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Reinforced and sandwiched PU foam for higher strength and energy absorption

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Abstract. Nowadays lightweight materials are being widely used in most engineering applications. Among them, PU foam is a versatile material that finds potential applications in the automotive and aerospace industries. This paper explores reinforced and sandwiched PU foam for applications where higher strength and energy absorption within the limited volume is required. Three different categories of reinforcements are considered in this study: foam-filled PVC tubes, PVC tube-reinforced foam, and jute composite sandwiched foam and the volumes of the plain foam and jute composite sandwiched foam are the same. By conducting quasi-static compression tests on these specimens, the results show greater peak load and energy absorption compared to plain PU foam. The mode of collapse of axially crushed PVC tubes has been found to be regular three-lobed diamond mode and axisymmetric concertina mode in foam-filled PVC tubes. The energy absorption capacity of the PVC tubes is enhanced by foam compression as well as by extra stretching in the tube circumference due to shifting from multi-lobe to axisymmetric mode.

Keywords: PU Foam; Foam filled PVC tube; Reinforced foam; Jute composite; sandwiched composite

1. Introduction

The potential of foam-filled tubular structures in impact energy absorption applications such as crashworthy components has been studied by several investigators [1–7]. Material properties of such structures, their geometry and mode of collapse are some of the main factors that influence the quality of an energy absorption system [8]. Effects on environment, weight reduction and economical aspects of energy absorption systems have been investigated by several researchers to improve such systems from all aspects. Farley and Jones [9], and Kindervater and Georgi [10] are among those who have investigated the use of non-metal composites in the design of lightweight structures. Wirshing and Slator [11] explored the use of fillers in beer cans and observed that the entrapped air inside cans enhanced their energy absorption capacity.

Hinckley [12] investigated the crashworthy performance of a foam-filled metal tubular structure and studied the influence of variation of density and strain rate on the energy absorption performance of polyurethane foam filler. Thornton et al. [8] examined the collapse of foam-filled tubular structures of different cross-sections and concluded that irrespective of the enhancement in the overall strength of the structure, foam is not weight-effective with thicker tubes. On the other hand, Lampinen and Jeryan [13] experimentally studied common mode of failure of foam-filled thinner tubes over dense tubes and concluded that foam plays a major role in the stability of deformation of tubular struts. Reid et al. [14] investigated the collapse of foam-filled thin-walled metal tubes under quasi-static and dynamic conditions and found that the mean crushing load and the collapse folding length were dependent upon the foam density; similar effects were observed in [15 – 17, 24]. Kunze et al. [25] investigated axially crushed empty cans and observed that empty cans collapse into multi-lobe mode, whereas foam filled cans collapse in axi-symmetric mode. Wang et al proposed an innovative composite sandwiches that are composed of a nylon reinforcing upper layer and a flexible PU foam structures [18]. Sophia Sachse et al work showed that the addition of nanoclay in PU foams increased the energy absorption capacity during compression and low energy impact tests [19]. The collapse of axially crushed sawdust-filled PVC tubes was investigated experimentally and theoretically [20]. The influence of high-density foam or pine wood filler on the mode of collapse of quasi-statically and dynamically crushed non-circular metal tubes has been investigated by Reddy and Al-Hassani [21]. They found that the presence of filler reduced the wavelength of axially crushed square metal tubes and that due to the anisotropy of wood, different modes of collapse were encountered. The use of jute fiber mats in combination with polymer films potentially offers a rapid and simple means of manufacturing composites through film stacking, heating [22]. Flexural behavior of nonwoven fabric reinforced sandwich composites from jute and polypropylene (PP) fibers was investigated in some literatures [23]. Jute/PP composite plates reinforced with jute/PP commingled nonwoven fabrics of different jute/PP fractions were used as facing materials in sandwich production.

At present, rigid and low-density PU foams are used for most of the high-performance structural applications without any reinforcements, hence there is an enormous potential for improving the properties such as strength and energy absorption capacity of the foams by using reinforcements or by making sandwiched foams. In this work, rigid PU foam-filled polyvinylchloride (PVC) tubes, PVC tube-reinforced foam and jute composite sandwiched foams have been studied experimentally under quasi-static compressive loading conditions. To the author’s best knowledge, both these composite constructions using PVC tube and jute-polyester laminate may not have been reported earlier in published literature.

