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Progressive Crushing of Polymer Matrix Composite Tubular Structures: Review

Ali Rabiee, Hessam Ghasemnejad

Centre for Structures, Assembly and Intelligent Automation, Cranfield University, Cranfield, UK
Email: a.rabiee@cranfield.ac.uk, hessam.ghasemnejad@cranfield.ac.uk

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Abstract

The present paper reviews crushing process of fibre-reinforced polymer (FRPs) composites tubular structures. Working with anisotropic material requires consideration of specific parameter definition in order to tailor a well-engineered composite structure. These parameters include geometry design, strain rate sensitivity, material properties, laminate design, interlaminar fracture toughness and off-axis loading conditions which are reviewed in this paper to create a comprehensive data base for researchers, engineers and scientists in the field. Each of these parameters influences the structural integrity and progressive crushing behaviour. In this extensive review each of these parameters is introduced, explained and evaluated. Construction of a well-engineered composite structure and triggering mechanism to strain rate sensitivity and testing conditions followed by failure mechanisms are extensively reviewed. Furthermore, this paper has mainly focused on experimental analysis that has been carried out on different types of FRP composites in the past two decades.

Keywords

Crashworthiness, Fibre-Reinforced Polymer Composites (FRPs), Metal Tube

1. Introduction

Axial crushing of metal tubes has been studied by vast majority of researches. Metal tubes have energy absorption mechanism of plastic deformation due to progressive folding formation [1]. Some researcher increased wall thickness to increase mass volume energy absorption ratio [2] [3], and furthermore for better energy absorption, foam filled aluminium and stainless steel tube were introduced [4]. Other researchers introduced metals in inner core of sacrificial cladding structures [5] [6] [7]. However, due to high expense of material, manufacturing and maintenance for metals and also heavier sacrificial structure, these types of structures were found insufficient [8] [9]. Alternatively, in terms of specific energy absorption and weight reduction polymer composite materials are comparatively introduced to improve structural energy absorption capabilities as well as further weight reduction [10] [11].

In passenger carrying application such as aerospace and automotive where weight concerning application is an important factor, these improvements are no longer relevant due to fuel consumption. Consequently, fibre reinforced polymer (FRP) composites have been extensively studied due to weight to stiffness in comparison with metals [12] [13]. Researchers concluded that a well-engineered FRP composite structure would be an appropriate choice where energy absorption is concerned [14] [15] [16]. Composite materials such as carbon fibre reinforced polymer and glass fibre reinforced polymer encounter fractures in axial crushing to absorb energy unlike metals which absorbs energy by plastic deformation [17] [18]. Savona CS [15] stated that the majority of energy absorption is obtained through failure modes of Mode I and Mode II fracture, frond bending, fibre fracture and also friction at crushed fronds [19].

One of the main factors that FRP composite materials are commonly used in high performance automotive and airframe substructures is having capabilities of high-energy absorption. The structural elements used in high performance automotive and aerospace applications are mainly from FRP composites, which are economically beneficial due to weight reduction and lower fuel consumption. Furthermore, FRP composite materials provide enhanced level of structural vehicle crashworthiness that ensures high-energy absorption in sudden collision in a controlled progressive collapse. This is dominated as a result of extensive fracture mechanisms [17] [20] [21] [22].

FRP composite materials are known for being tailored to improve material properties based on specific applications with high specific strength and verification of fibre and matrix, and fibre orientations. This factor makes this type of materials more advanced compared to more conventional isotropic materials.

There are several ways to absorb impact energy. Deformation of solids is usually based on plastic flow, although appreciable amounts of energy can be absorbed by controlled brittle fracture mechanisms. Absorbers can also be reusable like a hydraulic damper; rechargeable with the energy absorbing component being replaced in a permanent container; or expandable, as in the collapse of a vehicle structure during a crash. Composite materials have a significant potential for kinetic energy absorption during a crash. The application of energy absorbers depends on the type of impact load. This can be distributed over the whole impact body, as in explosion loading, or it can be localised, with a small or pointed body hitting a large body. The large body may deform in an overall manner in the same way as if the load were distributed, or the small body may penetrate it locally.

Other studies [10] [23] [24] investigated the parameters that influence composite tubes crushing performance. Higher energy absorption is yielded by progressive crushing process which depends on mechanical properties, fibre orientation, laminate stacking sequence, fibre and resin volume fractions, and the geometry of the tube. However, different levels of the specific energy absorption for the same parameters can be achieved by only altering the geometry of composite structures [17]. Various dimensions affecting the energy absorption were studied [25] [26] for square and circular composite tubes. It is concluded from experimental studies that the D/t ratio of these composite tubes significantly affects energy absorption capability. Thornton *et al.* [27]

[28] stated that circular cross sectional composite tubes perform better compared to square and rectangular cross sectional composite tubes. Similar conclusion was also reported by Mamalis *et al.* [29] [30] that circular cross sectional composite tubes demonstrated a better performance in energy absorption capability. Jimenez *et al.* [31] investigated "I" sectional tubes. Based on the study square cross sectional composite tube absorbed 15% more energy compared to "I" section profile. Mamalis *et al.* [32] [33] [34] studied conical shells on their specific energy absorption capabilities, and concluded that specific energy absorption decreases by increase of semi-apical angle of the frusta. Many researchers [17] [24] [32] [33] [34] [35] [36] conducted experiments on energy absorption of composite tubes both circular and square cross sections. It was concluded that geometrical shape significantly influences the energy absorption capability of composite structures.

Farley and Jones [29] [37] studied various layup orientations on the carbon/epoxy composite tubes. According to their results, as lateral angle increases, the specific energy absorption decreases. An improvement of 10% - 30% in specific energy absorption corresponded to include angle reduction from 180˚ to 90˚. Elgalai *et al.* [38] studied carbon/epoxy and glass/epoxy composite tubes for their crush response under quasi-static axial loading.

Energy absorption capability of composite tubes reported to be enhanced by corrugation. Zarei *et al.* [39] investigated and experimented on hexagonal box with vertical ribs for their energy absorption capabilities using woven fibre glass/polyamide plates with thermoforming welding method. Abdewi *et al.* [40] studied radial corrugated glass/epoxy composite tubes both at quasi-static axial and lateral crushing. The conclusion of these studies stated that radial corrugation significantly influences the energy absorption of composite tubes.

Extensive experimental researches have been carried out on the effects of fibre orientations in composite fabrication on axial crushing behaviour. Carroll *et al.* and Mahdi *et al.* [41] [42] [43] carried out an investigation on filament-wound glass fibre/epoxy with ply orientations of ±55˚ under quasi-static compression, and reported that failure depends on rate of loading and stress ratio. Strength and stiffness were implied to be a function of loading direction and stress strain behaviour influenced the total energy absorption. It was also suggested that ply orientations of (±0) and (±90) of carbon/epoxy fibre are able to crush more progressively and absorb more energy in comparison with (±45) [7].

In axial crushing the aspect ratio of geometrical parameters were also studied. Mamalis *et al.* [19] studied the effect of L/w (length/inner width) ratio on axial crushing capability and concluded that as the aspect ratio of compressed tube increases, the peak load $(F_{\max})$ decreases. Palanivelu *et al.* [44] showed that crushing state was influenced by aspect ratio of t/d or t/w (wall thickness/outer diameter or width) of 0.045 in different shape *i.e.* both geometries of square and round tube crushed progressively, although catastrophic crush in square tube was observed, however in aspect ratio of 0.083 both shapes were progressively crushed [45]. It is proven that progressive crushing for composite tubes of circular cross section can be obtained by t/D ratio of 0.015 - 0.25 whereas t/D ratio of less than 0.015 results into catastrophic failure [46].

The energy absorption capability of composite materials offers an exceptional combination of structural weight reduction and vehicle safety improvement with providing an equivalent or higher crash resistance compared to metallic structures. In automotive industry the basic occupant crash protection since 1950s has been used to optimise crash safety and ever since it became the priority of any car design requirement. The study of first structural design requirements in aeronautical industry were crash protection in military helicopters and light flexing aircraft that were in crash survival design guide forms [47]. In aerospace application the material structures considered are high performing materials including epoxy resins reinforced glass fibres, and increasingly, carbon and aramid fibres on hybrids composites. In automotive field reinforced polymers must meet a complex set of design requirements among other crash energy absorption management in front-end and side of the car structures [48] [49] [50].

This paper, reviews the influence of various parameters on progressive crushing. Most review papers focus on one or two parameters whereas this paper focuses on the most critical parameters and covering mostly all parameters that could potentially alter progressive crushing behavior of composite structures. Anisotropic materials are non-linear and by consideration of the parameters introduced, explained and evaluated in this paper, a well-engineered composite structure can be tailored. This paper undergoes evaluation of well-engineered composite structure, followed by different trigger mechanism. Moving on to different aspect of strain rate sensitivity and loading parameters, followed by extensive evaluation of failure mechanism and interlaminar fracture toughness. Simply, composite structure design, testing conditions, and failure mechanisms are extensively reviewed.

The following sections are structured initiating from introduction of crushing behavior criteria and gradually moving on to factors effecting energy absorption capabilities and different failure modes. The paper then initiates with effect of fibre and matrix on energy absorption capabilities followed by laminate design, geometry. These criteria are sensitives; a simple alteration can lead to change in material behaviour. Trigger mechanism enables to initiate failure and avoid local buckling. At this stage a detailed review of composite structure from tailoring and triggering is complete and testing begins. Different types of strain rate and loading conditions are introduced and evaluated, followed by different types of failure mechanisms. Theoretical analysis is introduced to predict energy absorption followed by crashworthy of composite box structures. The last section is spent on interlaminar fracture toughness, this is accompanied by various fracture mechanism of interalaminar and interlaminar, which is a great evaluation of progressive failure modes that leads to high energy absorption capabilities of composite structures.

2. Valuation Criteria for Crushing Behaviour

In the study of energy absorption capabilities of FRP composite materials, important variables such as manufacturing process and method, microstructures, specimen geometry, crush initiator and trigger mechanisms, and crushing rate are investigated. Specific energy absorption (SEA) performance is considered to be of the most important parameters of specimens crushing material or collapsing or structural parts. SEA value is the relation between energy absorption compared to the absorber's mass or structure. Consequently, it becomes critically important for lightweight designs. Study of energy absorption for energy management capabilities is another critical factor, which is the shape of the force-crush distance curve. Identification of one measure is used to mark and indicate the shape of the curve, which is known as crush-force efficiency (CFE). This value relates the average crush force (F_m) to the maximum force $(F_{\max})$ of the crush characteristic.

