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Advanced composite sandwich structure design for energy absorption applications: Blast protection and crashworthiness

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ABSTRACT

This paper describes an experimental investigation on the response of composite sandwich structures with tubular inserts to quasi-static compression. The performance parameters, namely the peak load, absorbed crash energy, specific energy absorption; average crushing load and crush force efficiency were evaluated. The composite sandwich specimens were fabricated from glass fiber, polystyrene foam and epoxy resin. The primary mode of failure observed was progressive crushing with the composites exhibiting high energy absorption capabilities and high crushes force efficiency. The mechanism of progressive crushing of the sandwich structures and its relation to the energy absorption capabilities was deliberated. Furthermore, a statistical analysis was performed to investigate the effects of the design variables and also to determine if there were interactions between these variables. Such information is vital in the design of polymer composite sandwich structures as energy absorbers.

1. Introduction

Increase in terrorist bombings across the globe has reached to an alarming state since many lives were lost. Due to explosion, and poor energy absorbing capabilities of civil building structures, many structures collapsed, causing major human casualties. One of the potential solutions is to have sacrificial cladding structures. A cladding structure typically has two sub-structures [1]. The first sub-structure is the outermost which comprises of a thin plate (metal, composite or hybrid). The function of this thin plate is to distribute the blast pressure more evenly across the second sub-structure (core). The core then is responsible in absorbing the blast energy in a progressive controlled manner and reducing the effect of the blast force onto the civil structure by lowering the impulsive force level and increasing the duration of the pulse. In general, the solution for a cladding structure is in the form of an efficient energy absorber that is light weight to ease the installation and erection of the cladding structure.

Besides playing a role in a cladding structure, energy absorbers also play a crucial role in crashworthiness design. Crashworthiness is the capability of a material in absorbing high energy during collision in a progressive, controlled and irreversible manner. Crashworthiness ensures the vehicle to absorb crash energy with minimal attenuation of survivable space. The energy of the crash and the manner in which the forces are transferred to the occupants would determine the extent of occupant injuries. The amount of energy that can be absorbed by the vehicle is therefore vital as this will directly affect the impact experienced by the occupants [2]. During collision, the crush force on the vehicle due to impact should remain almost constant and kept below a threshold value to minimize changes in deceleration. Rapid changes in deceleration could cause brain injuries as indicated by the Head Injury Criterion (HIC) [2].

In view of these important energy absorbing applications, in the last two decades intense research has been carried out to understand the energy absorption capabilities of lightweight materials such as composite materials [3–13]. Mamalis et al. [14] explained that thin walled composite structures in the form of circular, square or frusta deform in deform in a manner different from conventional materials. Plastic deformation was not the governing mechanism, but rather the extensive micro-cracking that is the dominant failure mechanism in such structures. Based on these findings, composite materials if designed properly, i.e. to fail in a progressive manner, can possess good specific energy absorption capabilities. Although, much work has been done on polymer composite materials, little has been done to investigate the role of composite sandwich structures as energy absorbing devices. This should not be ignored since sandwich structures due to their extremely high flexural stiffness-to-weight ratio and high strength-to-weight ratio, offer greater potential and wider applications. The material best to be used as the core for such sandwich

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structures are foams. The foams, may it be metallic or polymeric based, have been studied extensively as fillers for steel and aluminium structures [15–18]. It has been shown in these researches that foams generally have positive effect on the energy absorption capability. Nonetheless, the use of foam with composite materials as energy absorbers has not been widely and systematically investigated if compared to the metallic counterparts.

Mamalis et al. [19,20], Found et al. [21], Sivakumar et al. [1] and Tarlochan et al. [22,23] have recently reported on the energy absorption capability of composite sandwich structures. Mamalis et al. [19] investigated the compressive properties and crushing characteristics of sandwich panels under edgewise compression. In this study, it was found that the sandwich panels failed predominantly in column buckling. Even though, one of the specimens was observed to fail in a progressive manner, the ratio of the average crushing load to the peak load was low. These authors also reported that the most important factor that determines the overall crushing response of the specimens was the strength properties of the foam core. Similarly, Tarlochan et al. [22] studied the compressive properties and crushing characteristics of sandwich panels having different constituent materials under edgewise compression test. They also found that all samples failed in a buckling manner and that the specific energy absorption capabilities were low due to the fact that the specimens buckle and there was little evidence of crushing. Mamalis et al. [20] and Found et al. [21] investigated the energy absorption capabilities of foam core sandwich panels having integral fiber reinforced plastic tubes and frusta. These authors showed that the usage of internal reinforcements made from fiber reinforced plastic tubes was beneficial in enhancing the energy absorption capabilities of composite sandwich panels. In a separate study, Tarlochan et al. [23] investigated several geometries and inserts as internal reinforcements for composite sandwich structures and they concluded that these internal inserts were effective in improving the specific energy absorption and crush force efficiency. Sivakumar [1] had shown that the usage of polyurethane foam has added wall strengthening and stability along with uniform and progressive crushing modes; nonetheless the usage of foams reduced the specific energy absorption capability. In another separate study by Kostopoulus et al. [26], the researcher has used expanded polystyrene (EPS) liner part of a composite helmet. They explained that even though EPS will suffer permanent deformation during impact, the material works well in absorbing energy hence keeping the motorcyclist safe.

