IARJSET
ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
International Advanced Research Journal in Science, Engineering and Technology
Vol. 7, Issue 6, June 2020

Review on Crashworthiness Studies of Foam Filled Thin Walled Structures

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Abstract: This article aims to review the major crashworthiness studies performed on foam filled thin walled structures. Crashworthiness studies are focused to enhancement in energy absorption, simplify the production processes, reduction in weight and material usage. The crashworthiness studies of foam filled tubes are carried out with various shapes such as square, circular, honeycomb etc., amount of foam filled, functionally graded components and materials like aluminium, steels, and composite materials also used. The experimental analyses were done in various loading conditions like quasi-static and dynamic loading. By the process of deformation, the energy absorption parameters of thin-walled structures are analyzed by many of scholars through various methods such as experimental, numerical, simulation and different optimization techniques. In automotive sector most of the crashworthiness research findings are adopted gradually. These types of efforts are very useful to identify the research gaps in the field of crashworthiness studies for future investigation.

Keywords: Crashworthiness, energy absorption, foam filled thin walled structures, functionally-graded components.

I. INTRODUCTION

Innovative concepts in the design of lightweight automotive structures are increasingly sought to meet ever increasing fuel costs and stringent environmental regulations. With the aggravation of energy crisis, energy together with safety has risen to one of the most concerned issues for the research and development of new generation of vehicles and systems with the objective of minimizing human suffering as well as the financial burdens on society [1-4]. Multi material approach is the key to the future vehicle construction, developing cost effective solution to produce energy absorbing light weight structure with reliable and predictable mechanical behaviour. Energy absorber is a material to disperse and dissipate impact energy for usefulness of protection. Double tube energy absorbers are mostly used in vehicle to absorb impact energy [5-11]. Foam filled thin walled structure has been widely adopted as main energy absorber due to its excellent capacity of energy absorption, light weight and low cost in automotive, aerospace, defence and other industries. The presence of the foam, in thin-walled structures helps improve crushing stability and changing collapse modes, thereby increasing the overall crashworthiness [12-17]. The physicalexperiments provide the necessary and uncontradictable data for the behavior of a crashworthy structure. On the other hand, in simulation there is no need of manufacturing procedure. It can help in design and test a component quite too fast and the resulting data representing the reality enough. These days, the vast majority of automotive and aeronautical manufacturers use specially built software to have an idea on the efficiency of newly designed components while they conduct some essential experiments in order to observe their actual performance.

II. DEFINITION OF CRASHWORTHINESS PARAMETERS

Crashworthiness parameters of thin-walled structures are described by brief explanation.

A. Energy Absorption (EA)

Energy Absorption (EA) is equivalent to the mechanical work done by crushing force during the crush distance.
Energy absorption (EA) can be calculated as:

$$\mathrm{EA} = \int_0^{\delta} F(\delta)\,d\delta$$

Where F(δ) is the instantaneous crushing force with a function of the displacement δ. The instantaneous crushing force can be obtained from experiments or numerical modeling.

B. Average Crush Force (F_{avg})

The average crush force (Favg) is the response parameter for the energy absorption capability.

$$F_{avg} = EA_{total} / \delta$$

Where,
EA_{total} absorbed energy during collapse and displacement (δ).

C. Peak Crushing Force (PCF) or (F_{max})

Peak Crushing Force (PCF) is Maximum load in the load-displacement curve usually corresponds to the formation of the first fold. PCF is able to determine the occupant's survival rate; therefore, it should be decreased and be close to the average crush load as much as possible.

D. Crush Force Efficiency (CFE)

Crush force efficiency is defined as the ratio of the average crush force (F_{avg}) to the peak crush force (F_{max}),

$$CFE = F_{avg} / F_{max}$$

It indicates consistency of force–displacement curve. For the better load consistency, higher CFE value is desirable. If CFE is equal to 100% that is an ideal crash absorber.

