy than the top, base, and non-constrained forms. The study also proved that the increase of mean load is the function of semi-apical angle (α). The Euler buckling load of frusta is more stable and found to be higher than cylindrical tubes. Further, the stroke and overall energy-absorption of frusta is higher than the cylinder of same weight and volume.
Alghamdi (2002a) also extended his work to investigate the effect of semi-apical angle as well as frustum wall thickness of capped aluminium frustum on the absorbed energy. The study was conducted by varying the thickness from 1.01mm to 3.05mm and keeping the constant angle in the range of $30^\circ$-$75^\circ$. The re-inverted test results of various categories of specimens were discussed. The influences of collapse mode, semi-apical angle and wall thickness on energy-absorption behaviours were also discussed. From the study, it was concluded that the accumulated absorbed energy increased with the increase in the angle of frustum, and the absorbed energy attained some maximum value at $\alpha = 60^\circ$ as shown in Figure 2.3. Further, the results showed that it was possible to use the inverted aluminium frusta several times, thus they are reusable collapsible absorbers. The study also revealed that the absorbed energy in the re-inversion mode is much higher than the values.

![Figure 2.3 Influence of apical angle and thickness of end capped conical frusta on SEA and inversion of conical frusta (Alghamdi 2002a)](image-url)
Alghamdi et al. (2002b) numerically and experimentally analyzed the modes of axial collapse of unconstrained capped frusta made by aluminium-6061 with different semi-apical angles (15°-60°), thickness and materials (steel and nylon) under quasi-static conditions. The study explored different mechanisms of deformation and they were classified as: (1) outward inversion, (2) limited inward inversion followed by outward inversion, (3) full inward inversion followed by outward inversion, (4) limited extensible crumpling followed by outward inversion, and (5) full extensible crumpling. The outward inversion of capped frusta is shown in Figure 2.4 (a). The studies also exploited the influence of semi-apical and wall thickness on the $SEA$ characteristics and it is shown in Figure 2.4 (b). From the study, it was observed that the $SEA$ of conical shell increased with the increase in shell thickness. The $SEA$ was found to increase with the increase of semi-apical angle in the range of 15°-25°, and then the $SEA$ was found to be decreased with the increase in semi-apical angle and thickness. Further, the plastic (nylon) frusta exhibited a higher specific energy than aluminium and steel frusta. Hence, the study proved that the material played an important role in determining the mechanisms of deformation followed by semi-apical angle than wall thickness.

Figure 2.4  (a) Outward inversion of capped conical frusta and (b) Specific energy as a function of semi-apical angle and wall thickness of aluminium frusta (Alghamdi et al. 2002b)
Easwara Prasad & Gupta (2005) conducted axial compression tests on spherical domes and conical frusta of various sizes to study their modes of collapse and energy-absorption capacities. The large-angled aluminium conical frusta of semi-apical cone angles (44.5°-67.1°) were considered for the quasi-static and impact tests. The impact velocities varied from 2 to 9 m/s. The study confirmed that modes of collapse were highly dependent on the mean-radius to thickness ratio ($R/t$) of the shells, and their mean collapse load was found to be increased with increase in their $R/t$ value. The study also proved that the mean collapse loads and the energy-absorption capacities of the frusta were found to increase with an increase in their slenderness ratio.

Gupta et al. (2006) investigated the collapse patterns and energy-absorption characteristics of thin-walled aluminium conical frusta through experimental and numerical analysis by changing the semi-apical angle and thickness in the range of 16°-29° and 0.7-1.62mm respectively. The study had been carried out by considering the material, geometry and contact non-linearity. The radiuses of rolling and stationary plastic hinges were also investigated experimentally, and the corresponding configurations of rolling and stationary plastic hinges were used for the mathematical modelling to predict the deformation mechanism of conical frusta. The numerical study also identified three stages of buckling modes of frusta such as inversion, concertina mode of failure, and fold formation under quasi-static loading, and the same were compared with experimental results. Figures 2.5 (a) and (b) show different buckling modes of actual and predicted collapse modes.

Gupta et al. (2007) investigated the thin-walled aluminium conical shells of semi-apical angles ranging from 6.84° to 65.35° under impact load over the frusta. The drop-weight impact tests were conducted on aluminium conical shells by varying the impact velocities in the range of 2.55-7.92 m/s, whereas the numerical study was performed using FORGE2 software to
simulate the collapse behaviour of aluminium conical shell. The cone material in this analysis was assumed as rigid-viscoplastic model with Von-Mises yield criteria, which was based upon the Norton-Hoff law.