At this juncture, it is premature to conclude that composite sandwich structures are not as efficient as hollow composite structures as energy absorbers. The authors believed that if the sandwich structures can be designed to overcome premature buckling, there is a good possibility that the sandwich structures would demonstrate progressive crushing, yielding an excellent energy absorption capability. Hence, the objective of this study is to design a sandwich structure with internal tubular reinforcement that exhibit good energy absorption capabilities along with good crush force efficiency and specific energy absorption. The study focused primarily on the mechanism of crushing of the sandwich structures and its relation to the energy absorption capabilities.

2. Experimental setup

2.1. Geometry, material and fabrication process

Based on the literature review, there is very little work conducted on edgewise compression or axial compression in the longitudinal direction of tubular polymer composite sandwich structures. Hence, the current research investigated the response of tubular sandwich structures to quasi-static edgewise compression under different design variables as detailed out in Table 1 and the schematic representations are shown in Figs. 1 and 2, respectively. Woven glass fiber fabric with an aerial density of 200 g/m^2 and epoxy resin was used in this study. The fiber fabric is weaved at a 0°/90° configuration. Two different thickness were investigated, namely 16 and 8 layers of fiber fabric. On an average, the 16 layers correspond to a thickness of 8 mm, whereas the eight layers correspond to 4 mm of thickness as described in Table 1.

Table 1
Specimen description used in the study.

No	Specimen ID	Outer tube thickness (mm)	Inner tube thickness (mm)	Inner foam, Cb	Initial mass (g)	General dimensions
(a)	O4I4-Ca	4	4	No	174	Length = 130 mm
(b)	O4I4-CaCb	4	4	Yes	178	
(c)	O4I8-Ca	4	8	No	210	Outer tube
(d)	O4I8-CaCb	4	8	Yes	212	mandrel
(e)	O8I4-Ca	8	4	No	268	diameter = 82 mm
(f)	O8I4-CaCb	8	4	Yes	281	Inner tube
(g)	O8I8-Ca	8	8	No	314	mandrel
(h)	O8I8-CaCb	8	8	Yes	321	diameter = 32 mm
(i)	Control	4	4	No	215	

The foam used was an expanded polystyrene (EPS) having a density of 32 kg/m^3. The compression deformation behavior for the polystyrene foam is given in Fig. 3. This compression test was carried out in accordance to ASTM 1621-91. Different stress states are marked as O, A, B and C in this figure. The region OA represents the linear response of the foam. The region AB corresponds to a near-plateau stress region. In this region, the cell structure within the foam loses stability and starts to compact drastically with little respond to the applied force, hence giving rise to a near-plateau like region. Once the cells are completely "flatten", the densification region starts where the force rises quickly with little deformation as designated by region BC. This was found to occur at about 80% strain as shown in Fig. 3.

Hand lay-up technique was used as the fabrication means with cylindrical mandrels. Tensioning was given during the fabrication process to ensure that all specimens have the desired thickness and that air was not trapped between wraps. The ends of the tubes were grind to ensure the tubes were free from burrs or uneven ends. This is important to avoid eccentricity loading during the test. A control sample made up from an empty composite tube with a tubular insert was also fabricated. The purpose of this control sample is to investigate the role of polystyrene foam in energy absorption capability.