2. Materials and Methods

2.1 *Materials*

Commercially available PVC pipes of 25 mm outside diameter and a thickness 1.2 mm were procured from Rajesh Traders, Bangalore, India to fabricate foam-filled PVC tubes and PVC tube-reinforced foam specimens. Bi-directional woven jute fabric having a yarn count of 17 x 15 (17 yarns in warp and 15 yarns in weft direction per square inch) and a density of 220 GSM (grams per square meter) was procured from Kolkata, West Bengal, India. Isophthalic polyester resin, cobalt naphthenate accelerator and methyl ethyl ketone peroxide (MEKP) catalysts were procured from Swathi Chemicals, Bangalore to make jute composite which is used in sandwiched foam specimens.

2.2 *Fabrication of Specimens*

To fabricate a foam-filled PVC tube, a predetermined volume of polyol and isocyanate mixture of 1:1.1 ratio [26] is directly poured into the hollow PVC tube as shown in figure 1(a) at room temperature allowing the foam reactions to take place and the resulting foam-filled tube is shown in figure 1(b). To prepare PVC tube-reinforced foam samples, four PVC pipes of dimensions mentioned above are placed in a symmetric manner in an acrylic mold box of 50 X 50 X 50 mm3 interior .A predetermined volume of polyol and isocyanate mixture is then poured into the mold filling up partially the tubes and the empty spaces surrounding the tubes. On formation of foam, the resultant PVC tube-reinforced foam specimen is shown in figure 1(c). Prior to the fabrication of a jute composite sandwiched foam cube, jute-polyester composite plates were fabricated by simple hand-layup technique followed with compression molding. The working surfaces of the compression molding machine were treated with polyvinyl alcohol (PVA) to facilitate easy removal of laminate. The matrix material is prepared from a commercially available general-purpose polyester resin, accelerator and catalyst in the weight ratio of 1:0.02:0.025. Each layer of fabric is impregnated with matrix material with a brush and placed one over the other, taking care to maintain practically achievable tolerances on fabric alignment. The laminates are prepared by applying pressure in a compression molding machine using spacers of desired thickness.

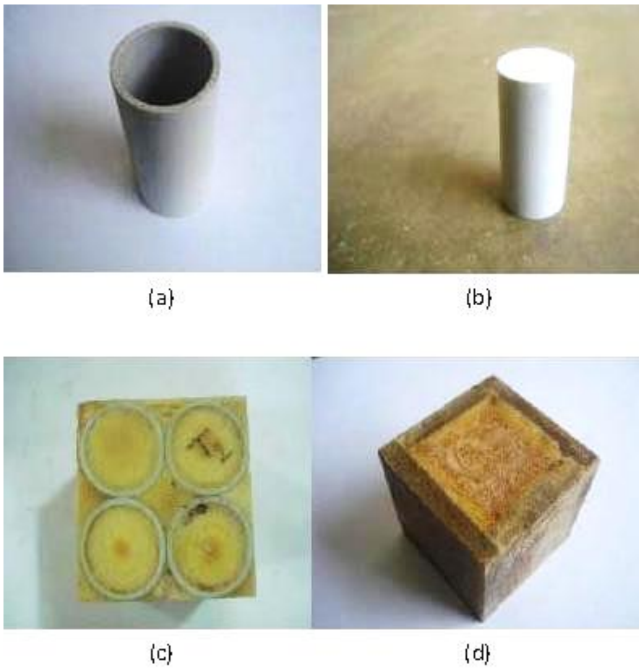

Figure 1. (a) Empty PVC tube **(b)** Foam filled PVC tube **(c)** PVC tube-reinforced foam **(d)** Jute composite sandwiched foam