E. Specific Energy Absorption (SEA)

The energy-absorption capacity measured by Specific Energy Absorption (SEA), which is the energy absorbed per unit mass of the thin-walled member.

$$SEA = EA_{total} / m_{total}$$

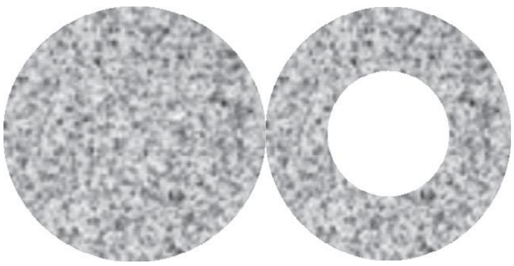
Where m_{total} is total mass of the structure. Obviously, a higher SEA indicates a higher energy absorption capability.

III. ENERGY ABSORBER

Thin walled structures used to absorbing the majority of the kinetic energy at the time of collision, in an irreversible manner thus ensuring minimum human injuries and less equipment damages. The conversion of the kinetic energy into plastic deformation depends upon the geometry of tube, foam density, the magnitude and method of application of loads, transmission rates, deformation or displacement patterns and material properties.

A. Circular tubes

A.G. Hanseen et al. analyzed the static and dynamic crushing of foam filled circular aluminum extrusions [23] and recommended for crashworthy as their high dynamic bending resistance and energy absorbing effectiveness. Uni-axial quasi static compressive test on Al-alloy AA6060T66 were performed and Al-alloy foams show three typical distinct deformation region (I) linear elastic, (II) plateau and (III) densification regions [19]. A good interface bonding between the foam core and the tube improves, (i) the load transfer from the tube's wall to the foam core, (ii) the breaking in the interfacial region between the foam core and the inner surface of the tube during the formation of the outward folding deformation and (iii) the constrained lateral deformation of the foam core by the outer tube [20]. The foam-filled double tube structure as in fig. 1.b could provide a better bending crashworthiness performance than the foam-filled single tubes as in fig.1.a [18]. Three different density polymeric structural foams have been studied for their energy absorption characteristics under uni axial compressive loading. The empty tubes filled with highest density foam proved to be the most efficient in terms of the peak stress and energy absorption [21].



(a) (b)

Fig. 1(a) Foam-filled Single circular tube, (b) Foam - filled double circular tube [18].

A. Ghamarian et al. analyzed the axial crushing of end capped circular tubes in experimental and numerical methods. The initial peak load of end capped circular tubes is 20-30% lowers than the ordinary circular tubes and the peak load is controlled by the fillet radius [22]. L.Ye et al. used the modified super folding element model for the shell, the mean crushing force is predicted through energy balance method. The proposed theoretical formula for calculating mean crushing force is as follows

$$P_m = \left\{ M_0 \left(C_1 \frac{H}{h} + C_2 \frac{R}{H} \right) + \sigma_f \left[C_3 H^2 + C_4 RH + C_5 (1-\eta^2) R^2 \right] \right\} \frac{2H}{\delta}$$

Where $Z=R_f/R$. This model was validated by finite element method in ABAQUS [42]. Abbas Niknejad et al. derived a new deformation model to predict the average folding force, the absorbed energy per unit of initial length and the absorbed energy per unit of total mass of foam filled grooved tubes as fig. 2. Theoretical analysis and experimental values and got the error percentage of all specimens is less than 31%. The result of experiment shows that the absorbed energy by the folding process of the polyurethane foam-filled tubes could be controlled by the introduction of grooves with different distances [54]. Costas et al [68] analyzed the crushing behavior of a circular aluminum alloy extrusion reinforced with a glass–fiber and filled with polymeric foam inside of the tube. They found that the interaction effect of the foam and glass fibers has a very remarkable contribution for more energy absorption than the foam–extrusion interaction. Dipen Kumar Rajak et al [80] conducted a compression test on steel tubes filled with aluminium foam and they resulted that the energy absorption capability of hollow tubes is 9.833 MJ/m^3 and foam filled tubes is 21.36 MJ/m^3. Wangyu Liu et al [81] investigated the effect of conventional/positive and negative Poisson's ratio of the foam on the energy absorption of the foam-filled tube by finite element method. Then they proposed a sandwich double tubes filled with mixed Poisson's ratio foam can take both the advantages of Positive and Negative Poisson's ratio foams which have the better energy absorption capability.