Within the initiation phase the highest force normally occurs. Absorbers with rectangular shape of force-crush distance curve demonstrate a crush force efficiency of 100%. It is not optimum to have the maximum force to be substantially larger than the average crush force, due to energy management's goal of absorbing all the energy without conveying or transmitting large amount of force to the passengers.

Another parameter in energy absorption management is stroke efficiency (SE), which is the ratio of initial length of the absorber to the stroke at 'bottoming out' and high ratios specify high efficiency of material used.

3. Factors Affecting Energy Absorption Capability

In this section several variables related to energy absorption of composite thin-walled components are reviewed. In composite materials, design with constituent material properties and reach macro-mechanical properties by micromechanics analysis [21]. Regarding different applications of composite materials, their suitability is defined by impact properties and energy absorption properties and then usual design parameters.

However, composite material constituent phases and the laminate layup is crucial in crashworthiness capability of composite structures as it effectively changes the mechanical property of the final product. Temperature is another important factor, which has considerable effects on material crashworthy response.

Quasi-static compression or impact loading is carried out in axial crushing. In static loading the crushing speed is within a range of 1 to 11 mm/s, normally a composite tube is compressed between two plates (crossheads) of one being hydraulic press. In dynamic impact loading a drop hammer or an impactor is used. To avoid buckling, specimen dimensions are determined based on the preliminary calculation [51]. Different shapes and geometries such as round, square, hexagon [44], cones [51], and plates [13] are used for instance. A typical specimen length is within a range of 50 - 125 mm in length, 20 - 100 mm in outside diameter or width and wall thickness of 1 - 3 mm.

In crushing event energy absorption capability is calculated to work out the specific energy dissipation rate. In composite crushing total work (W_T) that indicates the energy absorption capability is equal to the area under the load-displacement curve,

$$W_T = \int F \mathrm{d}s \tag{1}$$

where F is the corresponding force on the structure and s is the cross-head distance.

Specific Energy Absorption (SEA) is energy absorption capability, which is calculated as per unit mass absorbed.

$$\mathrm{SEA} = \frac{W_T}{m} = \frac{W_T}{qv} \quad (2)$$

where m is crushed mass, q is the material density, and v is the volume of crushed specimen.

In prior of material failure under buckling such as global buckling, local buckling, fracture or yield or progressive crushing peak load is measured [52]. Further buckling failure can lead to either catastrophic or progressive failure [53] where it illustrated on load displacement curve, where the area under the curve represents the total energy absorption. In occurrence of progressive failure, a larger area under the curve is gained with a progressive constant load with increase of crushing displacement.

Catastrophic failure leads to rapid load drop and lower energy absorption. This is due to specimen crush being from fracture in mid-plane [54] or longitudinal cracks [44]. Progressive failure results into higher energy absorption due to a combination of multi-failure modes initiated during crush such as local buckling, Mode I, Mode II, and Mode III [55]. More energy absorption is obtained from Mode I, Mode II, splaying mode and sliding mode respectively [56] due to bending and friction between ply laminates [13]. Fibre orientations influence the energy absorption in Mode I interlaminar fracture [57]. In study of Mode III although lower energy absorption is obtained of compressed tubes due to fracture in mid-plane and unstable collapse [19], this contradicts with another study that stated failure in Mode III is due to fibre fracture and matrix deformation that progressively extends through elliptical structure with ratio of 2, which resulted into higher specific energy absorption [55].

3.1. Fibre and Matrix Materials

The vast majority of literatures on crashworthiness of composites are focused on fibres of carbon, glass or aramid in thermosetting resin for instance epoxy. Farley [58], Thornton [59], Schmueser and Wickliffe [60] and Farley and Jones [61] all extensively experimented and compared energy absorption capabilities of various specimens made of glass, carbon and aramid epoxy. Hybrid composites were investigated to combine different types of fibres into a single laminate to optimise the energy absorption characteristics. Thornton and Edwards [62] stated that hybrids of glass-aramid and carbon-aramid cause an unstable folding collapse that would not have occurred if the specimens were composed of glass or carbon fibres alone. New fibre and matrix materials such as Dyneema PE fibre/carbon fibre hybrid [63] have been introduced to improve specific energy absorption capabilities. The majority of these investigations have been carried out with thermosetting matrix materials, usually an epoxy. Other thermoplastic matrix materials such as polyester and polyetheretherketone (PEEK) have been used as matrix material [64] [65].

Hamada *et al.* [65] conducted a study on the usage of a thermoplastic polyetheretherketone (PEEK) matrix with fibre carbon which concludes an outstandingly high specific energy absorption value of 180 kJ/kg. This value of energy absorption is even more than a double value of carbon-epoxy. This is credited to PEEK matrix that has high resistance towards crack growth between the fibres, which prevents failure and results into stable progressive crushing [66].

3.2. Laminate Design

In this section several variables related to energy absorption of composite thin-walled components are reviewed. In composite materials, design with constituent material properties and reach macro-mechanical properties by micromechanics analysis [21]. Regarding different applications of composite materials, their suitability is defined by impact properties and energy absorption properties and then usual design parameters.

However, composite material constituent phases and the laminate layup is crucial in crashworthiness capability of composite structures as it effectively changes the mechanical property of the final product. Temperature is another important factor, which has considerable effects on material crashworthy response. Various reports have been extensively concentrated on the effects of laminate design on energy absorption of composite structures. Thornton and Edwards [62] showed, in a stable collapse a $[\pm 45/\pm 45]_n$ layup resulted into obtaining lower energy absorption value than $[0/90]_n$ lay-ups. Furthermore, the specific energy absorption generally increases in $[0/90]$ aramid-epoxy and glass-epoxy circular tubes for $45^\circ < \theta < 90^\circ$, with increasing of θ. Schmueser and Wickliffe [60] showed variations in specific energy absorption of carbon-epoxy, glass-epoxy and aramid-epoxy $[0_2/\pm\theta]$ specimens all generally increase with increasing θ. Mamalis *et al.* [67] worked on different materials with various thin-walled circular and square tubes, and reported specimens made of a commercial glass fibre and vinyl ester composite material which consists of nine plies in the sequence of $[(90/0/2R_c)/(2R_c/0/90)/R_{c.75}]$, show better energy absorption behaviour than those made of a glass fibre composite material in which the glass fibres were in the form of chopped-strand mat with random fibre orientation in the plane of the mat. Hamada *et al.* [64] reported that the specific energy absorption for 0° carbon/PEEK tubes was due to high fracture toughness of PEEK.

Woven composites introduce a different approach to the fabrication of thick sections for use in primary and secondary structural applications. Interlacing two mutually perpendicular sets of yarn shapes woven composites. The lengthwise clothes are called warp and the crosswise clothes are known as fill or weft (see **Figure 1**).

Warp and weft's interlacing pattern are known as weave. The fundamental two-dimensional weaves are plain, twill and satin, where it provides more balanced properties in the fabric plane than a unidirectional laminate [68] [69] [70] [71]. The interlacing of fibre bundles in woven composites can often increase out-of-plane strength as in the case of three-dimensional woven fabrics. Woven fabrics are thicker than unidirectional lamina; therefore, fabrication of thick composites is less insensitive and less prone to assembly error.

The property improvements are achieved through in-plane stiffness and strength properties. The weave architecture influences the loss of in-plane stiffness and strength. This architecture is complex and therefore several parameters control the mechanical and thermal properties of woven composites. The classical laminate theory cannot be used to predict the mechanical properties of woven composite due to many specific factors including the density of the fibre bundles, the type of the weaving and the curvature that are essential to be considered [72]. Furthermore, the composite structure manufacturing is rather irregular in woven composite that can be eliminated in a

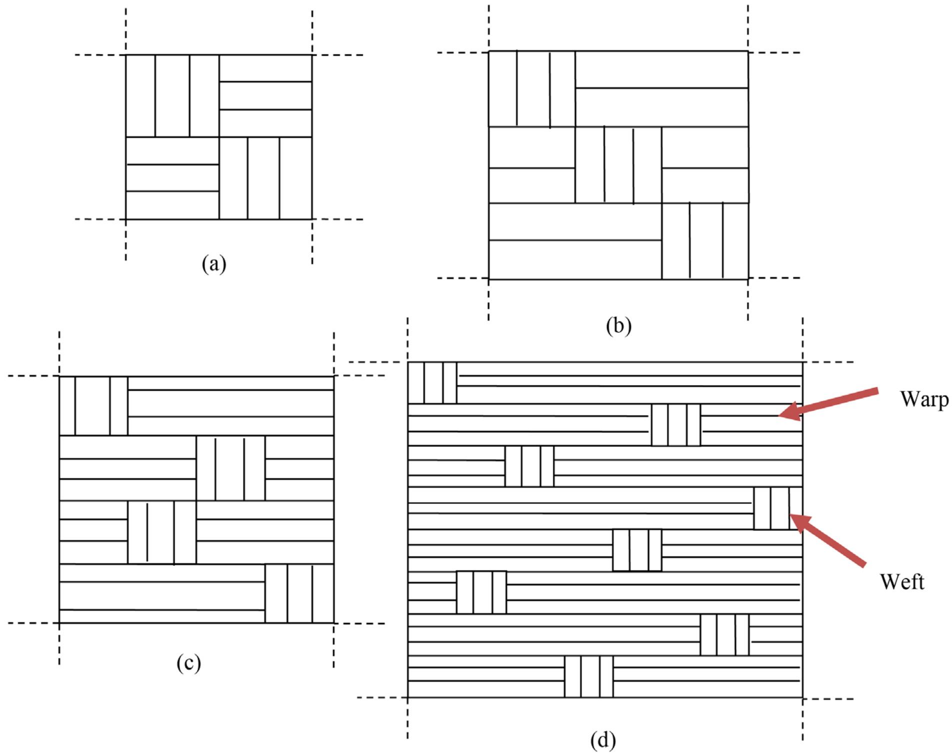


Figure 1. 2D-Weave composites: (a) plain, (b) twill, (c) 4-harness, and (d) 8-harness [57].

non-woven laminate.