2.3 *Compression testing of reinforced and sandwich PU foams*

To study the effects of various composite constructions described above, quasi- static tests are conducted in a 100 kN servo hydraulic UTM following a testing procedure that is consistent with ASTM D1621/94 for rigid cellular plastics [27]. The various foam-based reinforced and sandwiched samples are tested under compression with a crosshead speed of 1 mm/min, and load-displacement curves are obtained. The maximum compression stroke is fixed at about 70% of the initial height of each test specimen. Jute composite plates of dimensions 50 mm X 50 mm X 7.5 mm and 35 mm X 50 mm X 7.5 mm are carefully cut from the laminates using a diamond saw. Pairs of jute composite plates of the two sizes mentioned are placed (with 50 mm side along the vertical direction) within a 50 mm X 50 mm X 50 mm acrylic mold with the plates pressing against the inner walls of the mold. Inside the internal volume of size 35 mm X 35 mm X 35 mm, a predetermined volume of polyol and isocyanate mixture of 1:1.1 ratio is poured, and the top and bottom lids of the mold are closed. After formation of foam and removal of the mold parts, a sandwiched jute composite foam block as shown in figure 1(d) is obtained.

2.4 *Mechanical Performance Parameters*

A range of mechanical properties are computed [29, 30] to assess their variation with respect to foam density such as mean load, mean stress, energy absorption and specific energy by volume are obtained for the various concepts tested. For the same cross-sectional area, the foam-filled PVC tubes can be compared against empty PVC tubes, while the PVC tube- reinforced foam and jute composite sandwiched foam can be compared against each other as well against plain foam (of size 50 X 50 X 50 mm^3).

2.4.1 *Mean load*

$$P_m = \frac{E_{60}}{U_{60}} \tag{1}$$

where,

$$E_{60} = \int_0^{U_{60}} P du$$

Equation (1) gives the mean load when the energy absorbed at 60% foam compression, where P is the instantaneous compression load in a typical foam load-displacement curve shown in [29], u is the instantaneous axial displacement and U_{60} is the value of u at 60% foam compression.

2.4.2 *Mean Stress*

$$\sigma_m = 2\int_0^{0.5} \sigma \, d\epsilon \tag{2}$$

$$\sigma = \frac{P}{A_0} \quad \text{and} \quad \epsilon = \frac{u}{L_0}$$

Equation (2) computes the mean stress during 50% of the total strain, which is governed by instantaneous nominal stress and axial strain in a foam specimen in a compression test, A_0 being the original cross-sectional area of an undeformed foam specimen and L_0 is the original undeformed height.

2.4.3 *Specific energy absorption with respect to density*

$$e_v = \frac{E_{60}}{\rho} \tag{3}$$

Equation (3) is employed to calculate the specific energy for the varying effective densities ρ, of the foam and composites specimens respectively.

3. Results and Discussion

3.1 *Foam filled and empty PVC tubes*

Experimental load-displacement curves for empty and foam filled PVC tubes are shown in figure 2. Using these curves, mean load, mean stress and energy absorbed (up to 60% compression) are computed and presented along with densities (actual and effective).