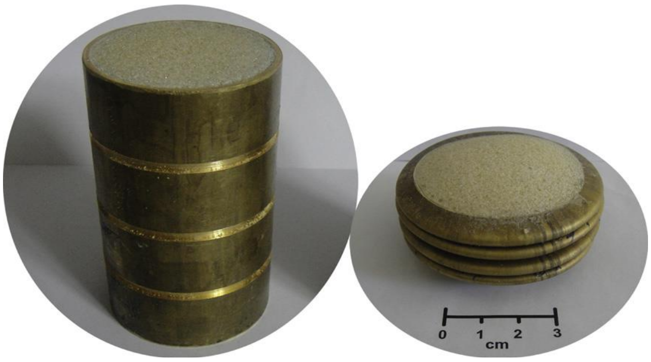


Fig. 2 Specimen S03 before and after the folding process [54].

B. Square tubes

Axial crushing of wood-filled square metal tubes was investigated by Reddy and Al-Hassani [49].A.G.Hanseen et al. conducted 144 tests on static and dynamic crushing of square column with aluminum foam filler. Aluminum foam filled columns shows no loading rate sensitivity [24]. A.G.Mamalis et al. investigated both theoretically and experimentally with aluminum foams by axial compression [17]. A.Othman et al. investigated the qausi static axial crushing behavior of polymeric foam filled composite pultrusion square tubes as shown in fig. 3, with various foam density of 50, 90 and 140 kg/m^3 the wall thickness 3.0mm to be found absorb more energy than 2.1 and 2.4mm. For 3.0 mm wall thickness, the quasi-static and specific energy ranges were observed at 4.6838 up to 6.7227 kJ/kg and 32.08 up to 36.22 kJ/kg, respectively [25].

(a) (b)

Fig. 3 (a) Failure pattern of composite pultruded density of 140 kg/m3 with wall thickness 3.0 mm and (b) Composite pultruded density of 50 kg/m3 geometry wall-thickness of 2.1 mm [25].

Multi objective crashworthiness optimization of functionally lateral graded foam filled tubes with axial dynamic loading investigated by Hanfeng Yin et al. in LS-DYNA and using MOPSO algorithm. The numerical results shows that the crashworthiness of type A-FLGFTs and type B-FLGFTs are better than that of the corresponding uniform foam-filled tubes (UFTs) [26]. M.S. Attia et al. analyzed the crash behavior in nonlinear finite element analysis for functionally graded foam filled columns. The FE model predictions and experimental results have in good agreement [13]. S.Shahbeyket al. investigated metal foam filled square column by numerical model. Numerically calculated mean forces for the square extrusions compared to experimental observations, the error increases when the sections filled with high density foams. [27]. The effects of column thickness and foam relative density on energy absorption of Al foam filled commercial 1050H14 Al crash boxes as shown in fig. 4 are analyzed by A.K.Toksoyet al. The energy absorption behavior of partially closed foam filled Al crash boxes in two different sizes and three different thicknesses were determined at quasi-static and dynamic deformation velocities. Empty boxes were energetically more efficient than fully and partially foam filled boxes until about a critical foam relative density, while partial foam filling was energetically the most efficient at increasing box wall thicknesses at relatively high foam filler densities [28]. Shu Yang et al. applies multi objective particle swarm optimization (MOPSO) algorithm for empty and foam-filled square thin-walled columns under oblique impact both without and with variation in the load angle and generated the Pareto fronts for different MOD problems based on Kriging meta models by using the FEA results [37]. H.R. Zarei et al. conducted impact crash tests on the empty and foam-filled square tubes to find some more details about crash behaviour, and simulate with explicit finite element code LS-DYNA and resulted the foam-filled tube absorbs the same energy as optimum empty tube but has more than 19% lower weight [40]. Ying L et al [74] studied crashworthiness performance of quenched boron steel tubes with functionally graded strength. They conducted axial crashing test in numerical simulation LS-DYNA and resulted that impact end yield strength gives the significant effect on the crushing performance of FGS tubes. Fang et al [69]analyzed the crashing performance of transverse functionally graded thickness (FGT) tubes filled with functionally graded foam (FGF) by numerically and validated with experimentally. They proposed four different configurations of transverse FGF-FGT structures, in terms of foam density and wall thickness for better crashworthiness performance. An X et al [66]analyzed both crushing and bending loading of functionally lateral graded thickness (FLGT) thin-walled foam-filled tubes. They resulted that SEAs of FLGTs are always greater than those of UT counterparts. Fan et al. [76] carried out experimental, numerical, and analytical analysis on energy absorption of the higher order hierarchical rectangular tubes. Performance of the tubes based on three folding deformation mechanisms and in plastic strength the additional hierarchical orders reached its full intensity.