In brief, two approaches that are usually employed to study non-woven composite laminates are *micromechanics*, and *macromechanics*. In micromechanics study, the mechanical properties of laminate are studied in details as (fibre, matrix and interface), while the macromechanics detects the material properties of laminate as a whole. Another approach, which is an intermediate of study, is called *mesomechanics*. This approach is provided to consider the mechanical properties of weave [73]. The major problem in the study of mesomechanics is the large variety of textile performs that are employed including weaves, braids, knits, mats, properties of weave stitched fabrics and two-dimensional or three dimensional.

3.3. Structural Geometry

Extensive research was carried out based on the effect of various type of specimen geometry on the energy absorption capability by varying the shell geometric parameters such as wall thickness, t, axial length, L, mean diameter, D, or circumference, C [21]. Farley [74] reported the energy absorption capability of diameter to thickness, D/t, ratio for carbon-epoxy and aramid-epoxy circular tubes are a non-linear function. Furthermore, Farley reported that carbon-epoxy tubes are dependent on D/t for tubes with various internal diameters. Mamalis *et al.* [50] indicated that energy absorption of glass polyester circular tubes in static axial loading increases with increasing t/D. Thornton and Edwards [62] concluded that the energy absorption of square and rectangular cross-section tubes is less than circular ones. The primary reason for this energy absorption reduction is due to the corners and the edges response to stress concentration leading to the formation of splitting cracks.

Axial crushing with cross sectional shape, Palanivelu *et al.* [44] investigated shapes of square and hexagonal with t/D or t/W aspect ratio of 0.045 and reported catastrophic failure whereas circular shape crushed progressively and uniform. An increase in aspect ratio to 0.083 resulted into progressive crushing mode for square and hexagonal shapes. This increase also resulted into higher SEA value of 30.4 kJ/kg in circular shape compared with square with 12.3 kJ/kg and hexagonal 16.4 kJ/kg. Abdewi *et al.* [75] studied composite tubes of circular cross section (CCS) and radial corrugated cross section (RCCT), and concluded that circular cross section had lower peak loads and lower specific energy absorption compared with corrugated tubes. However, circular composite tubes with inner radial corrugated (RCSCT) did not succeed to show any improvement in load carrying capacity [76].

Mahdi *et al.* investigated structures of glass/epoxy composite, and the elliptical ratio effect on the normalised SEA, E_{Ns} [55]. SEA equation was divided by cross-sectional area of the elliptical area to modify E_{Ns}. It was concluded that compared to circular tubes, ellipticity ratio of 2.0 has higher E_{Ns} and an increase of ellipticity ratio results into higher E_{Ns}.

Mahdi [77] also studied four different GFRP tubes with various cross-section properties under quasi-static crushing. The specimens included circular cross section, fuselage-shaped cross section and circular cross section with radial-geometrical reinforcement. The author concluded from the results that tubes with radial reinforcements had the highest values for peak load and an average crushing load, crush-load efficiency, absorbed energy, and specific-absorbed energy in comparison to other geometrical shapes.

In study of geometry, Mahdi *et al.* [78] studied conical shell angles effect on the crushing capability. It was concluded that better energy absorption on SEA of cylindrical structure with E_s value of 24 kJ/kg. Furthermore an increase in cone vertex angle results into decrease of SEA, peak load (P_L) and volume reduction (V_R). Alkateb *et al.* [79] states that crushing behaviour was under influence of vertex angle within elliptical cone design. In more details, in elliptical cone vertex angle of 12˚, an increase in vertex angle decreases crushing load. Energy absorption improved with increase in vertex angle.

Libo Yan [80] studied crashworthiness characteristics of natural flax fabric reinforced epoxy composite tubes under quasi-static uniaxial compressive load. The author concluded that short length and large number of composite plies results into large value of peak load and CFE. Increase in number of plies for specimens with the same inner diameter and length also increases crushing energy absorption capability significantly. Energy absorption capability of flax/epoxy composite tube is dependent on geometry of the tube and the performance of composite tubes is superior to conventional metal energy absorbers.

Elfetori *et al.* [81] studied the effect of radial corrugation geometry on the crushing behaviour and energy absorption of circular composite tubes under quasi-static axial compression. The author based on experimental results concluded that structural geometry influences the crushing behaviour and also radial corrugation geometry improves sliding mode of the structure. Radial corrugation geometry of circular composite tubes also improves energy absorption capability.

Perowansa [82] studied FRP pultruded composite square tubes under axial or oblique impact load. The author concluded that higher impact angle causes lower energy absorption capability. The impact angle and eccentricity of impact load plays an important role in determining the energy absorption capacity.

Palanivelu *et al.* [45] studied different geometrical structures, mainly on conical circular (CC) type made of glass fibre reinforced polyester composites shown in **Figure 2**. It was concluded from the work that HG-A and HG-B showed higher SEA value of 21.1 kJ/kg and 22.5 kJ/kg, respectively compared to HG-Y and HG-X that had SEA values of 13.0 kJ/kg and 6.96 kJ/kg, respectively. The failure mechanisms of HG-X and HG-Y were not catastrophic but due to lack of circumferential delamination. Palanivelu *et al.* [17] [18] studied conical circular geometry of CC-Y and CC-X, and concluded that CC-X showed lower SEA compared with energy absorption value of 23.5 kJ/kg, and 28.8 kJ/kg, respectively.

Mahdi *et al.* studied similar cone-tube-cone composite structure to HG-A [83]. It was stated by the author that specific energy absorption was under influence of tubular part height where normalised tubular height and high SEA value was shown in height/ total height ratio between 0.06 and 0.11. In another study by the author HG-B cone-cone intersection composite with different vertex angle was studied [84]. It was concluded that more energy absorption was obtained from vertex angle of 20˚ and 25˚ compared to 10˚ and 15˚ vertex angle. In carbon and glass fibre comparison it is shown that using fibre as reinforcement enhances energy absorption capability due to enhancement in materials properties. Both materials showed similar trend in material behaviour, increasing vertex angle results into increase of SEA and crushing load.

In summary circular shapes geometry have outstanding performance compared to other geometry shapes tested. Moreover, compared to other shapes apart from radial corrugated circular, circular shapes geometry absorbs most of axial crushing energy. In studies of geometry, highest resistance in the event of crushing was obtained from structure body parallel to the applied load. Lastly in axial crushing, increase of structure angle in any part of structural body affects the SEA.

Farley [74] conducted a study of the influence of specimen geometry on the energy absorption capability and scalability of composite materials by static crushing tests on

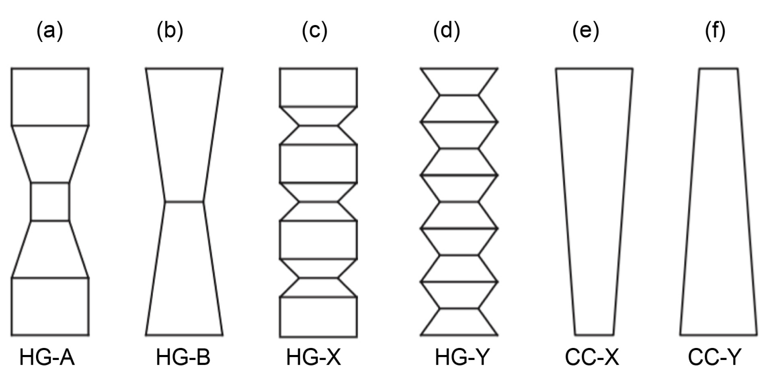


Figure 2. Types of hourglass (HG) and conical circular [44].

graphite/epoxy and Kevlar/epoxy square cross section tubes. Czaplicki *et al.* [85] reported that significantly higher energy absorption of tulip-triggered specimens were observed compared to bevel triggered specimens of the same geometry and material. An external bevel or chamfer ground into one end of the specimen is one of the most common types of crush initiators [86]. Various types of crush initiator are shown in **Figure 3**.

3.4. Trigger Mechanism

Triggering is a process that initiates failure, and avoids load transfer to the whole structure by formation of stress concentration on edges of the profile geometry. Triggering mechanisms therefore prevent composite structures from crushing catastrophically. A suitable selection of triggering helps with progressive crushing so the crush load is at maximum and the load is at a relevant constant value due to various fracture mechanisms such as splaying, fracture modes, etc.

Few studies [34]-[40] [46] stated that more energy was obtained by fibre orientation along the axis of the tube compared to other orientations. Other researchers studied the performance of composite structures based on the effect of *t*/*D* ratio and size [87] [88]. The conclusions of these studies were that the overall energy absorption capability of composite tubes determined by the fracture mechanisms that influenced by structure dimensions. To maximise energy absorption and decelerate crushing process, all the composite tubes during impact should exhibit axial cracking, fibre fracturing modes, delamination and bending [24]. Many researchers [23] [25] [26] [34] [89] [90] studied edge chamfering and "I" sectional tubes to investigate its effects on the energy absorption capabilities [31] [36].

Jimenez *et al.* [53] investigated the effect of triggered composites profile on energy absorption capabilities. Composite tubular type-B with triggering angles of 30˚ and 60˚ (see **Figure 4**) reported to perform 25% deference in level of specific energy absorption. Type-B at 60˚ showed a peak load value of 74.7 kN which is the highest. Other investigations were reported on the effect of triggering of different cross-sectional shapes. It is reported that under quasi-static axial crushing the peak load is at maximum with edge triggering at 45˚ compared to 90˚ tulip triggering [45]. However, tulip triggering showed higher specific energy absorption for all cross section tubes tested than edge

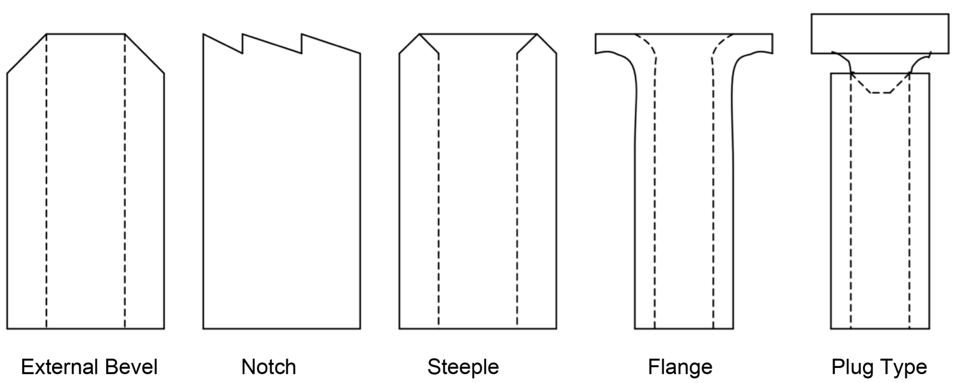


Figure 3. Various types of trigger mechanism [70].