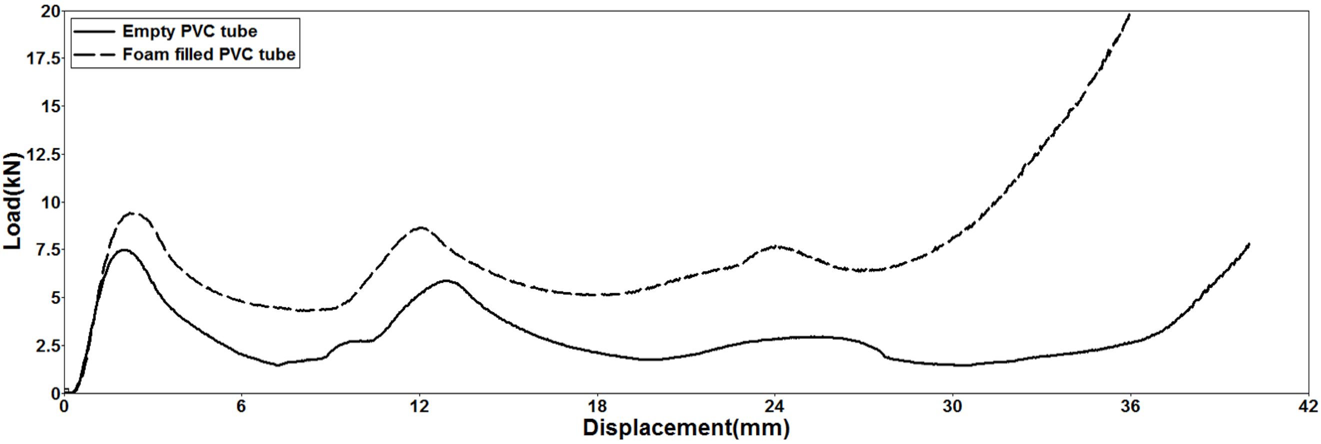

Figure 2. Load vs. displacement behaviors of empty and foam-filled PVC tubes

It is observed mean load of a foam-filled PVC tube is 5.3 kN which is 82% higher than that of an empty PVC tube. The mean stress for the foam-filled PVC tube is found to be 60 MPa which is 3 times the mean stress of the empty PVC tube. There is also an 100% increase in absorbed energy for the foam-filled PVC tube (180 J) as compared to the empty PVC tube (90 J). In contrast, from table 1, when the density decreases by a factor of 2, the specific energy increases considerably (350 %).

Table 1. Mechanical characteristics of empty PVC tube and foam filled PVC tubes

Specimen type	Density (g/cc)	Mean load (kN)	Mean stress (MPa)	Energy absorbed at 60% compression (J)	Specific Energy by density (kJ/g/cc)
Single empty PVC tube	1.4	2.9	20	90	0.064
Single foam- filled PVC tube	0.66 (effective)	5.3	60	180	0.272

3.2 *PVC tube-reinforced foams*

The mechanical behavior of PVC tube-reinforced foam is compared against that of plain foam in the form of load-displacement curves in figure 3. Mean load, mean stress and absorbed energy along with densities for the foams are given in table 2. Mean load of PVC tube-reinforced foam is found to be 50 kN which is 72% higher than that of plain foam (29 kN). Mean stress (0.018 GPa) is found to be 80% higher than that of plain foam (0.010 GPa). The energy absorbed by PVC tube reinforced foam specimen (1506 J) is 72% higher than that of plain foam specimen which absorbed 871 J. However, for the same volume, the weight of PVC tube-reinforced foam has increased substantially when compared to that of plain foam. From table 2, the specific energy values of the foam and foam-filled tubes are nearly same (1.45% decrease) even though the density decreases by a factor 1.8 [31]. Also, from tables 1 and 2 it can be observed that, there is an enhancement of specific energy (656 % approximately) for single foam-filled PVC tube and multiple foam-filled PVC tubes.

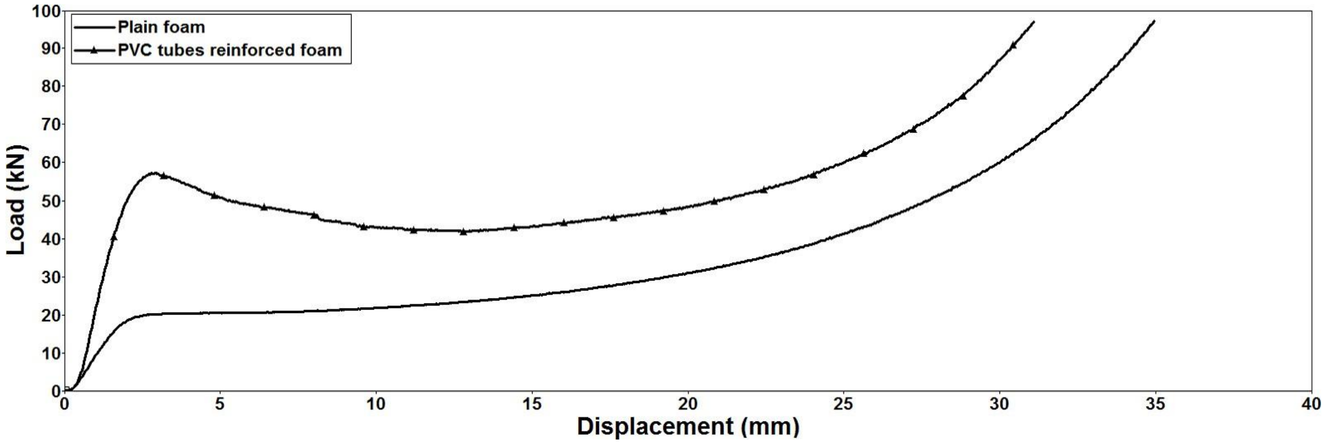

Figure 3. Load vs. displacement behaviors of PVC tube-reinforced foams

Table 2. Mechanical characteristics of PVC tube-reinforced and plain foam samples