2.2. Test procedure

The compressive and crashworthiness behavior of the tubular composite sandwich structures were experimentally studied by applying axial quasi-static compressive loads in the edgewise direction of the specimens. The load was applied by using a standard 100 kN Instron servo-hydraulic machine. All the specimens were compressed and loaded at a crosshead speed of 10 mm/min. Load and displacement were recorded by an automatic data acquisition system with sampling rate of 5 Hz. From the load displacement curves that were recorded during the test, the following crashworthiness parameters were obtained: the peak load ($\boldsymbol{F_{MAX}}$) corresponds to the maximum load achieved by the specimen before crushing, the total crash energy absorbed ($\boldsymbol{E_{ABS}}$) corresponds to the area under the load displacement diagram, the specific energy absorption ($\boldsymbol{E_{SEA}}$) is termed as the total absorbed crash energy per unit mass of the crushed portion of the specimen, the average crush load ($\boldsymbol{F_{AVG}}$) is defined as the ratio of the energy ab-

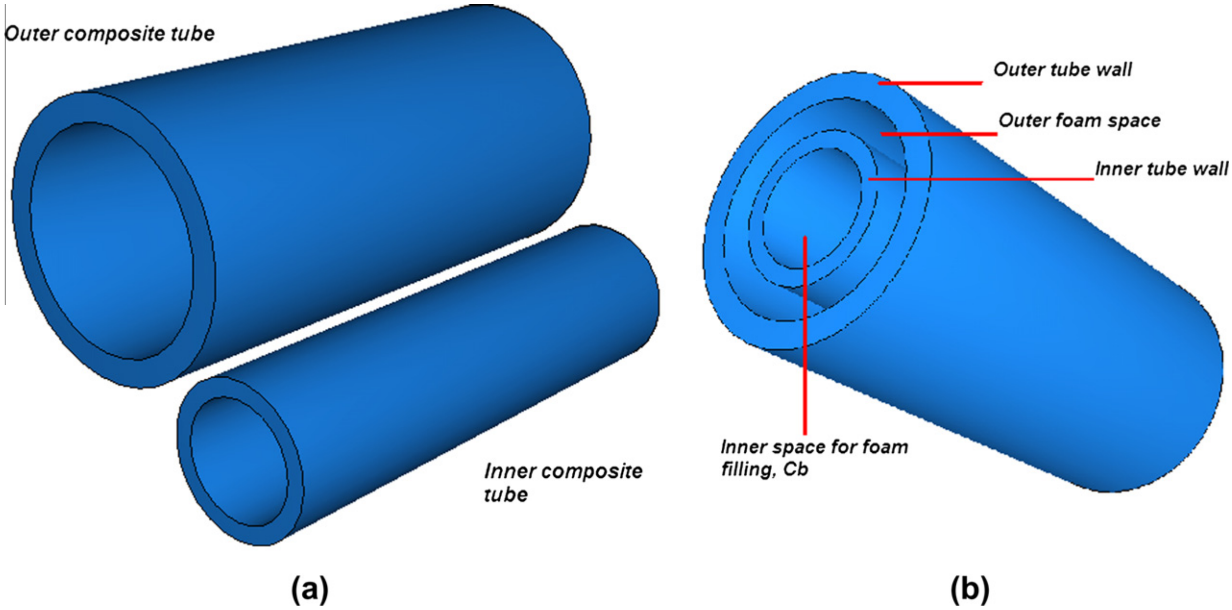

Fig. 1. Polymer composite sandwich tubular structure (a) inner and outer tubes and (b) final assembled view.