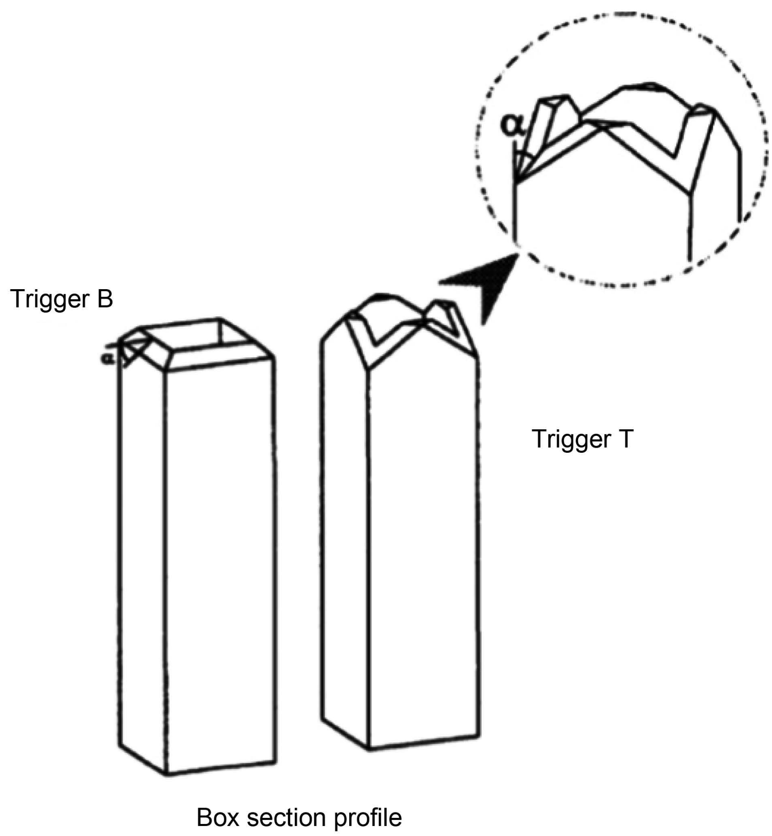


Figure 4. Types of triggering [53].

triggered. Palanivelu *et al.* [91] investigated the effect of edge trigger and tulip type triggering for round shape on specific energy absorption, and reported an increase of 7% - 9% with edge trigger. However, opposite reaction was observed from square shapes. Tulip type triggering showed higher specific energy absorption of an increase of 16.5%. Energy absorption analysis on triggered effect was carried out using carbon and glass hybrid and non-hybrid composite braided rod [92]. It was concluded that progressive crushing was observed from conical triggered rod compared to non-tapered rod that leads to axial crack.

3.5. Strain Rate Sensitivity

Extensive work of many researchers has been studied to investigate the influence of strain rate on energy absorption of composite thin-walled structures. Farley [93] reported that matrix stiffness and failure strain are a function of strain-rate and the energy absorption of interlaminar crack growth (delamination) may be considered as a function of crushing speed. Later Farley reported that in $[0/\pm\theta]_2$ carbon-epoxy tubes the energy absorption was not a function of crushing speed, and also found that the energy absorption in $[\pm\theta]_3$ carbon-epoxy specimen is a weak function of crushing speed with an over the speed range tested, which resulted into an increase in energy absorption of around 35%. Mamalis *et al.* [21] showed that the strain-rate effects the friction mechanisms developed between crushing surface and different new surfaces created after interlaminar crack growth.

3.5.1. Low Impact Velocity

FRP composite have mechanical property of orthotropic that results into complex damage modes including delamination and microbuckling. FRP composite have complicated with multiple forms of damage mechanisms. At different stages of impact matrix cracking, delamination and fibre breakage can occur and one or more being dominant [94].

In case of low velocity impact according to Cantwell and Morton [95] either of striking velocity that referred to velocities up to 10 m/s reconstructed by testing a falling weight impact, and according to Abrate [96] impact velocity test of less than 100 m/s or as suggested by Liu and Malvern [97] the extent of damage on the material that arise from different sources including drops, foreign object hits, hailstone impact, maintenance and in-service impacts. In metallic materials the stress induced from low velocity impact due to ductile nature and high potential of energy absorption may not be considered threatening. However, in composite materials at micro-scale level, low velocity impact may induce significant damages, resulting into reduction of strength and stiffness of the material [96] [98]-[106].

Extensive research of FRP composites has been conducted at low velocity impact damage to study further the complex nature of damage mechanisms. Both properties of impactor and impacted material which influence the impact loading in FRP composites and could result into different failure modes [107] [108]. Composite materials subjected to low velocity impact encounter failure modes of matrix mode, delamination mode, fibre mode and penetration [109]. Incipient impact energy, Fibre/matrix configuration, composite laminate thickness, impact velocity and impactor shape are essential parameters towards different types of failure modes. In composite materials, the interaction between failure modes affect energy dissipation properties and damage progress.

Low velocity impact in composite material has two critical threshold forces, Hertzian failure load and maximum impact load, with two critical threshold energies, penetration energy and perforation energy. Initial sign of significant damage in laminated composites subjected to low velocity impact is delamination. Delamination failure is categorised as damage threshold known as Hertzian failure force [110] [111]. Delamination failure occurrence is due to lack of fibres contribution to overall strength within the thickness direction whist subjected to out of plane stresses generated by impact loading. At the interfaces delamination transpire between plies that debonds individual laminas due to bending deformations of adjacent plies differences.

Fibre fracture and laminate failure modes, which are the main damage mechanisms occur whist reaching maximum force threshold and develops up until maximum energy level is reached [110] [112] [113]. However, at low impact energy, matrix cracking occur although it does not degrade the mechanical properties, delaminations significantly affect the laminates performance. Fibre damage, additionally, result laminate failure (main failure) in laminates of composites.

Shyr and Pan [110] studied the effect of low velocity impact damage characteristics on various reinforced fabric structures with different laminate thicknesses. The study signifies number of ply layers which determines the energy absorption capability. In thick laminates the dominating failure mode was fibre fracture whereas in thin structures delamination is more influential. The author concluded that the major threshold load damage was independent to incipient impact energy, but dependent to laminates thickness. Similar conclusions were reached and stated by Belingardi and Vadori [112].

Yang and Cantwel [114] investigated experimentally the effect of varying key impact parameters on the damage initiation threshold of temperatures of 23˚C to 90˚C at low velocity impact tests on (0˚, 90˚) glass/epoxy laminated composites. The authors concluded that initial threshold damage showed a $t3/2$ dependency, where *t* is thickness of the laminate, at both room and elevated temperatures.

Energy thresholds of penetration and perforation, which are among the main characteristic properties subjected to low velocity impact in FRP composites can be determined using energy profiling technique. A correlation between characteristic impact properties and major failure modes can be developed using energy profiling technique [115]. Quaresimin *et al.* [116] studied the effects of laminate thickness and stacking sequence on energy absorption capability under low velocity impact using woven carbon-epoxy composite laminates. The authors concluded that threshold energy and delamination threshold load for initial failure are inconsiderate to laminate lay-up and impact energy. Whereas laminate lay-up showed to be quite independent by maximum contact force which increases slightly with impact energy.

3.5.2. Loading Conditions

In engineering applications generally, the loading classification are static, fatigue, high speed/rapid loading and impact. These loads are categorised according to the rise time of the load. For static loading this time is 3 times greater than the fundamental period of the mechanical system. Fatigue loading occurs when rise time from one magnitude to another magnitude is greater than 3 times of fundamental periods. This time for high speed loading is between 1.5 to 3 times the fundamental periods of the mechanical system. The rise time for impact loading is less than half times the fundamental period of the mechanical system. Impact is an important area of applied mechanics, which is strongly related to engineering practice, such as structural engineering, manufacturing engineering, aerospace engineering and material engineering. The application of impact is endless and has resulted in significant achievements both technically and economically [117] [118] [119].

For a period of short time the impact process involves relatively high contact forces acting over a small area. At the point of contact of two solids, local strains generated that results into energy absorption [86]. The impact event may result in damage if energy absorption exceeds a threshold. A laminated composite facing a projectile strike, results into fracture processes involving delamination, matrix crack and fibre fracture. Impact is defined for studying of force acting locally as a resulting of the impact event. Contact law relates a connection between the contact force and the indentation, which can be interpreted into the difference between the displacement of the projectile and the back face of the laminate.

The initial response of impact loading is to cause damage near the surface of the laminate. Although the inner layers of the composite are damaged as well and the material stiffness changes locally as the projectile penetrate into the laminate [120]. In the duration of the impact event it cannot be assumed that the contact force to be constant [121] [122]. Furthermore, different projectile geometries were employed in order to reproduce real loading situation to measure the modifications of the composite reaction [123].

In quasi-static model testing, the impact response is a function of time dependant and the composite model is expressed as a time dependent force that is represented by an equivalent mass with equivalent stiffness [124] [125]. All forms of damage should be studied and considered due to the likelihood of the influence of the material residual mechanical properties, from each damage form.

4. Collapse Modes and Failure Mechanisms

Three main modes of brittle collapse are categorised as mode I, II and III which were studied on square tubes in the series of static and dynamic axial compression tests, respectively [126]. According to Hull classification [17] Euler overall column buckling or progressive folding with hinge formation were not found for fibre-reinforced plastic (FRP) composite tubes. Energy absorption in most fibre-reinforced composites are through a combination of fracture and friction [127]. The two main failure mechanisms of composite tube are catastrophic and progressive failures (see **Figure 5**). A stable progressive crush is established by localised failure that initiates at one end of the specimen and progress through the specime. To reach this failure mechanism, crush initiator is used for FRP tubes. During catastrophic failure the initial maximum force is very high and drops rapidly, therefore the average force is low.