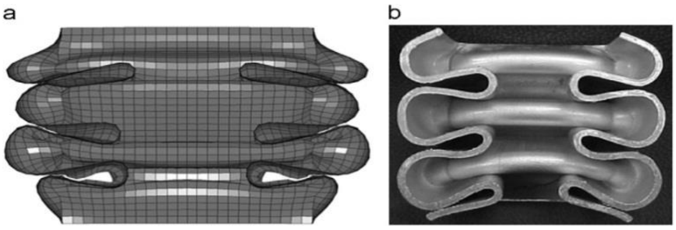


Fig. 4 Deformed square tubes (a) FEA (b) Experimental [28].

C. Multi cell thin walled structures

Multi-cell thin-walled structure has more excellent crashworthiness than the traditional single-cell thin-walled structure. H.yin et al. investigated six kinds of foam-filled multi-cell thin-walled structures (FMTS) with different cell numbers using the nonlinear finite element code LS-DYNA is shown in fig. 5 [29]. Functionally graded foam-filled multi-cell thin-walled structure analysed using nonlinear finite element code LS-DYNA implemented MOPSO algorithm [30]. The energy absorption efficiency of multi-cell columns was found about 50–100% higher than that of foam-filled columns and the numerical results were in good agreement with theoretical predictions. The formula for theoretical prediction is

$$P_{\mathrm{mf}} = P_{\mathrm{m}} + \sigma_{\mathrm{p}} b^2 + C\sqrt{\sigma_{\mathrm{p}}\sigma_0}bt$$

where C is a constant, is the $\sigma_0$characteristic stress of tube material, b and t are width and thickness of column respectively [31].

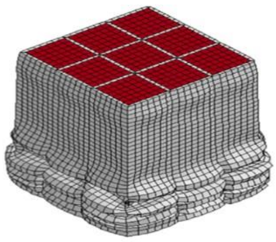


Fig. 5 Simulated multi cell thin walled structure [29].

Crashworthiness optimization of a foam-filled bitubal structures with axial impact loading is analyzed by J.Fang et al. [16]. Yin H et al [73]studied the bending performance of nine kinds of foam-filled multi-cell thin-walled structure (FMTS) under lateral impact by nonlinear FE code LS-DYNA. They applied the complex proportion assessment (COPRAS) method to evaluate the bending behaviour of FMTSs. Yaozhong Wu et al [77] proposed a circular-joint quadrangular honeycomb structures to improve the crashworthiness performance. Their analytical and numerical results are in good agreement and they found that the length ratio and relative density are the main parameters which affecting the crashworthiness indicators of the second-order structures significantly. Saeidi Googarchin et al [78] carried out a theoretical and numerical energy absorption investigation on foam-filled tapered multi-cell tubes. They resulted that the taper angle and the wall thickness lead to an enhancement of the mean crushing load and the SEA and their numerical results are in consistence with experimental results of the previous works.