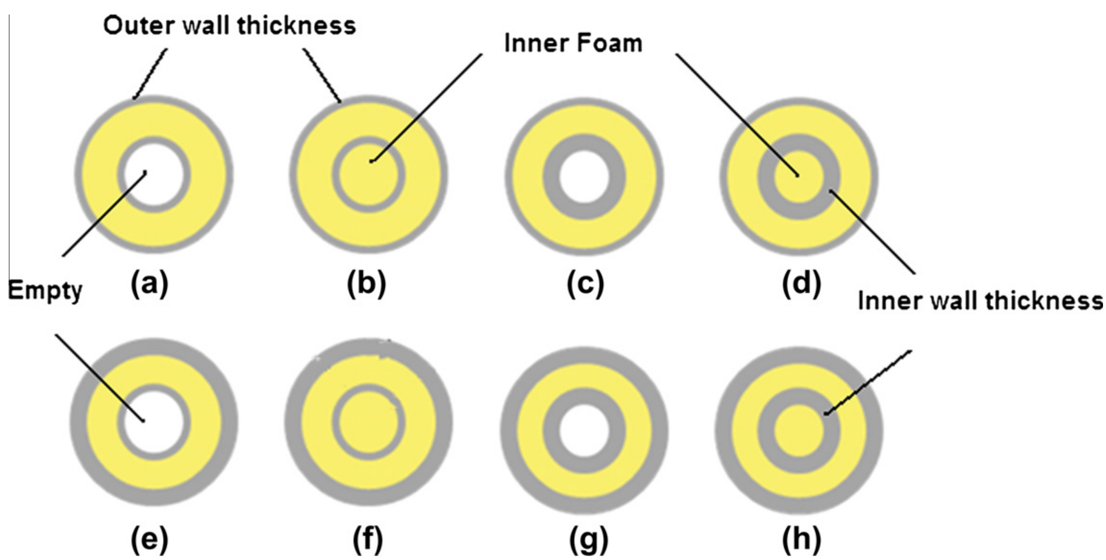

Fig. 2. Various specimen geometry configurations (refer to Table 1).

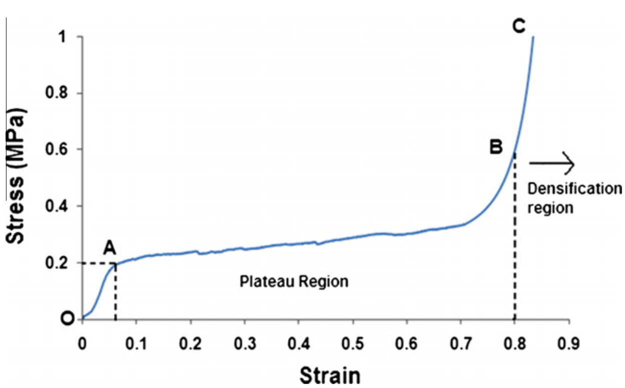

Fig. 3. Stress strain diagram for polystyrene closed cell with a density of 32 kg/m^3.

sorbed in the crush zone ($\boldsymbol{E_{CRUSH}}$) to the displacement ($\boldsymbol{\Delta d_{CRUSH}}$) in this zone, the crush force efficiency ratio (***CFE***) is defined as the ratio of the average crush load ($\boldsymbol{F_{AVG}}$) to the peak load ($\boldsymbol{F_{MAX}}$).

3. Results and discussion

3.1. Force displacement characteristics

The force displacement diagrams for the control sample and other samples tested in this study are shown in Figs. 4–12. All specimens tested crushed in a progressive manner. In the study of crashworthiness of energy absorbing devices such as tubes, attention must be given to the energy absorption mechanism. This is because if the failure is progressively stable, it would lead to safely smooth decelerations (stable impulsive force) during a crash.

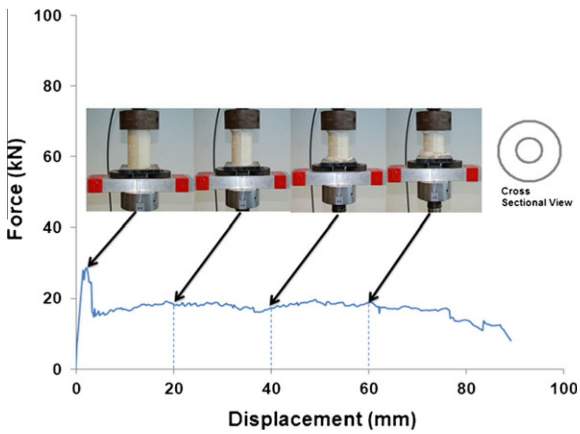

Fig. 4. Force displacement diagram for control sample.

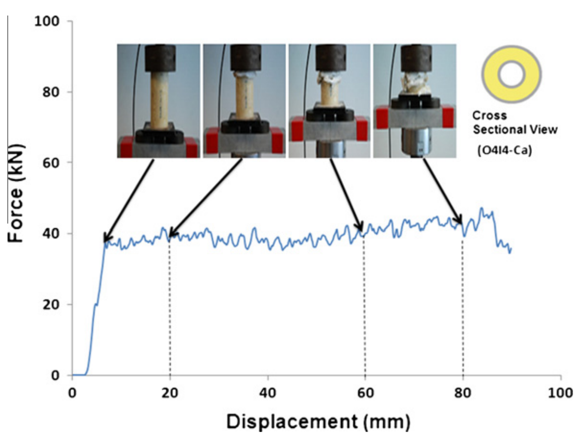

Fig. 5. Force displacement diagram for specimen O4I4-Ca.