Specimen type	Density (g/cc)	Mean load (kN)	Mean stress (MPa)	Energy absorbed at 60% compression (J)	Specific Energy by density (kJ/g/cc)
Plain foam	0.42	29	10	871	2.04
PVC tubes- reinforced foam	0.74 (effective)	50	18	1506	2.04

It can be observed that the combined mean load of 4 separate foam-filled PVC tubes would be 5.3 X 4 i.e., 21.2 kN (from table 1). On the other hand, the PVC-tube reinforced foam specimen which has 4 foam-filled PVC tubes has a mean load of 50 kN (from table 2) which is far higher than the mean load of 4 individual foam-filled PVC tubes. The absorbed energy (i.e., 1506 J) is similarly substantially higher for the PVC-tube reinforced foam as compared to the sum of absorbed energies (i.e., 4 X 160 = 640 J) of 4 separate foam-filled PVC tubes. Hence, foam is seen to be an extremely effective matrix for PVC tubes.

3.3 *Jute composite sandwiched foams*

To know the effects of sandwiching, a separate study has been carried out to determine the energy absorption capabilities of jute plates alone. Mean load, mean stress and absorbed energy for the jute plates of dimensions 50 mm X 50 mm X 7.5 mm and 35 mm X 50 mm X 7.5 mm are presented in table 3 and the load-displacement curves are shown in figure 4.

Table 3. Mechanical characteristics of jute plates

Jute plate dimension	Mean load (kN)	Mean stress (MPa)	Energy absorbed at 60% compression (J)
35 mm X 50 mm X 7.5 mm	3.4	1	17
50 mm X 50 mm X 7.5 mm	4.5	2	27

It is apparent from table 3 that the jute plate of higher sectional area (50 X 50 mm^2) developed 32% more mean load and absorbed 58.8% more energy as compared to the plate of lower sectional area (35 X 50 mm^2).