4.1. Failure Mechanism

According to Mamalis *et al.* [126] in general the failure modes observed are greatly affected by the shell geometry, fibres arrangement, matrix and fibres properties of the composite material and the stacking sequences. Moreover, the macroscopic collapse modes in **Figure 6** was classified by Mamalis *et al.* [126] [127] [128] from various geometries in extensive experimental treatment of axisymmetric tubes made of fibre-reinforced polymer matrix composite materials.

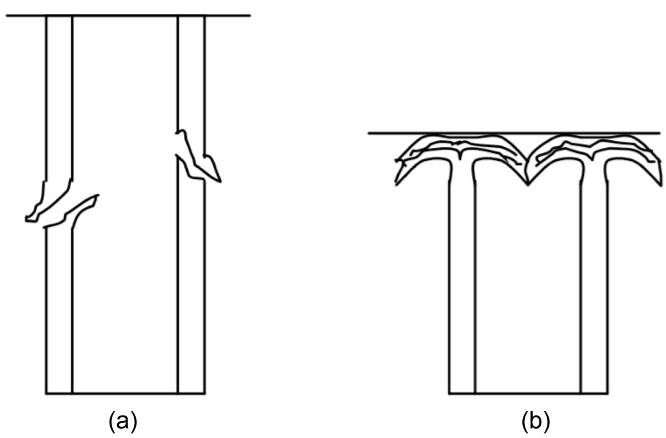


Figure 5. Typical collapse modes for composite tubes (a) catastrophic failure (b) progressive failure [127].

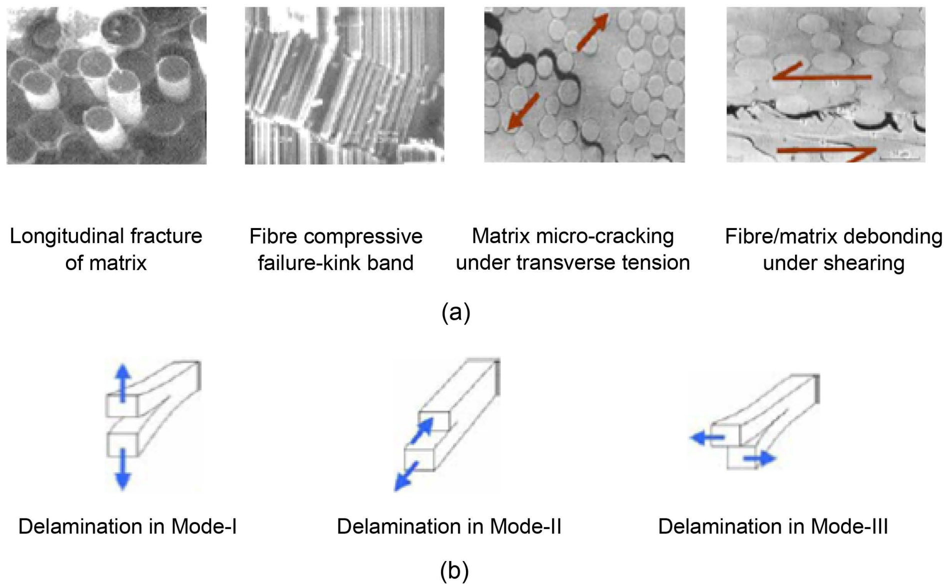


Figure 6. Fracture mechanisms observed in laminates (a) Interalaminar and (b) Interlaminar Failures [129].

4.1.1. Progressive Failure

Composite material progressive crushing with micro-fragmentation, associated with high crush energy, is designated as mode-I. Progressive failure mode is classified by the progressive end-crushing with splaying of the laminate tube starting at one end of the specimen. This causes the tube to form continuous fronds which spread outwards and inwards.

4.1.2. Catastrophic Failure

The component's brittle fracture with little energy absorption resulting in catastrophic failure is designated either as Mode-II or Mode-III depending on the crack formation. Mode-II is classified by a spiral or longitudinal crack propagation developed along the shell circumference. Mode-III is classified by the circumferential fracturing formation of the specimens approximately equal to the mid-height of the shell into irregular shapes, and described as mid-length collapse mode.

4.2. Progressive Folding

Similarly, to crushing behaviour of thin-walled metal and plastic tubes, progressive folding and hinging have a very low energy absorbing capacity, which is introduced as Mode-IV. Mamalis *et al.* [48] [49] reported that the collapse modes can be categorised into two groups of stable and unstable collapse modes. Stable collapse modes have similar features as static loading whilst at the same geometries. According to Mamalis *et al.* [126] in some applications a failure could be considered by a very small deformation, and in others a total fracture or separation constitutes failure. In composite materials generally, the internal material failure initiates before any alteration in macroscopic appearance or behaviour. This indicates that failure takes place before any indication in macroscopic molecules.

Various fracture modes can be defined for a laminate composite. These modes are divided into intralaminar and interlaminar fracture modes. Intralaminar mode consists of longitudinal matrix fracture, transverse matrix fracture, fibre-matrix debonding and fibre fracture. Interlaminar mode is also referred to as delamination. Delamination is described as separation of layers from one another (see **Figure 6**). The fracture mechanisms depend upon the nature of the constituents including architecture of the layers, and mechanical loading mode [129].

Mamalis *et al.* [21] reported that the main microfracture mechanism features of composite tubes are similar to that obtained for circular tubes. These microfracture mechanisms are:

- An annular wedge of highly fragmented material, axially forced downwards through the shell wall;
- Ahead of the crush-zone an intrawall microcrack is developed at the apex of the annular wedge with approximately a propagation of the compression rate;
- Plies delamination in the crush zone causes two continuous fronds, mainly developed by the central bundle wedge that radially spreads inwards and outwards from the wall;
- Between the central crack and the shell wall edges a severely strained zone is formed showing a combined tensile-compressive type of deformation.

Farley and Jones [130] named and classified three main crushing modes for progressive failure of composite box in crushing process as follow.

- **Transverse shearing**

Fragmentation or transverse shearing mode is characterised by the laminate wedge-shaped cross section with a single or multiple short interlaminar and longitudinal cracks. In this mechanism the energy absorption is controlled by the interlaminar crack propagation and bundle fracture.

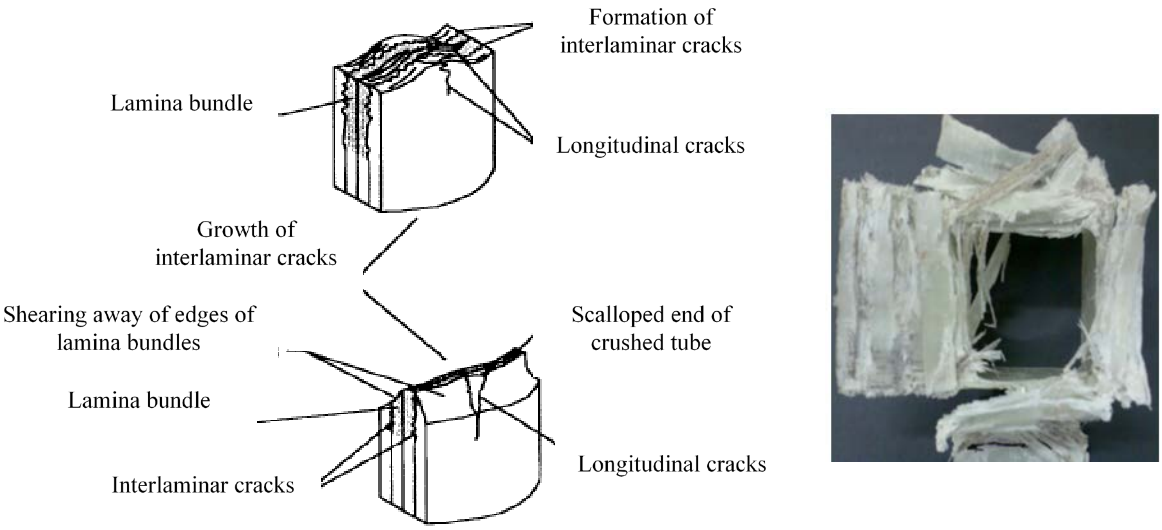
- **Lamina bending**

Lamina bending mode is parallel to fibre cracks shaped with long interlaminar, intralaminar. This mechanism initiates the formation of inwards and outwards spreads of continuous fronds. The energy absorption of lamina bending mode is controlled by inter/intra laminar fracture and friction. However, the fragmentation and lamina bending modes combination is known as brittle fracture mode. In composite tubes the highest energy absorption ever observed is from the combination of brittle fracture and lamina bending crushing mode.

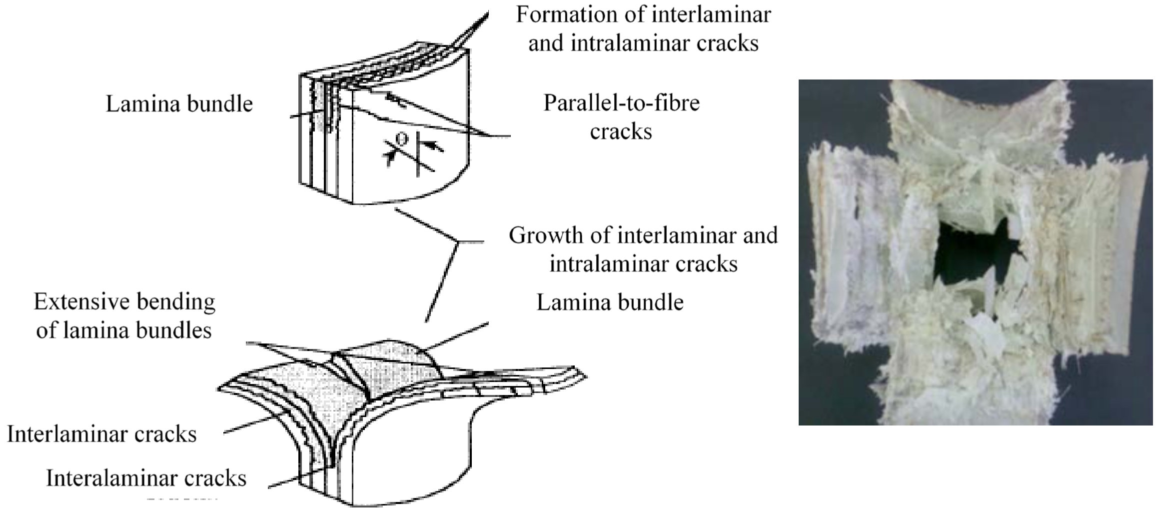
- **Local buckling**

The local buckling crushing mode involves local buckle formation meaning plastic deformation of the material. The result of ductile fibre-reinforced composites integrity in post crushing is from fibre and matrix plasticity without any fracture and fibre splitting. Local buckling can exhibit from brittle fibre-reinforced composites when small interlaminar stresses relative to the strength of the matrix, or the matrix has a higher failure strain than the fibre, and when plastic deformation under high stress exhibited from the matrix.