D. Tapered tubes

Z.Ahmad et al. investigated the crush and energy absorption responses of empty and metallic foam-filled conical tubes under quasi-static axial loading and validated with FE models, for variations in wall thickness, semi-apical angle and foam density. Energy absorption performance of foam-filled conical tube is better compared to empty or foam-filled straight circular tube for use as energy absorbers [32]. L. Mirfendereski et al. investigated the axial crushing of empty and foam-filled tapered thin-walled rectangular tubes under quasi-static and dynamic loading with FE model. The absorbed energy for a rectangular foam-filled tube can be maximized by: a) increasing the foam density; b) using a tube with three or four tapered sides; c) increasing the tapered angle; d) increasing the wall thickness [33]. Dynamic effects of off-axis angle loading as shown in fig. 6 were examined by A.Othman et al. at an angle of 0, 5, 10, 15 and 20 degrees. Numerical analysis has been verified by experimental studies. The results shows that the energy absorption capacity has been significantly affected with various oblique angle, impact velocity and wall thickness [34]. Shujuan Hou et al. presents the optimal design for tapered tubes in three different configurations, namely hollow single, foam-filled single and collinear double tubes and utilized three different multi objective optimization methods, namely the linearly weighted average, geometrical average and particle swarm optimization methods, are utilized to design these tubes. Comparing the three optimization algorithms, although the linearly weighted average method could generate a number of solution points by changing the weight allocation, these points could concentrate on a small region and do not distribute in the Pareto space evenly [38].

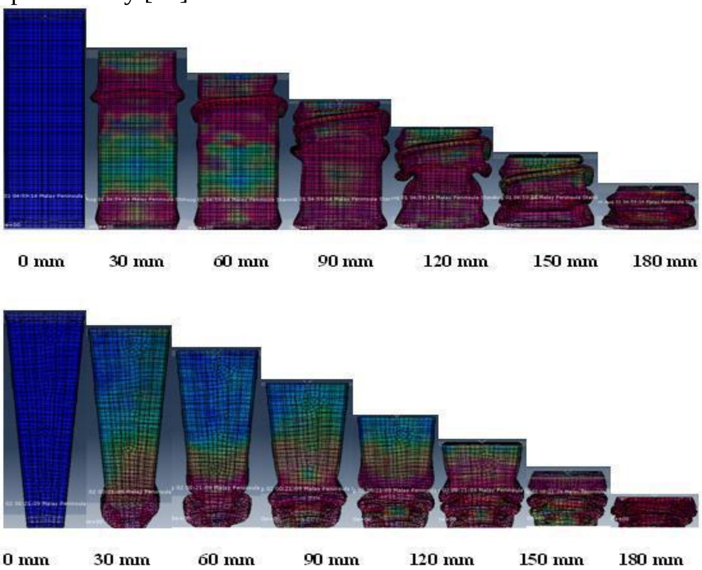


Fig. 6 Dynamic loading of deformation pattern of polyurethane foam straight and four tapered mild steel tube [34].

E. Special structures

Jing Bi et al. performed numerical simulations of single and triple-cell hexagonal columns filled with aluminum foams using nonlinear finite element crash simulations. The results of numerical simulations showed that foam-filled columns had significantly larger crushing force than those of non-filled columns due to interactions between the tube and foam and also observed that triple-cell composite columns further increased the crushing forces of three single-cell columns due to corner effects [35].Fangyi Li et al. proposed a multi objective robust optimization procedure using Kriging formula with presence of both random and interval variables in crashworthiness design of foam filled column and expressed effective crashworthiness design for the foam filled structures, where specific energy absorption and peak impact force were taken as the objectives, and average crash force as a constraint. Sergey L. et al. developed a theoretical model to predict the quasi-static energy absorption of metal foams under two ideal cases, i.e., homogeneous deformation and progressive collapse and found that the progressive collapse of metal foam absorbs more energy than the homogeneous deformation. The fig.7 illustrates the progressive collapse of foam-filled tubes [36]. Y. Zhang et.al. concluded that the foam-filled bitubal structure could provide a better crashworthiness performance than the foam-filled monotubal column and empty bitubal column. It can be a potential structural component for vehicle engineering applications [39]. Based on energy method theoretical relations are derived by A.Niknejad et al. to predict instantaneous crushing force and absorbed energy during initial fold formation in polyurethane foam-filled quadrangle tubes under the axial crushing load [41].Sivakumar Palanivelu et al. evaluates the crushing performance of small-scale composite tubes (nine different shapes with two different thicknesses) as shown in fig.8 filled with polyurethane foam and concluded that polyurethane foam prevented the circumferential delamination and subsequent fibre fracturing and

 DOI 10.17148/IARJSET.2020.7608

ISSN (Online) 2393-8021
ISSN (Print) 2394-1588
Vol. 7, Issue 6, June 2020

the architecture of the composite tubes also played a role, in this study the reinforcement fibres are oriented along the axis of the tube [45].