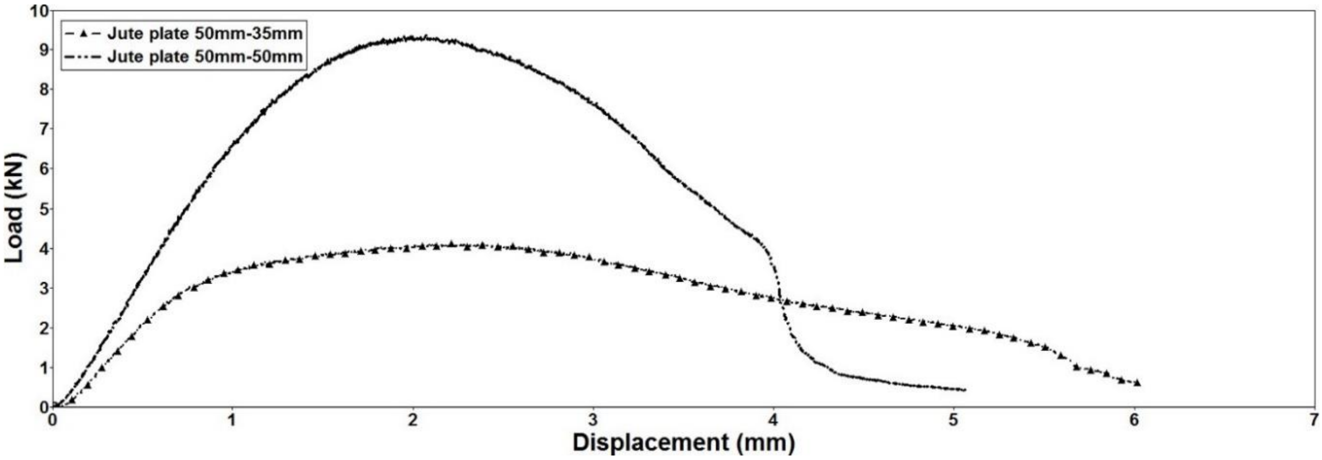

Figure 4. Load vs. displacement behaviors of jute plates

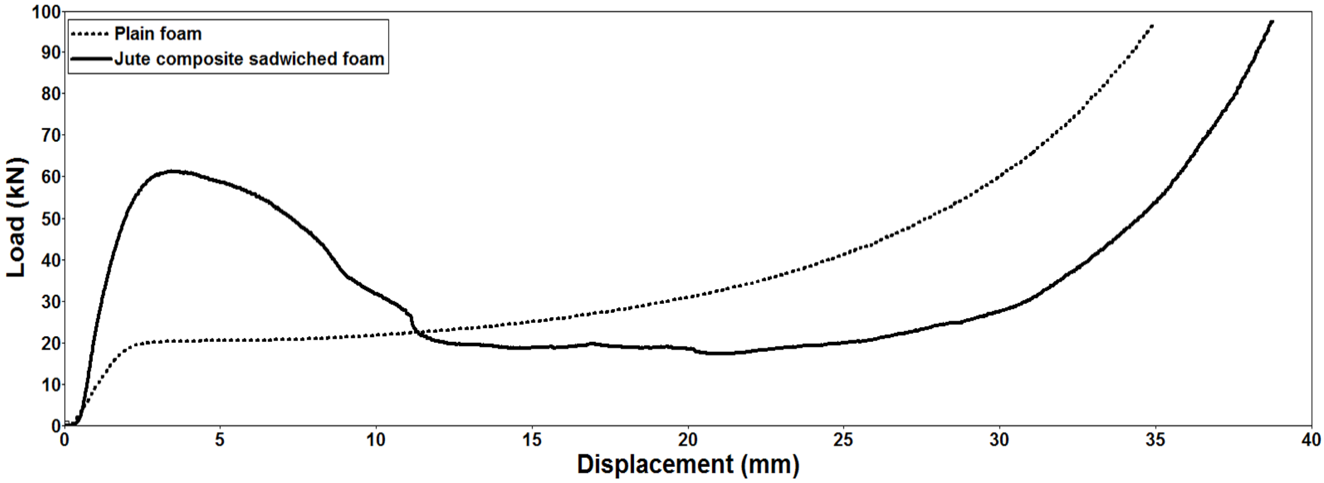

Figure 5. Load-displacement behavior of plain foam and jute composite sandwiched foam

Table 4. Mechanical characteristics of jute composite sandwiched and plain foams

Specimen type	Density (g/cc)	Mean load (kN)	Mean stress (MPa)	Energy absorbed at 60% compression (J)	Specific Energy by density (kJ/g/cc)
Plain foam	0.42	30	10	871	2.04
Jute composite sandwiched foam	0.81 (effective)	39.5	12	1187	1.47

The compression test result for jute composite sandwiched foam is compared with that of plain foam in figure 5. Mean load, mean stress and absorbed energy along with densities for the foams are given in table 4. Mean stress and absorbed energy for jute composite sandwiched foam are found to be respectively 33% and 36% higher than those of plain foam. However, for the same volume (i.e., 50 X 50 X 50 mm3), the jute composite sandwiched foam specimen is heavier than the plain foam cube. As in the case of PVC tube-reinforced foam, it may be pointed out that the mean load (i.e., 39.5 kN from table 4) of the jute composite sandwiched foam is substantially higher than the sum of mean loads of 4 component jute plates (i.e., 2 X 3.4 + 2 X 4.5 = 15.8 kN, from table 3). Hence, PU foam can be considered as an effective core material for a sandwiched construction with jute composite plates. Manufacturers might consider using a jute fibre composite mat for products that require the characteristics of wood but have a shape that cannot be made with a standard wood product. Typical products made using jute fibre composite are molded door skins, automotive interior trim and architectural moldings. When the PVC is replaced with jute material, there is a decrease in the specific energy (28%) which is relatively higher when compared with the composites made from PVC as base material.

3.4 *Deformation patterns of reinforced sandwiched foams*

A primary reason for the superiority of PVC-reinforced foam and jute composite sandwiched foam constructions over individual foam-PVC tubes and jute laminates respectively is the difference in failure mechanisms of the various structural entities. As a pointer to this direction, experimentally obtained deformation patterns of empty PVC tube, foam-filled PVC tube, PVC tube-reinforced foam and jute composite sandwiched foam are shown in figure 6. It is observed from figure 6 (a) that an empty PVC tube collapsed in a sequential diamond pattern while sequential concertina folding is present in a tested foam-filled PVC tube in figure 6 (b). These deformation patterns appear to correlate with similar cases in published literature [28]. Figure 6 (c) shows the progressive deformation of PVC tube- reinforced foam where the tubes are deformed in sequential concertina folding but are skewed outside because of the constraint towards the center of specimen. In the case of jute composite sandwich foam in figure 6 (d), jute plates appear to buckle locally which is an improvement as compared to a single jute laminate under compression which fails in an unstable manner due to global buckling.