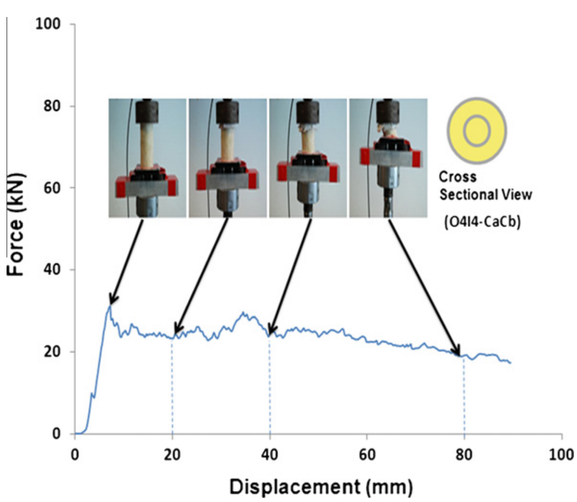

Fig. 6. Force displacement diagram for specimen O4I4-CaCb.

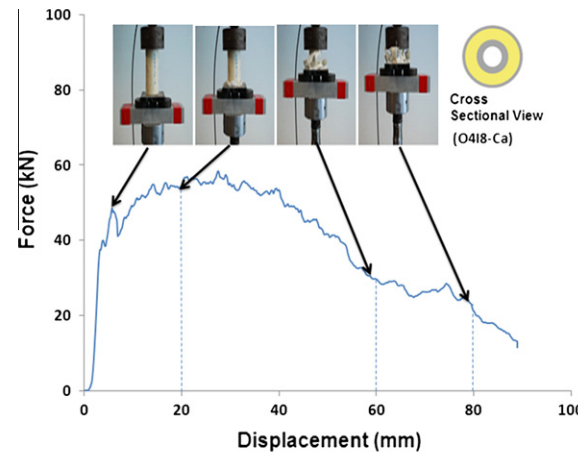

Fig. 7. Force displacement diagram for specimen O4I8-Ca.

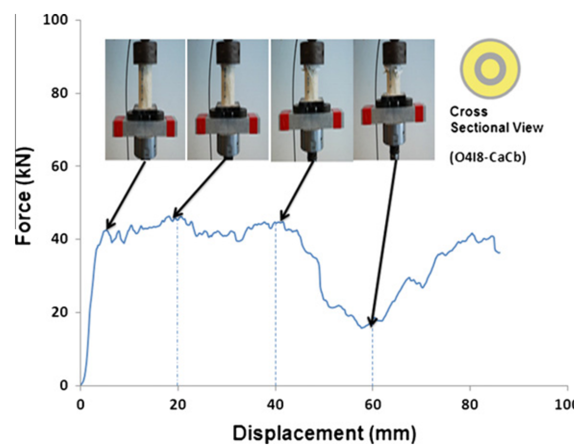

Fig. 8. Force displacement diagram for specimen O4I8-CaCb.

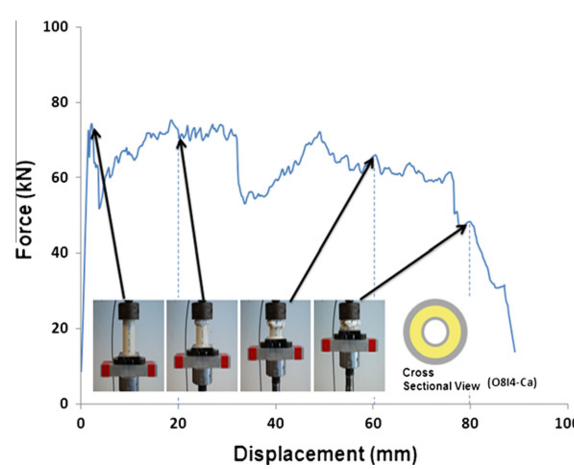

Fig. 9. Force displacement diagram for specimen O8I4-Ca.

In this study there are two distinct progressive crushing failure modes (collapse mechanism) that were observed, subsequently labeled as Modes I and II.