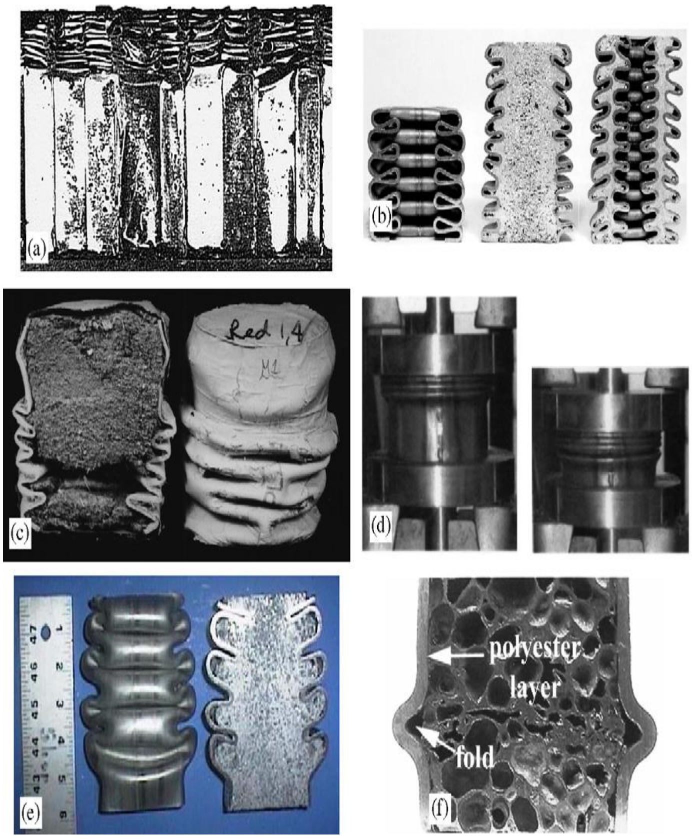


Fig. 7 Progressive collapse of foam-filled tubes, (a) Progressive collapse of honeycomb, (b) progressive collapse of hollow and Al-foam-filled steel tubes (c) progressive collapse of redwood sawdust filled PVC tube (d) progressive collapse of polyurethane filled steel tubes,], (e) progressive collapse of Al-foam-filled tubes and (f) densification of Al-foam at the location of tube instability [36].

A new analytical model for plastic deformation during the flattening process on hexagonal metal columns under the lateral quasi-static loading is presented by Abbas Niknejad et al. [43]. The braid/foam system for energy absorption under uni axial tension was investigated by RamsinAudysho et al. using the ProAnalyst software to track the tube deformation and found that the dominant failure mode in specimens containing a rectangular foam core is the combination of core and braided tube [44]. Hasan Gedikli et al. done a work on optimal design for empty and foam-filled tailor welded tubes (TWTs). They found that SEA and peak force increased with thickness of upper part and foam density. Moreover, CFE decreased with increasing thickness of upper part whereas CFE slightly increased with increasing foam density [47].

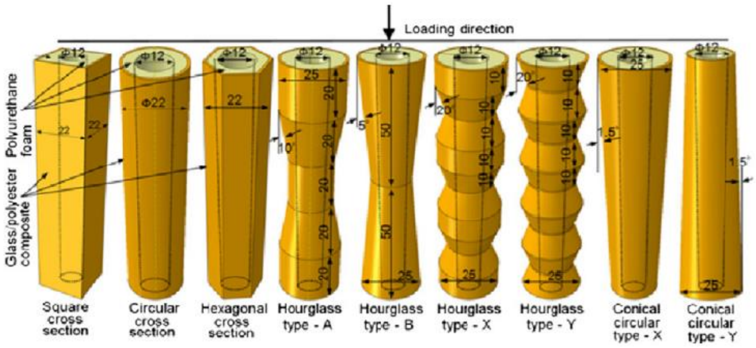


Fig. 8 Different geometrical shapes of the composite tubes (1 mm thickness) and their dimensions considered for the study [45].