![Figure 2.5 Buckling modes of aluminium conical frusta obtained through (a) quasi-static experiments and (b) FE simulations (Gupta et al. 2006)](image)

Gupta (2008b) investigated the mode of collapse of varying wall thickness of aluminium metallic frusta subjected to quasi-static axial compression. The frusta of semi-apical between 7° and 9° with diameters to thickness (D/t) values ranging between 26 and 49 were axially compressed with the velocity of 10 mm/min. From the study, it was observed that all the frusta were found to be collapsed with the formation of an axi-symmetric mode of collapse due to the development of the associated plastic hinges. In addition to axi-symmetric mode of collapse, some portions of the frusta move radially inward and outward. This corresponding deformation was identified as a new mode of collapse during axial deformation of frusta. Figures 2.6 (a-c) show the axial compression of conical frusta of varying wall thickness, deformed specimen and the corresponding load-deformation plot.
(a) (b)  (c)

Figure 2.6  (a) Quasi-static axial compression of conical frusta of varying wall thickness, (b) deformed specimen and (c) corresponding load-deformation plot (Gupta 2008b)

Mohamed Sheriff et al. (2008) carried out investigations to optimize thin-walled conical shells for their use in the design for energy-absorption. Geometrical parameters such as bottom diameter, height, and semi-apical angle were considered to obtain the design space. Further, to investigate the influence of flow stress on the energy-absorption characteristics, numerical simulations were also carried out by considering aluminium, zinc, and mild steel material properties for the conical frusta FE model. From the results, mathematical models were created using response surface methodology to analyze the influence of various design parameters on energy-absorption behaviours. Hui Zhang & Xiong Zhang (2016) studied the crashworthiness performance of conical tubes with various thickness distributions were investigated. The study proved that the thickness increase and material hardening during tube shrinking lead to increase energy absorption up to 120%.

2.3 STUDIES ON FRP COMPOSITE CONICAL FRUSTA

Thornton et al. (1985) reviewed the energy-absorbing characteristics in axial collapse of structures made from fibre-reinforced plastic (FRP) composites. From the review, it was observed that the type and nature of the fibre-resin, geometry of the structure and fibre arrangement
influenced significantly the energy-absorbing capability of FRP member. The study reported that the combination of glass/epoxy matrices has higher \( SEA \) than glass/phenolic or glass/polyester FRP members. Further, among different simple cross sections of FRP geometry, the rounded section has higher \( SEA \). The triggering mechanism was found responsible for increasing the \( SEA \) of the member. However, the conical sections are self-triggering, which increased the \( SEA \) through stable progressive collapse during crushing.

Price & Hull (1987) studied the axial compression of axi-symmetric truncated composite cones of semi-apical angles 11°, 22° and 45°. The work was to examine the crush behaviour of a range of cone geometries, and to compare the failure modes and \( SEA \) levels of truncated composite cones with cylinders. The study indicates that the cones with wall thicknesses less than 2mm showed unstable crushing, and the specific energy absorbed during crushing varies with the change of cone angle, wall thickness and section diameter. Further, the cones with semi-apical of 45° and a wall thickness greater than 8 mm had the highest \( SEA \) characteristics compared to axi-symmetric tubes made of the same material. They also reported the effect of semi-apical angle on the collapse behaviour of laminate. Figure 2.7 shows the crushed zones of cylinder and cone with different semi-apical angles.

![Figure 2.7 Crushed zones of (a) cylinder, (b) cone of semi-apical angle \( \theta = 11^\circ \) and cone \( \theta = 22^\circ \) with (c) external chamfer and (d) internal chamfer (Price & Hull 1987)](image-url)
Liyong Tong & Tsun Kuei Wang (1993) performed buckling analysis of laminated conical shells with orthotropic stretching-bending coupling under axial compressive load using eight first-order differential equations. Further, buckling of a series of conical shells, the effects of boundary conditions, elastic coefficients and the stretching-bending coupling on the buckling loads and circumferential wave numbers were investigated. The investigation proved that stretching-bending coupling had a significant influence on the critical buckling loads and circumferential wave numbers of conical shells.

Ferreira & Chattopadhya (1994) developed an optimization procedure for maximizing the energy-absorption capability of symmetric ply oriented graphite/epoxy, glass/epoxy, and kevlar/epoxy of composite cylindrical shells under axial compressive loading. The sensitivity of both geometric and material properties was investigated by studying thin-walled shells of several thicknesses, made of different types of orthotropic laminates. The study predicted that the energy-absorption capability of shell increased linearly with the number of plies. They also found that the graphite/epoxy shells absorbed comparatively more energy followed by kevlar/epoxy and glass/epoxy shells respectively.

Mamalis et al. (1994) studied an axial collapse of thin-walled fibreglass composite tubular components at elevated strain rates. The axi-symmetric composite structures consisting of circular-tubes and conical-frusta \( (\alpha = 5^\circ, 10^\circ, \text{ and } 15^\circ) \) made from a chopped-strand glass fibre mat and polyester resin were subjected to dynamic axial compression by a drop hammer setup. The effect of specimen geometry and loading rate on the energy-absorbing efficiency of each specimen was studied in detail. The study concluded that the radius of curvature of the internal frond increased with increasing semi-apical angle whilst the external frond was constrained to
deform through a smaller radius. It was also observed that the total energy dissipated by the frusta was directly dependent upon the semi-apical angle. Further, the SEA characteristics of conical frusta were found to decrease as the semi-apical angle (α) increased.

Hamada & Ramakrishna (1995) studied the energy-absorption characteristics of carbon/PEEK composite and reported that the compressive strength increased rapidly with the increasing $D/t$ ratio from 50 to 125 and then it remained constant. The author obtained the highest energy-absorption for tube wall thickness ranging between 2 mm and 3 mm, beyond which it decreased.