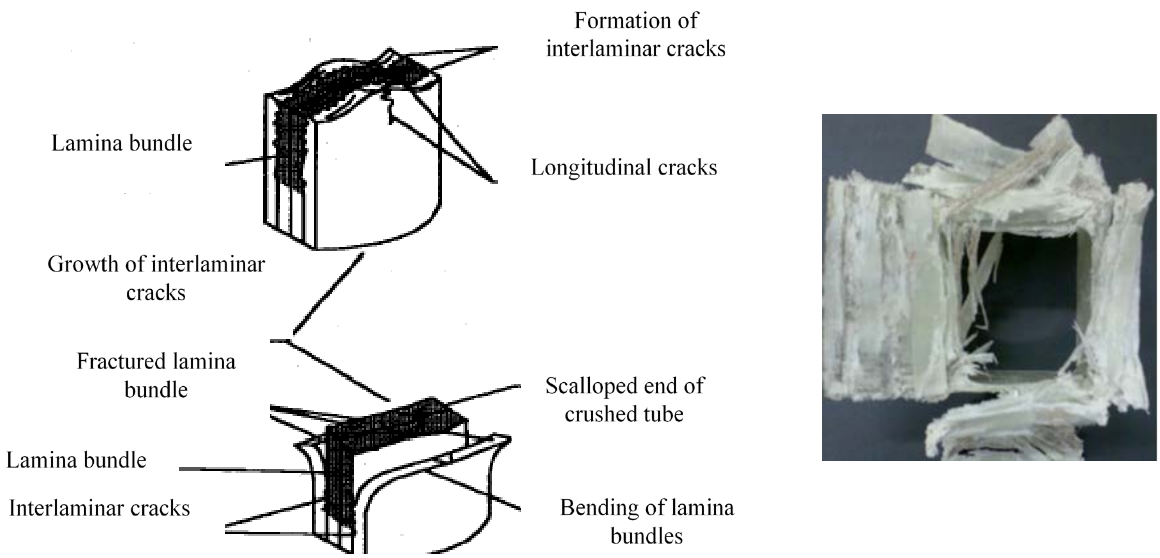
Brittle fibre-reinforced composites exhibit the transverse shearing and lamina bending crushing modes, although ductile fibre-reinforced composite materials have similar mode behaviour as ductile metals in local buckling crushing see **Figure 7**.


Formation of interlaminar cracks
Lamina bundle
Longitudinal cracks
Growth of interlaminar cracks
Shearing away of edges of lamina bundles
Scalloped end of crushed tube
Lamina bundle
Longitudinal cracks
Interlaminar cracks

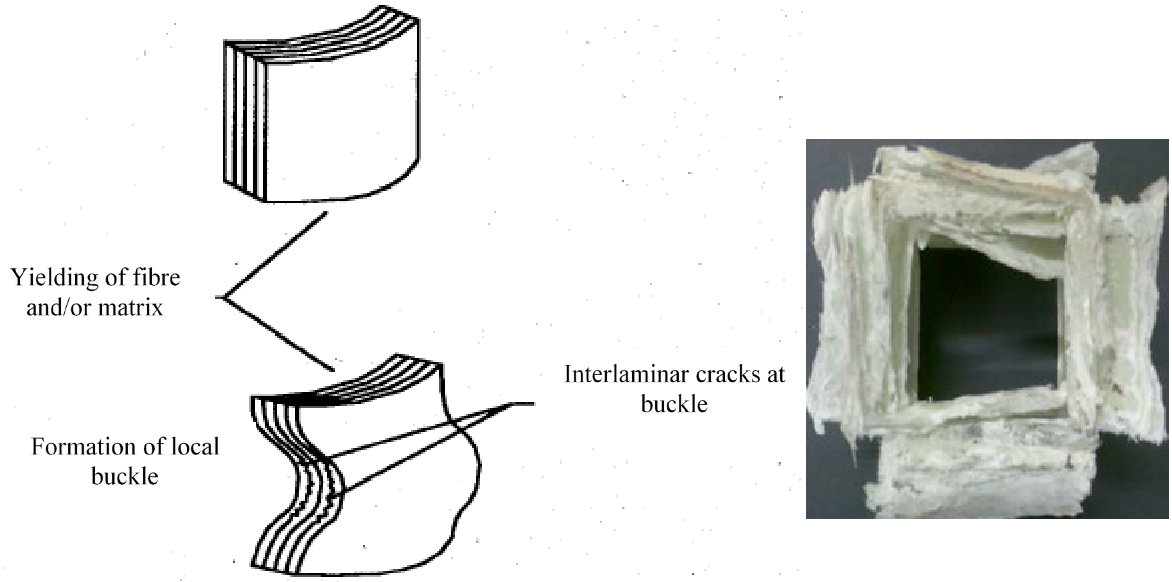
(a)


Formation of interlaminar and intralaminar cracks
Lamina bundle
Parallel-to-fibre cracks
θ
Growth of interlaminar and intralaminar cracks
Extensive bending of lamina bundles
Lamina bundle
Interlaminar cracks
Interalaminar cracks

(b)


Formation of interlaminar cracks
Lamina bundle
Longitudinal cracks
Growth of interlaminar cracks
Fractured lamina bundle
Scalloped end of crushed tube
Lamina bundle
Interlaminar cracks
Bending of lamina bundles

(c)



(d)

Figure 7. (a) Transverse shearing crushing mode, (b) Lamina bending crushing mode, (c) Brittle fracture crushing mode, (d) Local buckling crushing mode [131].

5. Theoretical Prediction of Crushing Energy

Various theoretical approaches have been proposed to study static axial collapse energy absorption of composite multi-layered shells. Farley and Jones [130] proposed the following simplified phenomena to encounter the crushing process:

- Friction between the fronds and annular wedge, and between the platen of the press and fronds.
- Fronds bending,
- Crack propagation.
- Axial splitting.

Mamalis *et al.* [132] introduced another composite circular tubes analysis subjected to static axial compression, which has been modified and used on analysis of collapse mechanism. Using this model, the estimation of the related energy absorption subjected to axial crushing of square tubes is obtained. According to Mamalis *et al.* [133], during the elastic deformation of the shell, the load rises at a steady rate to a peak value, $F_{\max}$. The cracks formed at four corners of the tube in length, L_c, propagate downwards along the tube axis causing the shell wall to split (see **Figure 8**), accompanied by circumferential central intrawall crack development at the top end of the shell. It is assumed that the crack follows an ellipsis configuration. At the middle of each side of the square cross section the maximum value of the crack length, L_c, is attained, and is an equal correspondence to equivalent circular tube loaded under the same condition. Therefore, the energy absorption of associated part, which is equivalent to external work, can be obtained by measuring the area within the elastic regime under the force-crush distance curve,

$$U_{LC} = 2\left[\pi \cdot L_C \cdot \left(\frac{b}{2}\right)\right] \cdot R_{ad} + n\left(\frac{t}{2}\right) G \cdot L_C = \frac{1}{2} F_{\max} \cdot S_1 \quad (3)$$

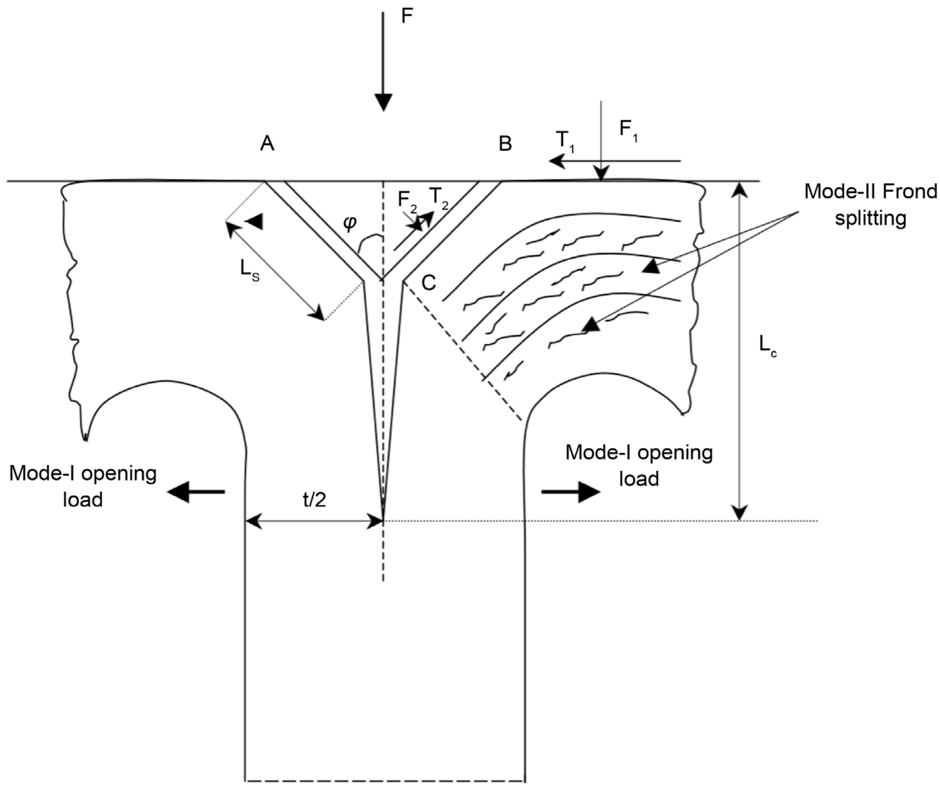


Figure 8. Configuration of the crush zone in the middle of the tube side [133].

where R_{ad} notation is the fracture energy required for a unite area of adhesive to get fractured at the interface between two adjacent layers, obtained by fracture theory,

b = Tube side width,

n = Number of layers,

t = Shell wall thickness,

G = Fracture toughness,

S_1 = Elastic crush distance.