Fig. 4 depicts the force displacement diagram for the control specimen. The control specimen failed in a controlled progressive manner throughout the length. The initial crushing state displayed slight local Euler Buckling at quarter of the length after achieving the critical/peak load. This caused the sharp decrease in the force. After this initial steep decrease in the force, the remaining of the tube crushed by forming petal shaped fragmentations. These fragmentations are caused by axial cracks, initiating from the location where the local buckling took place. The amount energy absorbed

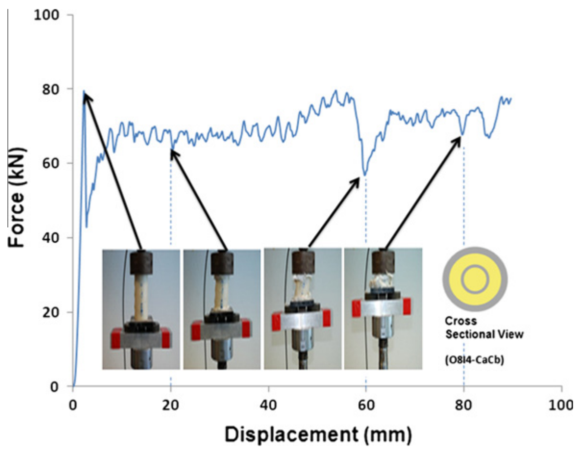

Fig. 10. Force displacement diagram for specimen O8I4-CaCb.

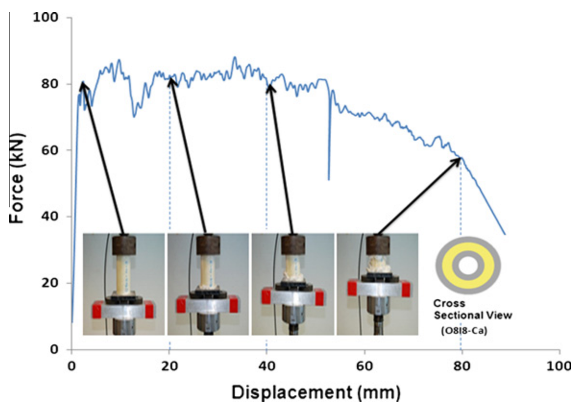

Fig. 11. Force displacement diagram for specimen O8I8-Ca.

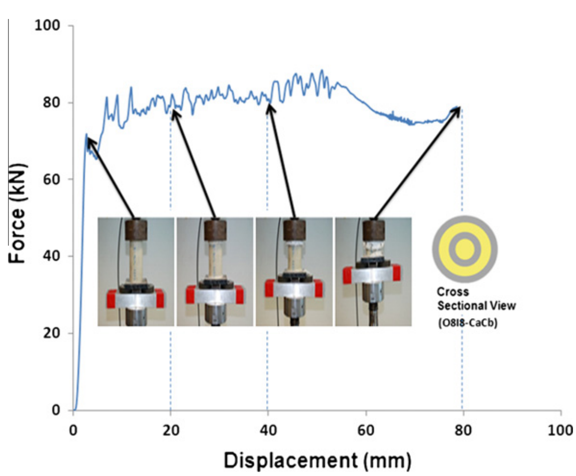

Fig. 12. Force displacement diagram for specimen O8I8-CaCb.

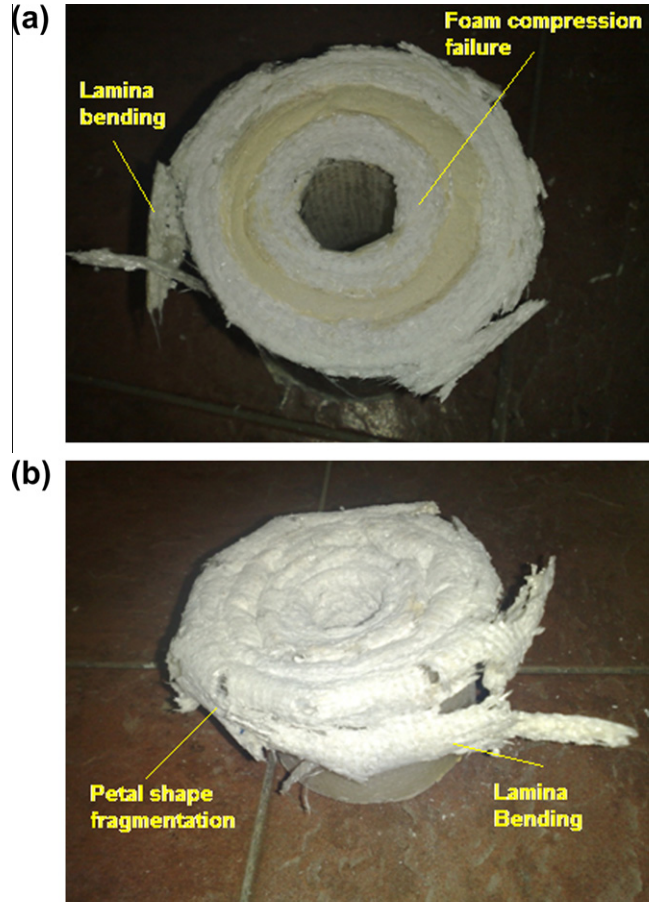

Fig. 13. (a) Mode I failure type and (b) Mode II failure type.