QingwuChenga et al. compares the energy absorption predictions of the analytical model and experimental observations were found to be in good agreement. For the tensile loading conditions and geometry of aluminium foam filled braided tubes considered in this research energy absorption ranged from approximately 5.2 to 7.9 kJ with corresponding tube elongations of 400 mm [50]. S.H. Yoo et al. carried out compressive tests on foam-filled composite egg-box panels which were carried out to assess their performance as energy absorbers. Material type, number of plies and stacking angle were varied and resulted that the foam-filled composite egg-box sandwich panels had a good energy absorption capacity with a stable collapse response resembling the ideal energy absorber [46]. R.B. Gover et al. conducts the tests with the impactor striking the PWFB (Portable Water Filled road safety Barriers) perpendicularly with impact energies up to 7.40 kJ and demonstrated the importance of the internal steel frame in providing the requisite stiffness to the structure during impact. It was greatly reduce the peak loads and externally mounted foam filled panels absorbing a significant amount of the kinetic energy [48].

Zhiliang Tang et al. given a strategy to improve energy absorption efficiency of thin-walled columns by introducing extra non-convex corners in the cross section and derived a Explicit formulations for predicting the mean crushing force of non-convex multi-corner thin-walled columns based on the theory of Super Folding Element method. The predicting results of these formulations have good agreement with the numerical simulation performed by explicit non-linear finite element method. The comparisons of the non-convex columns with square column show that the non-convex multi-corner thin-walled columns have higher energy absorption capacity [51]. Abbas Niknejad et al. tested polyurethane foam-filled composite tubes in lateral compression and measured their energy absorption capabilities. It was found that the foam-filled composite tubes with bigger lengths and more fibre fabric layers are the best energy absorbers under lateral compression. Also, resulted that foam-filler causes the tubes deformation more orderly [52]. S.A. Meguid et al. investigated the crush behaviour of ultralight polymeric foam-filled structures by conducting comprehensive finite element simulations and concluded that the relative axial stiffness plays an important role in dictating the mechanical response of the structure [53].

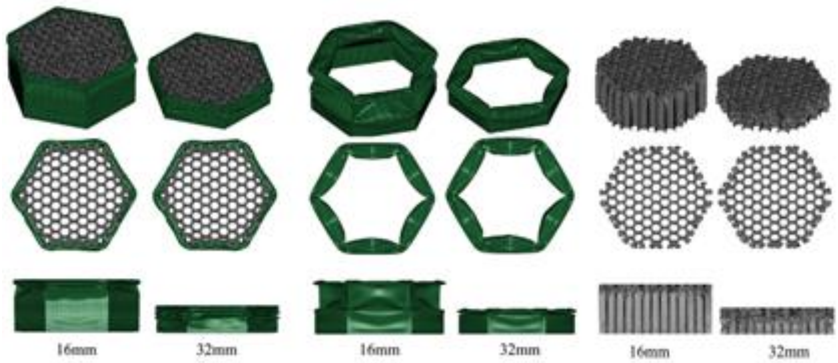


Fig.9 Deformation of the structures (case 4), (a) honeycomb-filled single regular hexagonal tube, (b) empty single tube, and (c) honeycomb filler [61].