The amount of energy required for the deformation mechanism in reference to the history of the formation of the crush zone, is equal to the deforming shell in this regime absorption of external work (see Figure 8),

$$U_{tr} = \left[2\int_0^{\varphi} \sigma_0 \cdot l_s \left(\frac{l_s}{2} \right) \mathrm{d}\theta \right] 4b = \int_{s_2}^{s_1} F \cdot \mathrm{d}s \tag{4}$$

where

σ_0 = The normal stress applied by the wedge to frond,

l_s = The side length of the wedge inscribed to the bent fronds,

φ = The semi-angle of the wedge,

s_2 = The related shell shortening corresponding to the completion of the wedge formation.

The total dissipated energy for a crush distance due to friction between the annular wedge and fronds, and between fronds and platen can be written as:

$$U_1 = 2\left(F_1 \cdot \mu_{S_1} + F_2 \cdot \mu_{S_2} \right)(4b)(S - S_1) \tag{5}$$

where F_1 is the normal force per unit length applied by the platen to the internal and external frond, F is the normal force per unit length applied to the sides of the wedge, s is the total crush distance, μ_{S_1} is the coefficient of friction between frond and platen and μ_{S_2} is the coefficient of friction between the wedge and the fronds. F_2 and σ_0 are equal to,

$$F_2 = \sigma_0 l_S \tag{6}$$

And

$$\sigma_0 = k \cdot \sigma_u \tag{7}$$

where k is a constant and σ_u is the ultimate tensile stress of the composite material.

Other energy dissipated due to fronds bending, crack propagation, and axial splitting are;

$$U_2 = 2\left[\int_0^{\varphi}(F_2)\left(\frac{l_s}{2}\right)\mathrm{d}\theta + \int_{S_2}^{S_1}(F_2)\cdot\theta\cdot\mathrm{ds}\right]4b \tag{8}$$

$$U_3 = G_{IC}\left[4b(S - S_1) + \pi \cdot L_C \cdot b\right] \tag{9}$$

$$U_4 = 4\left(\frac{t}{2}\right)\cdot G_1 \cdot S \tag{10}$$

$$G_1 = \frac{k^2}{E}. \tag{11}$$

From Equations (3), (6), (7) and (8), the total energy dissipated for the deformation of the shell is obtained as,

$$U_1 = U_1 + U_2 + U_3 + U_4. \tag{12}$$

Therefore, the total force applied by the platen to the shell can be calculated as,

$$F_m = \frac{U_{\text{cocal}}}{s}. \tag{13}$$

6. Off-Axis Crashworthy Behavior of FRP Composite Box Structures

Although most study concentration of previous works have been on crushing under axial loading. In a real life crashing event scenario the likelihood of having a non-axial collision is very high. Quite recently few researches have concentrated on the energy absorption capabilities of elements such as box under two types of non-axial loadings. Non-axial loadings are also known as off-axis loading and angled loading. Occurrence of off-axis loading is when the impact of an object is from a direction not along its longitudinal axis. Occurrence of angled loading is when the impact of an object is from being perpendicular to longitudinal axis. It is essential to undertake all of the effects of collision in crashworthy composite structures on the capabilities of energy absorption. In off-axis crushing the formation of fracture mechanisms defer from axial crushing observations. During non-axial progressive collapse, an important role in dissipation of crushing energy is non-symmetrical crack propagation at the interwall box and between fronds.

Few researchers have been investigating the effects of off-axis crushing on the energy absorption of composite materials and structures [133] [134] [135]. Czaplicki *et al.* [133] investigated on off-axis loading and angled loading crushing process of E-glass/polyester pultruded tubes. It was concluded that off-axis loading and angled loading conditions dissipate energy in different friction mechanism but both loading conditions observed a similar energy absorption tendency by increasing the inclination angle. It was also concluded that at 10˚ off-axis angle the mean crushing force increases in comparison to mean crushing force of axial crushing and a steady decrease with increase of angle of inclination. Song and Du [134] studied the energy absorption capabilities of off-axis loading of glass/epoxy and glass/polyester composite tube laminated from various lay-ups. Three characteristic crushing stages were identified according to their extensive research, triggering stage (Tr), sustained crushing stage and toppling stage. In general, as the off-axis inclination angle increases the energy absorption decreases, caused by a change in two factors of toppling tendency and fracture pattern. They also concluded that 0˚ ply can prevent the circumferential cracks and therefore longitudinal resistance to delay the toppling stage (see **Figure 9** and **Figure 10**).

Ochelski and Gotowicki [135] conducted experiments on the effect of fibre reinforcement type, structure type, fibres orientation in a layer and layers stacking sequence on the energy absorption capabilities of tubes and truncated cones. Also carried out analysis on the effect of the specimen's thickness and applied loading direction on the specific energy absorption (SEA).

7. Interlaminar Fracture Toughness

The energy absorption from interlaminar fracture toughness is accompanied by various fracture mechanisms of intralaminar and interlaminar. In study of fracture toughness, delamination growth is one of the most important areas to concentrate on the study of energy absorption capability of composite structures. Progressive failure mode and

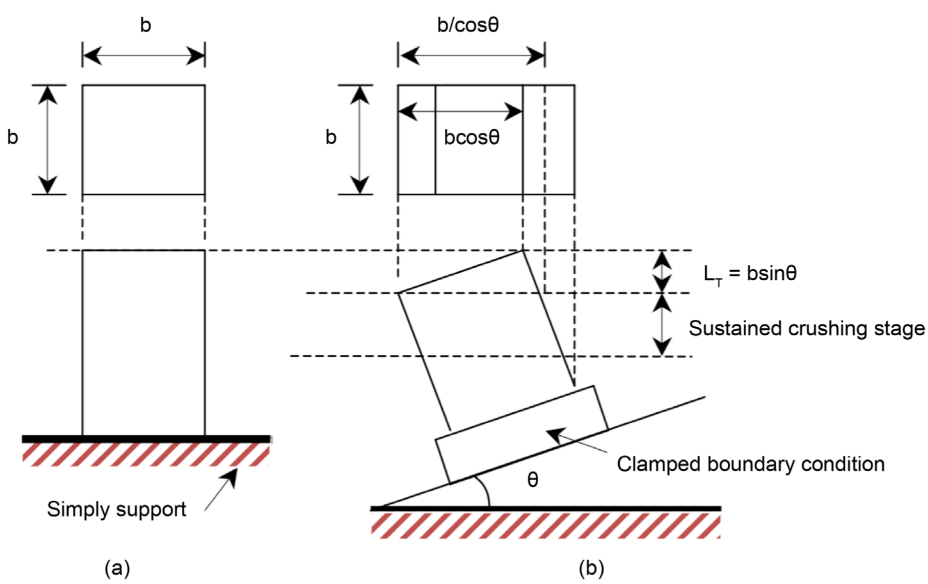


Figure 9. Comparison of axial and off-axis crushing process, (a) axial crushing and (b) off-axis crushing [143].

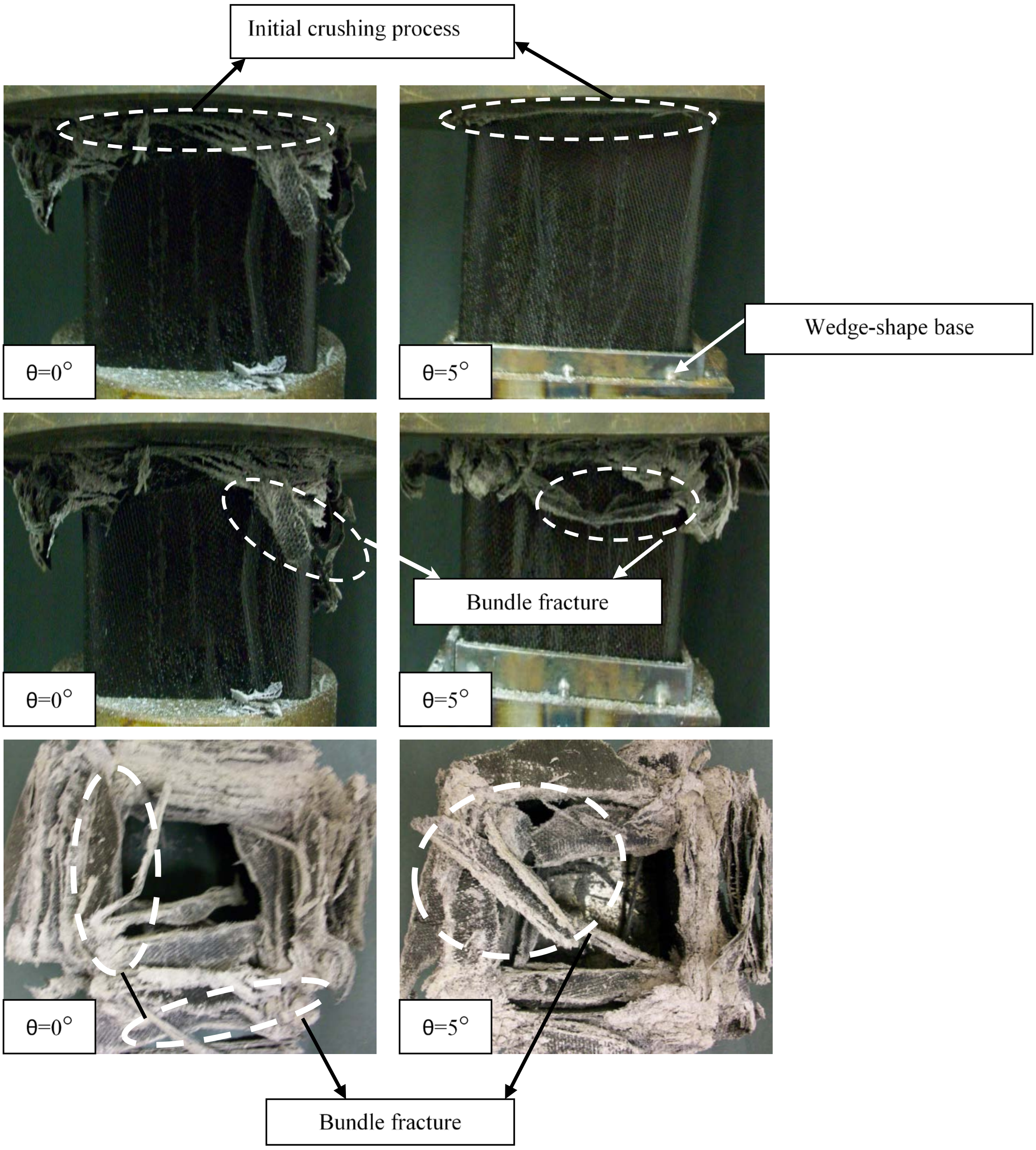


Figure 10. Various crushing stages of woven glass/epoxy composite box in axial crushing ($\theta = 0$) and off-axis loading at ($\theta = 5^{\circ}$) [143].

energy absorption of composite structures, are effected mainly by various fracture mechanisms including fibre breakage and buckling, matrix cracking and crushing, debonding at the fibre-matrix interface and especially plies delamination. Shear and tensile separation between fronds cause delamination. Energy absorption is the effect of these two crushing mechanisms that are due to interlaminar and intralaminar crack growth and fracturing of lamina bundles. The sources of energy absorption during progressive collapse are mainly from [136]:

- Frictional resistance between wedge and fronds and between fronds and platen: about 45% of total absorbed energy.