Mamalis et al. (1996) examined the energy-absorption capability of fibre-glass reinforced composite square and circular frusta subjected to static and dynamic axial loading. The study explored four types of collapse modes such as Mode-I (mushrooming failure), Mode-II (longitudinal corner cracking), Mode-III (mid-length collapse) and Mode-IV (progressive folding and sharp hinges). Further, the study concluded that the collapse behaviour of square frusta under static and dynamic loading was similar to axial collapse of circular frusta at elevated strain rates. The study also explored that $5^\circ$ square frustum seemed to be the more efficient under both static and dynamic loading conditions. The crashworthy characteristic of the circular frusta was also higher than that of square frusta.

Mamalis et al. (1997a) theoretically analyzed the stable collapse mechanisms of thin-walled circular frusta and tubes under axial static and dynamic loading to assess the crush load and energy-absorption capacity. The study was also carried out by considering two different materials, namely fibre-glass with polyester resin and glass fibre with vinyl-ester resin. From the tests, it was found that the micro-fracturing mechanism of Mode-I collapse
was found to be similar for both statically and dynamically loaded shells. It was also proved that the absorbed energy due to friction between wedge-fronds and fronds-platen constituted the most significant energy-absorbing source during the crushing process.

Mamalis et al. (1997b) also studied the failure mechanisms of thick-walled glass fibre reinforced circular frusta subjected to axial compression. The article discussed the influence of changes of wall thickness and the semi-apical angle on the collapse modes. Figure 2.8 shows the different failure modes of conical frusta observed during axial collapse of the thick-walled composite conical shells. The test results confirmed that the specimens with semi-apical angles greater than 25° constituted a transition mode from stable collapse to catastrophic collapse. The study also proved that the progressive crushing was found to offer the higher energy-absorption characteristics than the other modes of collapse.

![Figure 2.8 Various collapse modes of axially collapsed thick-walled composite conical shells (Mamalis et al. 1997b)](image)

The study also concluded that the conical shells having semi-apical angle less than 25° exhibited progressive mode of collapse, i.e. Mode-Ia and Mode-Ib types, during crushing. Further, it was found that the gradual transition of collapse mode from Mode Ia to Mode Ib as the semi-apical angle increased from 5° to 20°, and cones with semi-apical angle greater than 20° exhibited catastrophic splitting after a short distance of progressive crushing.
i.e. Mode II. Mostly, the Mode-II type of collapse was observed, i.e. global splitting, occurred when the \( L/D \) ratio of the conical frusta was greater than 1.75. The Mode- II failure caused a localized outward bending at the base of the cone that induced a high state of tensile straining in the hoop direction, resulting to initiate global splitting from the inside bottom edge of the conical shell. Figure 2.9 shows typical load-deflection plot for conical frusta that failed by Mode-I and Mode-II types of collapse.

![Figure 2.9 Typical load-deflection plot for Mode-I and Mode-II of collapse of FRP frusta (Mamalis et al. 1997b)](image)

Arnaud & Hamelin (1998) studied the parameters that affected the energy- absorption characteristics in composite structures under dynamic loading conditions. The studies proved a variation of the specific energy of the composite tubes according to the nature of the fibres, the matrix, the stacking sequence and the loading speed. Further, the study indicated that during dynamic testing, some structures exhibited the crushing behaviour leading to significant increase in the specific energy. Knack & Vizzini (2001) investigated the energy-absorption characteristics of truncated kevlar-epoxy composite cones with tapper angles of 1°, 5° and 10° under off-axis loads. The study proved that the kevlar/epoxy cone exhibited significant structural integrity and did not show brittle fracture as in the case of graphite/epoxy.
cone. However, the SEA characteristics of kevlar/epoxy cone geometry were significantly lower and least sensitive to the angle of the applied load. The study also proved that the performance of cone with 10° taper angle had the best performance in both uni-axial and off-axis loading conditions. Mahdi et al. (2001) carried out experimental investigation on static crushing behaviour of filament-wound laminated cone-cone intersection composite shell under uniform axial compression loading. The effect of cone vertex angle on the crushing behaviour, energy-absorption, failure mechanism and failure mode of filament-wound laminated (FWL) cone-cone intersection composite shell were investigated. Two types of composites were tested, namely carbon fibre/epoxy and glass fibre/epoxy having the stacking sequence of [(90)₃ (55/-55)₂], with different cone vertex angles. Failure modes were examined during crushing of the specimens. The results showed that the initial failure was dominated by interfacial and shear failures, while the delamination fibre fracture dominated the failure mechanism after the initial failure.

Khalid et al. (2002) examined the crashworthiness performance of cotton/epoxy and glass/epoxy composite cones of semi-vertex angles 5°, 10° and 20° under quasi-static axial compression. From the investigations, it was found that the crashworthiness of glass/epoxy cones were higher than cotton/epoxy cones. It was also found that the crashworthiness performances of 80° fibre-ply orientated cones were slightly better than 90° fibre-ply orientated cotton/epoxy and glass/epoxy cones. Mahdi et al. (2003) studied the effect of residual fabrication stresses on the crushing behaviour, energy-absorption, failure mechanism and failure mode of a filament wound glass/epoxy laminated composite conical shell. Experimental study showed that the initial failure dominated by interfacial shear failure while, the delamination and fibre fracture were dominated failure mechanism after the initial failures. It was also reported that the static crushing behaviour of the conical shell was highly sensitive to the change in cone vertex angle, which
strongly dominated the residual fabrication stress development. The test results also proved that the increase in axial residual stress resulted in decreases in initial failure load and specific energy. Alkateb et al. (2004) evaluated the behaviour of composite elliptical thin walled cones subjected to quasi-static axial crushing. Goldfeld et al. (2005) analyzed optimum laminate configuration for the maximum buckling load of filament-wound laminated conical shells. The design variables such as thickness and ply orientation were considered as functional variables of the shell that influenced both the buckling load and weight of the structure. The study showed that the variation of thickness in the axial direction usually had more influence on the buckling load than variations of the fibre-ply angle.