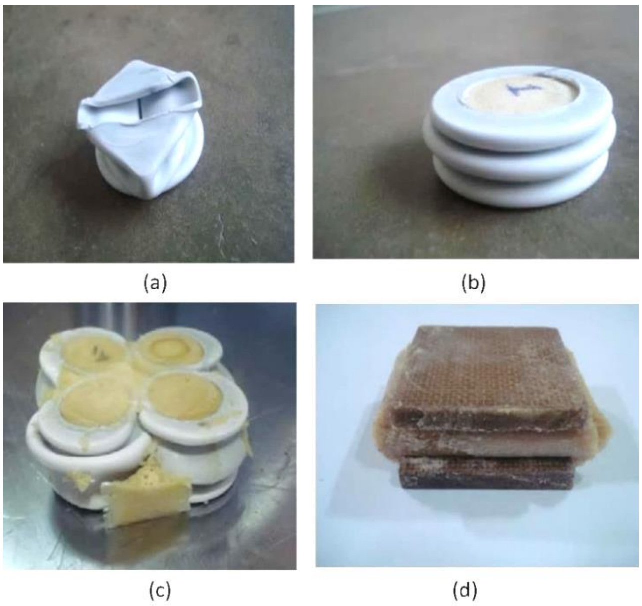

Figure 6. Deformation patterns of **(a)** Empty PVC tube **(b)** Foam filled PVC tube **(c)** PVC tubes-reinforced foam **(d)** Jute composite sandwiched foam

It was observed that with aspect ratio (ratio of radius to thickness) R/h~10, the empty PVC tube had a diamond pattern collapse, initiated by a concertina fold [2]. However, as the foam is filled in and around the empty PVC tubes, densification strain increases, resulting in higher mean load and axisymmetric tri-lobe mode failure (comparing figure 2 and figure 6 (b)). However, in case of PVC tube-reinforced foams, the internal pressure from the composite tube is resisted by the outer foam there by reducing the number of peak loads, resulting in increased energy absorption (figure 3 and figure 6 (c)). Also, progressive deformation of PVC tube-reinforced foam was noticed where the tubes are deformed in sequential concertina folding but are skewed outside because of the constraint towards the center of specimen. Since the reinforced composite tubes are arranged in a parallel configuration, the energy absorption capacity is also enhanced. In the case of jute composite sandwich foam in figure 6 (d), jute plates appear to buckle locally which is an improvement as compared to a single jute laminate under compression, which fails in an unstable manner due to global buckling.

4. Conclusions

The current study is concluded by demonstrating that the mechanical performance of PU foam can be significantly enhanced by using suitable reinforcements such as PVC tubes or by sandwiching foam between lightweight composite plates. Rigid PU foam is shown to be an effective matrix for PVC tubes and an effective core for fiber-reinforced composite laminates. In both cases, the gain in mean load and absorbed energy are quite substantial as compared to plain foam of comparable dimensions under quasi-static compression. These composite constructions have the potential for supplementing foam as lightweight energy - absorbing materials for applications in which plain foam may not be adequate due to requirement of higher energy absorption in a constrained space. Main advantage of using the PU foam material is the effective density of the composite structure. By definition, specific energy decreases as density increases; the same finding can be noted in our experiments as well. However, the drop in the specific energy is not very high or is of the same order of magnitude. Additionally, multi-cell tubes provide better crushing strength as well as energy absorption capacity. The peak strength of sandwich configuration is same as that the reinforced type for same strain values. But the specific energy is more for reinforced structure mainly because of the geometry and deformation patterns that induce structural instabilities. The proposed work is useful for designers to analyze the crashworthiness of foam-filled structures in different configurations, loading conditions and specimens geometries.

Conflict of Interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data Availability

The data is available in the electronic supplementary file.

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