- Frond bending due to delamination between plies: about 40%.
- Interwall crack propagation: about 12%.
- Axial splitting between fronds: about 3%.

Warrior *et al.* [137] studied the influence of thermoplastic resin additives, toughened resins, stitching through-thickness, thermoplastic interleaving on the interlaminar fracture toughness (G_{IC}), SEA for continuous filament random mat (CoFRM) and 0/90 non-crimp fabric (NCF) E-glass reinforced polyester composite tubes. It was concluded that the above factors increase G_{IC}, but toughened resin and through-thickness stitching affect increase in SEA. In general a tougher matrix result into a higher G_{IC} in composites, this is beneficial in crashworthiness design [138]. Cauchi Savona *et al.* [139] studied the relation of glass fibre reinforced plastic composite plates between sustained crushing stress with their Mode-I and Mode-II fracture toughness properties. It was concluded that materials with low Mode-I and Mode-II fracture toughness, yield low crushing energies. Solaimurugan *et al.* [140] [141] studied the effect of stitching, fibres orientation and stacking sequence on G_{IC}, SEA, and progressively crushing of glass/polyester composite cylindrical shells under axial compression. It was concluded that placing axial fibres close to outer surface tube cause formation of more petal and stable crushing process, whereas placing axial fibres close to inner surface tube led to higher energy absorption. Moreover, circumferential delamination increases energy absorption for higher values of Mode-I fracture toughness. Also reported stitching causes higher energy absorption of cylindrical tube due to increase in Mode-I interlaminar fracture toughness.

Ghasemnejad *et al.* [142] studied the energy absorption of GFRP composite box affected by Mode-I interlaminar fracture toughness. It was concluded that during progressive collapse, a significant amount of energy absorption is attained by frond bending following the growth of a main central inter-wall crack due to delamination in the sidewall. The main central inter-wall cracks are Mode-I interlaminar crack propagation. Also concluded that engineering the laminate design for composite box improves energy absorption capability due to improving interlaminar fracture toughness. For different lay-ups the variation of specific energy absorption (SEA) with interlaminar fracture toughness is non-linear.

Hadavinia and Ghasemnejad [57] investigated the energy absorption of laminated CFRP composite box by the effect of Mode-I and Mode-II interlaminar fracture toughness. In combination of lamina bending/brittle fracture crushing mode according to their results, crack propagation development in Mode-I and Mode-II causes higher crushing energy absorption relative to combination of local buckling/transverse shearing crushing mode that consists of only Mode-II interlaminar crack propagation. Ghasemnejad and Hadavinia [143] studied the off-axis crashworthy behaviour of woven GFRP composite box structures. They concluded that two fracture mechanisms of bundle fracture and crack propagation delamination in Mode-II for all composite boxes at various off-axis loading was observed. In Mixed-Mode I/II due to crack propagation and more resistance and friction at side of composite box that initially contacted the crushing platen, at off-axis loading of 10˚ the amount of SEA was maximum compared to other off-axis crushing load. Ghasemnejad *et al.* [56] have conducted more detailed study of hybrid composite box structures crashworthy behaviour affected by delamination failure. It was concluded that the hybrid laminate designs have higher fracture toughness in Mode-I and Mode-II. Hybrid composite box structure have shown a great increase in energy absorption capabilities in crushing process. Most recently, author [144] studied the effects of delamination failure of stitched composite box structures, where the specimen's crashworthy behaviour and performances were compared and studied against simple non-stitched specimens, under the same geometry and condition. A combination of unidirectional CFRP and GFRP composite materials with lay up of $[C_{90}/G_0]_7$ were used to laminate the composite boxes. The laminate design obtained the highest energy absorption capability within the previous study of authors. Delamination study in Mode-I was carried out using the same lay-up to study the effect of crack growth of delamination on energy absorption of natural stitched composite box structures. Using double cantilever beam (DCB) standard test for delamination studies. It was concluded stitching significantly increased interlaminar fracture toughness and consequently energy absorbing capability of composite materials and structures (see Figure 11).

In recent years two techniques have been developed to increase crack propagation resistance and reduce delamination. One is three-dimensional composites constructed from yarns or tows. Authors [141] [142] [143] [144] [145] studied the effect of stitching and stitching pattern on energy absorption capabilities and found an increase of delamination resistance by introducing stitching pattern and increase of SEA. 3D composites include, 3D woven composites, 3D braided composites, 3D stitched composite, 3D

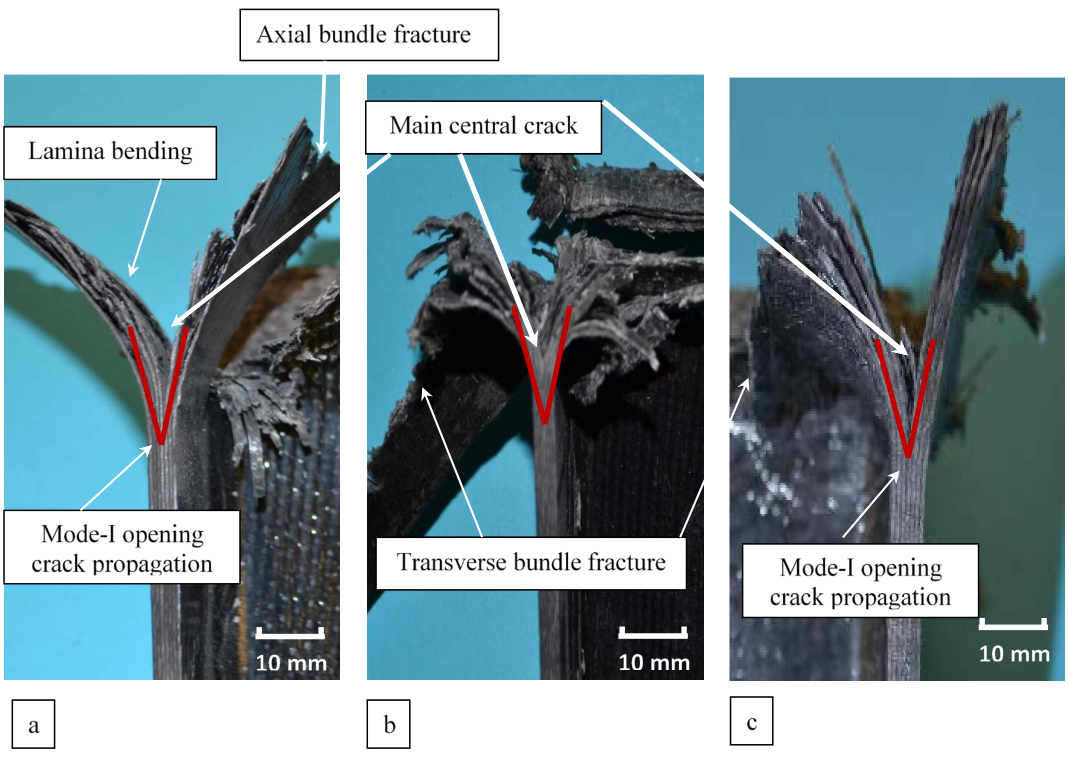


Figure 11. Mode-I interlaminar crack propagation at the central inter-wall, (a) lamina bending crushing mode for non-stitched, brittle fracture mode for (b) stitched-10 mm and (c) stitched-20 mm composite crush box [144].

Table 1. Overview of investigated concepts.

Crushing factors	References
Fibre and matrix type	[58]-[66]
Structrual geometry	[21] [44] [50] [55] [62] [74]-[84]
Laminate design	[60] [62] [64] [67]-[73]
Strain rate sensetivity	[21] [93]-[125]
Theoretical analysis	[13] [19] [21] [42] [44] [45] [51]-[57] [130]-[133]
Loading condition	[23] [25] [26] [34]-[40] [45] [46] [47] [53] [58] [70] [87]-[92]
Fracture Mechanism	[17] [21] [48]-[58] [126] [127] [128] [129] [130] [136]-[145]

Z-pinning. All of these have been studied extensively and are still being studied for further improvements. Author [145] for instance developed a novel technique of stitching pattern to increase energy absorption using glass yarn on composite absorber sections without increasing structural weight. This is useful in automotive and aerospace industry.

Another technique is resin based to reinforce the composite structure by increasing the resistance between plies. Three main types of resins are available polyesters, Vinyl ester, epoxy. Altering the chemistry of the resin improves its strength, consequently energy absorption capability is increased. Author [131] states that further analysis of thermosetting resin matrices needs to be carried out to understand its effect on energy absorption capabilities.

Further investigations can be carried out on the effect of stitching on woven composite with resin infusion. This gives the best of the two worlds. No damages are caused on to the woven composite by introducing stitching pattern along with having a well-constructed resin injected to create the final 3D composite structure.

8. Conclusion

This paper has extensively reviewed progressive crushing behaviour of FRP composite tubular structures in past two decades. In axial crushing of composite, high-energy absorption was contributed by fracture failure. Two fracture failure types are catastrophic and progressive failure. Catastrophic failure results in minimal energy absorption whereas progressive failure due to multi-failure modes results in high-energy absorption. This paper reviewed the literature in 7 sections as material type, structural geometry, laminated design, strain rate, loading conditions, theoretical analysis, and consequently fracture mechanisms. The details of references included in this work are summarised in Table 1.

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