Morthorst & Horst (2006) studied the effect of loading direction through numerical and experimental analysis by considering the influence of specimen geometry, material composition and loading conditions on the crushing response of truncated glass and carbon reinforced conical shells of semi-apical angle ranges from 5° to 25° under quasi-static loading condition. The test results showed that the SEA characteristics of carbon-reinforced were found to be higher than that of glass fibre-reinforced specimens. Patel et al. (2008) investigated the post-buckling characteristics of the angle-ply laminated composite conical shells subjected to torsion, external pressure, axial compression, and thermal loading using the semi-analytical finite element approach. The detailed study revealed that the critical load decreased with the increase in the semi-cone angle (α). Ochelski & Gotowicki (2009) assessed the influence of fibre reinforcement, type of structure, geometry and shape of specimens, orientation of fibres in a layer and stacking sequence of layers on the energy-absorption capability of carbon/epoxy-glass/epoxy composite tubes. From the study, it was proved that the SAE of tubes and cones increased with increase in wall thickness.
Blom et al. (2009) discussed four theoretical fibre path definitions for a generalized conical shell surface, namely (a) geodesic path, (b) constant angle path, (c) linearly varying angle path, and (d) constant curvature path. The study concluded that the curvature-constraint fibre-placement process could be considerably limiting the amount of variation of fibre-ply orientation during fibre lamination process on conical shell surfaces. Sofiyev & Kuruoglu (2011) investigated the non-linear buckling behaviour of cross-ply laminated orthotropic truncated conical shells under axial load. The basic relations of the cross-ply laminated orthotropic truncated conical shells were derived using the von Karman–Donnell-type of kinematic non-linearity. The study confirmed that as the semi-vertex angle increased, the values of the linear and non-linear axial buckling loads decreased in the single layer and symmetric cross-ply laminated orthotropic truncated conical shells with different ordering of the layers.

Shadmehri et al. (2012) proposed a semi-analytical approach to obtain linear buckling response of conical composite shells under axial compression load. Parametric study was performed to find the effect of cone angle and the fibre-ply orientation on the critical buckling load of the conical composite shells. The results showed that the axi-symmetric buckling loads were always lower than the non-axi-symmetric ones and the critical buckling load decreased as the semi-cone angle (α) increased for all the cases considered. The study also proved that the buckling strength of angle-ply conical shells was reduced up to 77% as the fibre angle (θ) varied from 0° to 45°, particularly, the reduction in critical buckling load became more pronounced as the semi-cone angle exceeded 20°.

Lin et al. (2015) studied the collapse loading and energy-absorption behaviour of fibre-reinforced conical shells. An analytical solution was presented to predict the mean axial collapse forces of a fibre-reinforced
conical shell under thermal loading in which the arbitrary ply orientation of fibres was considered. The study proved that the energy absorption of fibre-reinforced conical shells increased as the semi-apical angle of the conical shell increased. When the angle of fibre wrapped orientation equalled 90°, the energy-absorption capability of the fibre-reinforced conical shell was found to be higher than the cylindrical shell of the same ply orientation. Further, the collapse loading of fibre-reinforced conical shells with the thickness of composite layer equal to 0.4 mm and fibre-reinforced orientation great than or equal to 45° were found to have the best crashworthiness characteristics. Recently, Boria et al (2015) studied the axial energy absorption of CFRP truncated cones by applying quasi-static and impact loading. The study proved that the increase the thickness of the laminate and the average diameter and to reduce the wall inclination would resulted in better energy absorption characteristics of conical frusta.

The crashworthiness study was also extended to Fibre Metal Laminated (FML) members. The metallic layer was laminated with fibre which formed FML or hybrid laminate. The structural member made by this technique was having more energy-absorption characteristics and the strength to weight ratio. Since various materials were involved in hybrid laminates, the collapse behaviour mechanism involved were also complex. Still some more level of research work is under progress to utilize the hybrid members effectively for specific applications. The next section discusses the literatures on the investigations of hybrid structural members in detail.

## 2.4 STUDIES ON HYBRID STRUCTURES

The researchers named the fibre over-wrapped metallic member as hybrid member or compound member. Many researchers investigated the
different forms of hybrid members through quasi-static and impact loading procedures to study the collapse behaviour and energy-absorption characteristics.

Wang (1991) studied the collapse behaviour of multi-material tubular structures in which the steel cylinders were wrapped with glass/resin. The study concluded that the compound tubes collapsed with the diamond mode regardless of the metal thickness. Hanefi & Wierzbicki (1996) proposed simplified analytical model to investigate the axial crush resistance and energy-absorption of externally reinforced metal tubes. In this study, the classical Alexander's solution was suitably modified for the compound metal/composite wall. By considering the collapse of reinforced tubes in the concertina mode with straight-sided convolutions, the mean crushing force and the length of the local folding wave were derived. The study proved that compound tubes, i.e. metal-composite hybrid tubes, offered much higher specific energy absorption than conventional metal tubes.