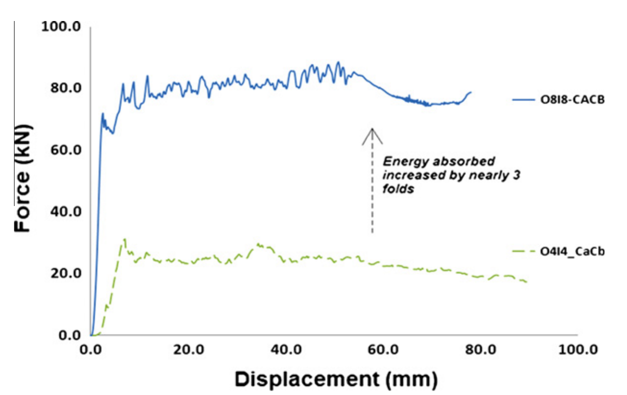

Fig. 14. Increase in energy absorption (area under the curve) due to increase in mass of specimen.

by this control specimen was 1.52 kJ with specific energy absorption of 10.3 kJ/kg. The average crush load was recorded to be 28.7 kN.

For the remaining specimens studied in this research work, all specimens displayed good progressive crushing. The details of the performance parameters are tabulated in Table 2 and are compared within specimens in Figs. 15–17. From observing these figures and Table 2, it is noted that specimens O8I4-CaCb, O8I8-Ca and O8I8-CaCb are good choices for an energy absorber. The total energy absorbed and specific energy absorption of these specimens is around 6 kJ and 30 kJ/kg, respectively. These values are much higher than the control specimen indicating the importance of having foams as an integral component in designing an energy absorber. In Figs. 8–11, the specimen experienced a second sudden drop in load carrying capability. This was due to second progressive crushing beginning at the base of the specimen. Nonetheless, this second progressive crushing did not last long, which gave rise to the load once again.

Table 2
Performance parameters.

No.	Specimen ID	Energy absorbed (kJ)	Specific energy absorbed (kJ/kg)	CFE	Average crush force, F_{avg} (kN)	Peak force, F_{max} (kN)	Failure mode
(a)	O4I4-Ca	3.4	30.4	0.84	39.6	47.1	II
(b)	O4I4-CaCb	2.0	17.7	0.75	23.3	31.1	I
(c)	O4I8-Ca	3.5	24.9	0.68	39.8	58.4	II
(d)	O4I8-CaCb	3.1	23.3	0.77	35.6	46.3	I
(e)	O8I4-Ca	5.4	30.1	0.81	60.7	75.2	II
(f)	O8I4-CaCb	6.1	32.6	0.87	69.5	79.6	II
(g)	O8I8-Ca	6.5	30.6	0.82	72.5	88.2	I
(h)	O8I8-CaCb	6.3	32.4	0.88	78.1	88.5	II
(i)	Control	1.52	10.3	0.59	17.0	28.7	II

3.2. Failure modes

Two detail modes of failure were observed, namely Modes I and II. Essentially, both modes of failures are similar. They are characterized by the progressive end crushing of the axially compressed specimen with the formation of fronds which spread outward and inwards (Mode I) and several fronds spreading outwards (Mode II) as depicted in Fig. 13, steadily splitting the specimen with high energy being absorbed. These collapse modes correspond to the "splaying" and "lamina bending" type of stable brittle fracture. Once the peak load is achieved at the end of the linear elastic range, the progressive crushing of the specimens (Modes I and II) initiated with cracks formation parallel to the longitudinal axis of the specimens geometry which could be associated to local stress concentration. These crack formations are followed by an immediate drop of the compressive load as well as its progressive crushing parallel to the longitudinal axis of the specimen. The crushing causes fronds to be developed, where some were found to grow inwards and outwards (Mode I) and some only outwards (Mode II) like petal shapes.

Based on the experimental observations, the energy dissipated that is related to the collapse mode can be associated with any of the following failure characteristics:

- Bending of the fronds and composite lamina bundle.
- Splaying and fragmentation of the composite skins.
- Cracks that grow in the longitudinal direction of the specimens.
- Sliding of the external and internal fronds against the crosshead.