J.M. Babbage et al. performed a static axial crush of both round as well as square hybrid tubes can be improved using an E-glass fibre/epoxy overwrap and also indicates that material parameters, such as fibre orientation angle, the number of layers in the over warp and porosity in the foam, influence crush performance of hybrid tubes [55]. Rasoul Nasirzadeh et al. studied the effect of variation in rigid foam core density in a composite sandwich panel under high velocity impact loading and resulted that Foam core density of 49 kg/m^3 has highest energy absorption in foam density range and in high density foam core tested, no projectile yawing [56]. R.A. Alia et al. developed a novel tube-reinforced sandwich core structure in which chamfered CFRP (carbon fibre reinforced epoxy tubes) are embedded in low density core materials and suggested that these structures represent an attractive option for use in dynamically-loaded structures [57]. Qingchun Wang et al. performed a theoretical analysis to predict the dynamic axial crushing behaviour of aluminium foam-filled top hat and double hat sections made from mild steel and focused on interactive effects between aluminium foam and mild steel sections [58]. V. Miranda et al. investigated the role of the plastic deformation on the dynamic behaviour of aluminium foam-filled columns with respect to their energy absorbing capabilities and concluded that an increase of 50% of the impact speed leads to the same increase in the average dissipation energy [59]. Reid SR [60] presented load–displacement curves for central transverse loading of tubes filled with sand. Foam-filled circular or square tubes under axial crushing were investigated by many researchers including Reid et al. [64], Abramowicz and Wierzbicki [65] and Reddy and Wall [63]. Zonghua et al. introduced six different innovative composite structures composed of two circular aluminium tubes filled with core shaped honeycomb lattice [62]. Wang J et al [75]studied about enhancement of tensile strength in carbon fiber-reinforced plastic and aluminum honeycomb structures. They used three types of reinforcement for strengthening the CFRP/aluminum sandwich-structures. Hanfeng Yin et al. investigated the energy absorption characteristics of honeycomb-filled single and bitubular polygonal tubes (HSBPT) as Fig.9 by nonlinear finite element analysis through LS-DYNA [61]. Caliskan et al [67] carried out anexperimental investigation of low velocity impact behavior on various foam core densities, face-sheet and foam core thicknesses. Then they found that the maximum deflections occurred at lower foam core density whereas the minimum deflections were observed with higher density foam. Performance in energy absorption and strength of discrete layered and continuous graded foams with various gradient functions were investigated by Koohbor et al [70]. Then they proposed a semi-analytical approach to analyze the effect of density gradation in graded polymeric foams in crashworthiness applications. Qin et al [71] fabricated and analyzed the crashworthiness performance of a new sandwich beam, which consists of the sub-beam and basic-beam. In this analysis local denting is predicted in sub-beam and global deformation predicted in basic-beam system. Xiao et al [72] conducted a parametric study to investigate the influence of functionally graded foam (FGF)-filled bumper beam parameters on crashworthiness performance and it is compared with the uniform foam (UF)-filled bumper beams performance. They found that the bumper beam with FGF absorbing more impact energy than the UF-filled beam.

Baumgart et al [79] conducted a numerical and experimental investigation on honeycomb structures. The SEA of Kagome profile is compared with square-celled structure under both considered load directions. In in-plane direction the compression test exposed higher SEA than predicted by the simulation. Crashworthiness performance against material cost of different hybrid sandwich tubes consist of CFRP, aluminum foam and aluminum through experimentally and numerically investigated by Guangyong Sun et al [82]. The results of the finite element (FE) models were agreed well with the experimental results. Wentao He et al [83] investigated the low-velocity impact response of aluminum honeycomb structures with CFRP face plates by experimental and numerical methods. They concluded that the length of honeycomb and thickness of cell wall have remarkable influence on stiffness and the impact load of the structures but they do not play a major role in energy absorption. Dayong Hu et al [84] proposed a bionic honeycomb tubular nested structure (BHTNS) and its energy absorption performance under the axial crushing was investigated by experimental, numerical and theoretical analysis. They developed a theoretical model to predict mean crushing force of BHTNS and it was in good agreement with numerical simulation results. This work offered an idea for the design of new bionic structures with excellent energy-absorption capability.

IV. CONCLUSION

Strength and energy absorption of thin-walled sections are increased by filling them with fillers. Using filler in the form of honeycomb or foam in thin walled tubes is one of the best approach than the changing the geometry of the structure to improve the crashworthiness performance. Crashworthiness performance of foam-filled thin-walled sections mostly depends upon density of foam, i.e., energy absorption increased up to critical density. Researchers proposed enormous optimization methods to find out the critical foam density. The combinations of tubular structures with multi-cellular honeycomb or foam have better energy absorption capability. The interaction between the tube wall and the filler material leads to absorb more energy. Compared with monolithic tubular structures, the multi-cell tubes offers better crushing response due to interaction effect. Multi-cell or multi wall tubular structures with fillers absorb maximum amount of energy with high structural stability. This review can be useful for researchers and designers to enhance the crashworthy capabilities of foam filled thin wall structures by using other geometries, materials and loading conditions.

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