Song et al. (2000) investigated the axial impact crush behaviour and energy-absorption efficiency of glass/epoxy composite externally wrapped around circular metal tubes. Compound tubes were made by utilizing glass/epoxy composite and plastic, brittle metal by winding with various ply orientations such as $[\pm 15^\circ]_3$, $[\pm 45^\circ]_3$ and $[90^\circ]_6$. The study explored four main collapse modes such as (a) compound diamond, (b) compound fragmentation, (c) delamination and (d) catastrophic failure as shown in Figure 2.10 (a). The study also proved that the dynamic and static results are identical and they have similar types of collapse modes. However, the SEA capacity of hybrid member was found to be increased due to strain rate effect. The corresponding SEA of hybrid member under quasi-static and dynamic loading is shown in Figure 2.10 (b). Further, the study proved that the SEA was found to increased with increase in winding angle fibre-ply orientation, which resulted in higher energy-absorption efficiency.
Figure 2.10 (a) Various collapse modes of hybrid tubes and (b) Comparison of dynamic and quasi-static SEA performances (Song et al. 2000)

Bouchet et al. (2002), conducted experiments to investigate the dynamic axial crushing of combined composite aluminium tube. The effect of both reinforcement and surface treatments on SEA and mode of collapse behaviours were investigated. The study indicated that the thinner aluminium alloy tube, with or without the carbon fibre-reinforced plastic composites, collapsed with a diamond mode regardless of surface treatments. Further, the thin-walled aluminium-fibre hybrid tubes were found to absorb higher level of specific energy than the thick-walled hybrid tubes. It was also proved that the surface treatment did not create significant contribution on increasing SEA characteristics of a member.

Shin et al. (2002) investigated the axial crush and bending collapse behaviour of GFRP, aluminium/GFRP hybrid square tubes and their energy-absorption capability. The glass fibre/epoxy composite prepregs were wrapped around an aluminium tube, and then it was allowed to cure completely in the autoclave under the recommended cure cycle. Failure mechanisms of the hybrid tube under the axial compressive load and the bending load were investigated experimentally, and the collapse modes were also analysed. Some of the collapse modes are shown in Figure 2.11.
The modified plastic hinge collapse model and the modified Kecman’s model for hybrid tube were suggested for calculating the energy-absorption capability of axial crush and bending collapse behaviours of the hybrid tube. The axial crushing test results witnessed that the energy-absorption performance of hybrid tube with the 90° ply orientation showed better than the other ply-oriented hybrid tubes. In the bending collapsing test, it was most effective to strengthen the aluminium tube with 0° and 90° ply-orientation composite tube among all kinds of hybrid tubes.

![Figure 2.11 Failure modes of the hybrid tube in axial crushing test](image)

Figure 2.11 Failure modes of the hybrid tube in axial crushing test (a) 0°, (b) 90°, (c) 0°/90° and (d) ±45° ply-oriented composite tubes (Shin et al. 2002)

Mahdi et al. (2003) studied the effect of hybridisation on the crushing behaviour, energy-absorption and failure mode of fibre composite cylinders. Five different hybrids and non-hybrid circular-cylindrical composite shells containing carbon and glass fibres were considered for the study. Examination on failure modes indicated that the hybridisation of fibre highly caused different modes of crushing. The study also proved that the structure with combination of glass-carbon-glass/epoxy exhibited better
energy-absorption capability than the other combinations of fibre arrangements.

Babbage & Mallick (2005) performed experimental investigation on static axial crush performance of both square and round aluminium-composite hybrid tubes, containing filament-wound E-glass fibre /epoxy wrapped around the aluminium tubes. Several layers of $[\pm 45^\circ]$ and $[\pm 75^\circ]$ ply-oriented E-glass/epoxy composite wrapped-over aluminium tubes of 1.60 mm wall thickness were considered for the study. The study also extended for epoxy foam filled hybrid tubes. Both unfilled and foam-filled hybrid tubes were quasi-statically compressed with the loading rate of 12.7 mm/min. The static axial crush resistances of these tubes were compared in terms of the maximum load, mean crush load, crush-energy and specific energy absorption. The various forms of deformation modes of these tubes were also investigated, and some of them are shown in Figures 2.12 (a-d). The study proved that the form filled hybrid tubes absorbed higher specific energy than the other categories of specimens.

![Figure 2.12](image-url)

**Figure 2.12** Folding pattern of (a) bare round and square aluminium tubes, (b-c) hybrid circular and square tubes and (d) Cut-away section of an epoxy foam-filled hybrid tube (Babbage & Mallick 2005)
El-Hage et al. (2006) performed numerical investigations on the quasi-static axial crush performance of aluminium-hybrid composite tubes containing a filament-wound E-glass fibre-reinforced epoxy wrapped around square aluminium tubes. The quasi-static axial crush resistance of the hybrid tubes were compared in terms of the maximum load, mean crush load, crush-energy and specific energy absorption. From the study, it was found that the folding initiation force, mean crush force and energy-absorption of the hybrid tubes were significantly higher than those of aluminium tubes of similar geometry. The thinner aluminium tubes showed greater improvement in crush resistance compared to the thicker tubes. Figures 2.13 (a) and (b) show the numerical and experimental modes of collapse of hybrid tube and the effect of hybridisation factor with the respect to fibre-ply orientation angle.

Bambach & Elchalakani (2007) performed experimental investigation on steel Square Hollow Section (SHS) tubes strengthened by externally bonded Carbon Fibre Reinforced Polymer (CFRP) tubes under quasi-static axial compression. The steel tubes were externally reinforced with
carbon/araldite 420 epoxy lamina of [0/90] and [0/90]₂ ply-orientations. The composite columns were crushed at a rate of 1 mm/min, and total height of the tube was compressed approximately to half of its original length. During the crushing, the hybrid tube was found to collapse progressively by initiating folding about concentrated hinge lines. Further, the transverse CFRP layers were found to increase the strength of the tube significantly.

Bambach et al. (2009) also presented experimental results of square hollow sectional (SHS) composite steel-CFRP tubes subjected to axial impact. A number of different steel SHS geometries and two different matrix layouts of the CFRP were investigated to find the corresponding crashworthiness behaviours. The test results confirmed that the steel-CFRP SHS provided superior dynamic crashworthiness parameters of mean crushing load, specific energy absorption and load uniformity, in comparison with steel SHS and CFRP SHS.

Bambach (2010) investigated the axial capacity and crushing response of thin-walled metal, fibre/epoxy and composite metal-fibre tubes under quasi-static loading. Three types of metals such as steel, aluminium and stainless steel were considered for the study. These materials were over-wrapped with carbon fibre layers of [0/90] ply-orientations through hand layup technique. Experimental results of thin-walled carbon fibre-epoxy SHS tubes were presented and compared with identical metal and composite metal-fibre tubes. The strength and mean crush load of composite metal-fibre tubes were found to be increased up to 1.8 times than the sum of the individual values for the metal tubes and CFRP tubes. It was also proved that the metal and metal-fibre tubes having reasonably equal strength to weight ratio; however the metal-fibre tubes tended to have larger specific energies for the same slenderness. Further, the addition of over-wrapped fibre laminates
controlled the mid length collapse of the column and the same was witnessed from Figures 2.14 (a) and (b).

![Figure 2.14](image-url)

**Figure 2.14** Different collapse pattern of square column made up of (a) carbon fibre laminate with [0/90] ply-orientations and (b) aluminium and carbon fibre over-wrapped shells (Bambach 2010)

Mirzaei et al. (2012) studied axial crushing behaviour of circular aluminium/glass-epoxy hybrid tubes under quasi-static loading condition. The effect of different parameters such as metal and composite wall thicknesses and stacking sequence of composite layers on the crashworthiness characteristics were discussed. The experimental results revealed that the stacking sequence had a considerable effect on crashworthiness characteristics. The energy-absorption capacity of hybrid specimen with [90/0/0/90] layup was found to be three times higher than that of uncovered aluminium tube of the same wall thickness. Further, the specimen with [90/0/0/90] layup had better energy-absorption compared to [90/90/90/90] layup as shown in Figures 2.15 (a) and (b). The analytical model was developed by including fibre-ply orientation, stacking sequence of each composite layer to study the axial crushing behaviour of hybrid tubes. An expression was derived for the mean crushing load and fold length in terms of thicknesses and material properties of metal as well as composite. The experimental results indicated that the SEA and load uniformity increased with the increase of composite wall thickness.
Figure 2.15 (a) Collapse mode of different ply oriented hybrid cylinders and (b) comparison of load-displacement plot of aluminium (M2) and hybrid (H1, H7) tubes (Mirzaei et al. 2012)

Bambach (2013) studied energy-absorption characteristics of carbon fibre composite strengthened thin-walled steel tubes for vehicle’s frontal collision applications through LS-DYNA software. The numerical results were validated by comparing the impact test results of Bambach et al. (2009). In numerical modelling, the hybrid laminate layers were modelled as a single shell layer for the full thickness of the fibre-steel composite tube walls and crushed with the impact mass and velocity of 574 kg at 6 m/s respectively. Integration points through a laminated shell thickness were defined arbitrarily. There were five integration points defined for the steel thickness, and one integration point was defined for each of the layers of carbon/epoxy lamina. Appropriate material properties were assigned for each sections of the layer according to the material and ply orientations. The study proved that fibre over-wrapping technique was found to increase the mean crush load. The study also suggested that a unit mass of steel might be replaced with around one third to one half of a unit mass of fibre-epoxy
composite, whilst maintaining similar vehicle performance in a frontal crash which might contribute to improvements in fuel efficiency of vehicle.

Kim et al. (2013) studied the energy-absorption capability and bending collapse behaviour of aluminium (AL)/carbon fibre-reinforced plastic (CFRP) short square hollow section (SHS) beam under transverse quasi-static loading. Kalhor & Case (2015) experimented the hybrid square tubes made from S2 glass/epoxy composites and 304-stainless-steel with different fibre orientation, stacking sequence, and thickness under quasi-static loading. The study discussed the influence of composite wall thickness on the change of crushing modes of stainless steel member. A new triggering mechanism was offered in the specimens that changed the collapse mode to a symmetric mode and led to improvement in the crush force efficiency ($CFE$) of hybrid tubes.

Junyuan et al. (2016) studied the crushing response of fibre-reinforced twelve right-angle section tubes based on kinematic approach. The author discussed the crushing energy-dissipation mechanism of metal tubes and derived an expression for mean crushing force. Roozbeh Kalhor et al. (2016) studied the effects of the design variables on energy absorption and failure modes square hybrid tubes consisting of S2 glass/epoxy composites and 304 stainless steel.

Some of the research works were carried out only through numerical procedures to assess the crashworthiness behaviours of various forms of structural members. In this regard, commercial software packages such as LS-DYNA, ABAQUS, ANSYS, FORGE2, LUCAS and PAMCRASH were used as a tool to solve the complex of issues elevated during crushing. The key points of quasi-static and impact loading procedures of FE analysis were collected from the literatures for the present study, and the same is discussed in the following section.
2.5 NUMERICAL STUDIES ON ENERGY-ABSORBERS

Nagel & Thambiratnam (2004) analysed the energy-absorption response of straight and tapered thin-walled rectangular mild steel tubes under oblique impact loading by varying the load angle, impact velocity and tube dimensions. The ABAQUS finite element analysis (FEA) tool was used to predict the collapse behaviours of the tube in which S4R element of size 5 mm was selected to model the tube section. This element is a quadrilateral element with four nodes, suitable for large strain analyses. Self-contact between the tube walls during collapse, and surface-to-surface contact between each rigid surface and the tube were defined using the finite sliding ‘penalty’ based contact algorithm with contact pairs and ‘hard’ contact. A friction coefficient of 0.2 was used for contact between the sides of the tube and the rigid bodies. It was found that the mean load and energy-absorption decreased significantly as the angle of applied load increased. Therefore, the tapered rectangular tubes might therefore be advantageous in applications where oblique loading conditions were expected.

Nagel & Thambiratnam (2005) studied the energy-absorption characteristics of tapered thin-walled rectangular tubes subjected to quasi-static loading through ABAQUS software. The study proved that the initial peak load decreased with the increase of taper angle. The mean-load and energy-absorption response of tapered rectangular tubes subjected to axial quasi-static loading were more influenced by the wall thickness than the taper angle and number of tapers. Further, the crush force efficiency (CFE), i.e. ratio of mean crush load to initial peak crush load, increased with increasing wall thickness and taper angle.

Mirfendereski et al. (2008) analysed the crushing behaviour of empty and foam-filled thin-walled tubes under static and dynamic loading...
using FEA. The FE results were validated with the available experimental results. In FE model, mesh size of 3 mm was considered for modelling the tube geometry, and the corresponding artificial strain energy was investigated. The study provides guidelines for selecting optimum mesh size for FE model. According to the study, the artificial strain energy of FE model should be less than 5% of the total internal energy of the model to achieve better results. The internal energy was defined as the sum of the recoverable elastic strain energy, energy dissipated through inelastic processes, energy dissipated through visco-elasticity or creep, artificial strain energy, energy dissipated through damage and energy dissipated through distortion control. Further, the artificial strain energy was defined as the energy required or spent to overcome the uncontrolled deformation of zero-energy elements. The study also utilized Cowper-Symonds constitutive equation to represent strain rate effect of steel material in FE procedure. The FE results proved that the dynamic initial peak and the mean-loads of straight and tapered foam-filled tubes were found to be greater than the corresponding quasi-static loads.

McGregor et al. (2007) simulated the progressive damage development in braided composite tubes under axial compression using LS-DYNA explicit finite element code. A continuum damage mechanics-based model for composite materials was implemented as a user material model for the composite tube. The model was a physically-based macro-mechanical material model that represented the constitutive behaviour of polymer composite laminates through both the elastic (pre-failure) and post-initial failure regimes. The mechanical consequences of matrix cracking, fibre breakage, and delamination (main failure mechanisms in tension), and kinking and kink band broadening, in conjunction with matrix cracking and delamination (main failure mechanisms in compression), were represented in the FE model. The mechanical properties of carbon fibre tows and hetron-922 resin were considered for the tube. In the simulation, the tube was modelled
with 5 mm and 2.5 mm element sizes. Among them, element sizes of 5 mm were almost exclusively used to mesh the tube in this study which offered less computation time than 2.5 mm size of element model.

Fyllingen et al. (2010) performed modelling and analysed the tubes subjected to axial crushing using LS-DYNA software, and the results were compared with ABAQUS software. Belytschko-Tsay type shell element and S4R element were chosen to analyze the aluminium square column in LS-DYNA and ABAQUS software codes respectively. The force-displacement plots were obtained from both simulation software for different optimum mesh density. The results did not indicate important differences in the formulations used by the two finite element codes, and only minor deviations were observed in the force-displacement plots, and the same is shown in Figure 2.16 (a) and corresponding collapse mode is shown in Figure 2.16 (b).

![Comparison of force–displacement plots from LS-DYNA and ABAQUS simulations and (b) deformed geometry from LS-DYNA simulation (Fyllingen et al. 2010)](image)

Fan et al. (2011) performed low velocity impact tests on fibre metal laminates (FMLs) fabricated by laminating thick aluminium alloy sheet and thick woven glass fibre prepreg together. The low velocity impact tests were
performed by varying impact velocity. The numerical model was developed using ABAQUS/Explicit software to predict the perforation resistance of FMLs. In numerical modelling, the damage initiation of fibre laminate was modelled using Hashin & Rotem (1973) and Hashin (1980) failure criteria. This criterion employed four damage initiation mechanisms, namely (a) fibre tension, (b) fibre compression, (c) matrix tension and (d) matrix compression.

Batra et al. (2012) performed low energy impact on fibre-reinforced polymeric (FRP) composite laminates by including Hashin’s damage, Hashin & Rotem (1973), Hashin (1980), using ABAQUS software, and compared with experimental findings available in the literature. The damage of FRP composite was assumed to initiate when one of Hashin’s failure criteria was satisfied, and the failure of the laminate evaluation was modelled with an empirical relation proposed by Matzenmiller et al. (1995). In this analysis, an element was assumed to fail when at least one of the damage variables exceeded 0.95 and either the ratio of its final volume to the initial volume was less than 0.1 or more than 4.0 or the axial strain along the fibre direction equalled at least 5%. Figure 2.17 shows fibre and the matrix tensile damage during impact with rigid impactor.
Shi et al. (2012) analyzed the impact damage of composite laminates numerically using ABAQUS FE software. The intra- and inter-laminar cracking was modelled using stress-based criteria for damage initiation. The non-linear shear behaviour of the composite was described by the Soutis shear stress-strain semi-empirical formula. The material damage model was implemented in the ABAQUS/Explicit FE code through user-defined material VUMAT subroutine. Interface cohesive elements were inserted between plies with appropriate mixed-mode damage laws to model delamination.

Costas et al. (2013) studied the frontal crashworthiness capabilities of carbon-fibre reinforced polymers, glass-fibre reinforced polyamide, polyethylene terephthalate foam and cork conglomerates in combination with cold-formed steel polygonal tubes using quasi-static and dynamic numerical simulation and verified with experimental results. The study proved that the tube with glass fibre reinforced polymer composite (GFRP) insert had shown the best results.

2.6 SUMMARY AND LIMITATIONS OF THE EXISTING LITERATURES

Based on the above discussion, it was understood that the collapse behaviour and energy-absorption characteristics change according to the change of shape, materials, and the end conditions. Among the different types and shapes of energy-absorber, the cylindrical and conical shaped tubes with circular cross-section absorb higher level of crush-energy during progressive collapse than the other forms of tubular members. Further, the conical shaped structural members facilitate progressive mode of collapse without any triggering mechanisms, i.e. providing chamfering or creating bending over the initial crushing regions, and they are self triggered to progressive crushing.
Most of the research work proves that the progressive mode of collapse increases the chance of safety of occupants by absorbing crush-energy in a progressive way through which, high level of damage can be minimized.

It is also observed that the collapsible members made by the combinations of metal and FRP materials together are having higher level of crashworthiness behaviour than the standalone performance of metallic or FRP structural members. Much research work was reported on energy-absorption performance of hybrid members in the form of cylindrical, square tubes and plates. However, limited work was reported on the crush behaviour of fibre over-wrapped metallic conical frusta under static and impact loading perspective.

Hence, it is necessary to study the crashworthiness behaviour of different semi-apical angled hybrid conical frusta under quasi-static and low velocity impact loading conditions in order to suite conical shaped hybrid member for crashworthiness application. From the literature survey, it is also understood that the influence of semi-apical angle, ply orientation and loading condition play a major role on the energy-absorption behaviour of conical shaped structural member. Therefore, the effect of above-mentioned parameters on the energy-absorption behaviour of hybrid conical frusta has to be studied.

It is also necessary to investigate the standalone crashworthiness performance of metallic and fibre reinforced composite conical frusta individually. The results can be used to access the level of improvement on energy-absorption performance of hybrid conical frusta due to wrapping of FRP over the metallic member. The study would be useful for selecting optimum parameters of conical frusta for energy-absorption applications.
2.7 OBJECTIVES OF THE PRESENT RESEARCH WORK

The present study is to overcome the limitations of the existing literatures with the following objectives.

- To study the crush load-resistance parameters such as first peak load \((P_{fst})\), maximum load \((P_{max})\), and the average load \((P_{avg})\) of thin-walled bare metallic, FRP and hybrid conical frusta under quasi-static and low velocity axial-impact loading conditions

- To study the influence of semi-apical angle, material, and loading conditions on the energy-absorption and specific energy absorption characteristics of thin-walled bare metallic, FRP and hybrid frusta

- To investigate the effect of fibre-ply orientation and wall thickness on the energy-absorption characteristics of FRP conical frusta

- To study the effect of impact mass on energy-absorption characteristics of metallic, FRP and hybrid specimens under impact loading condition

- To study the quasi-static and impact crush behaviour of metallic, FRP and hybrid condition conical frusta through Finite Element Analysis (FEA) technique and to compare the experimental and numerical results

- To study the collapse modes of metallic, FRP and hybrid conical frusta

- To investigate the crush zones of metallic, FRP and hybrid conical frusta to understand the reason for the change of crashworthiness characteristics and the failure patterns