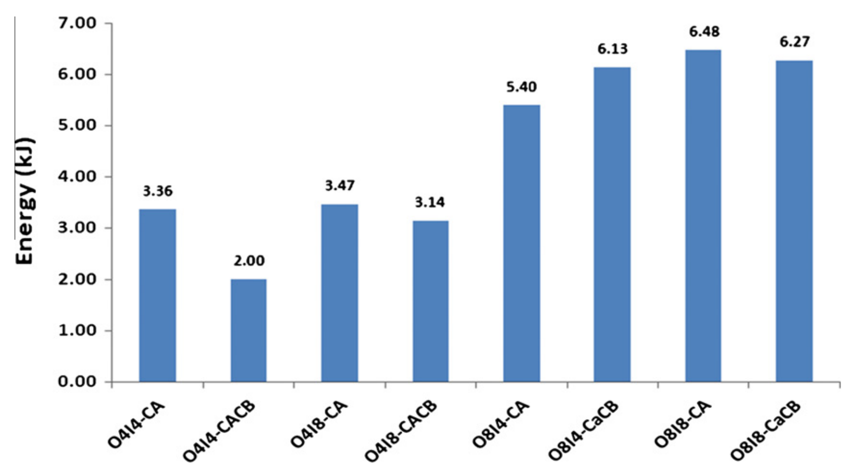

Fig. 15. Comparison of total energy absorbed between specimens.

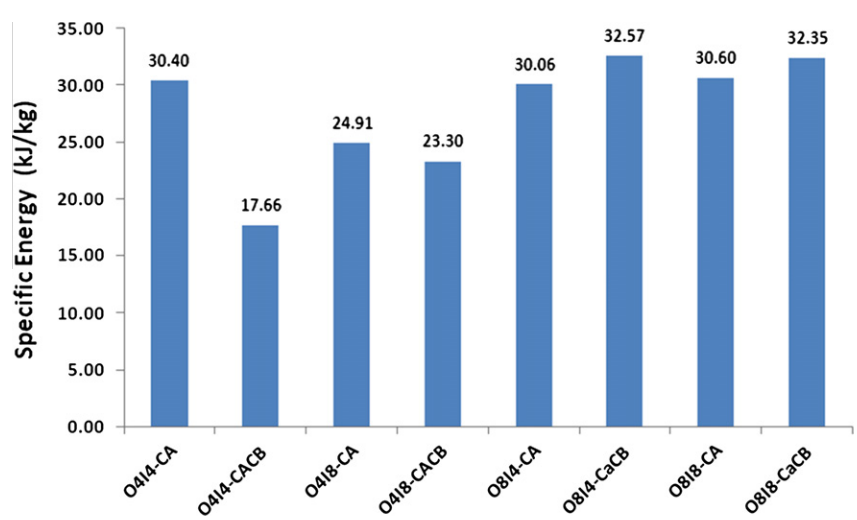

Fig. 16. Comparison of specific energy between specimens.

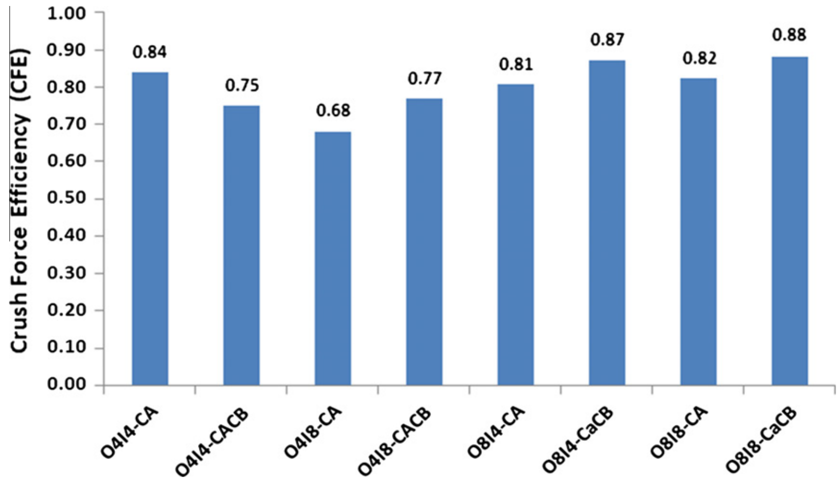

Fig. 17. Comparison of crush force efficiency between specimens.

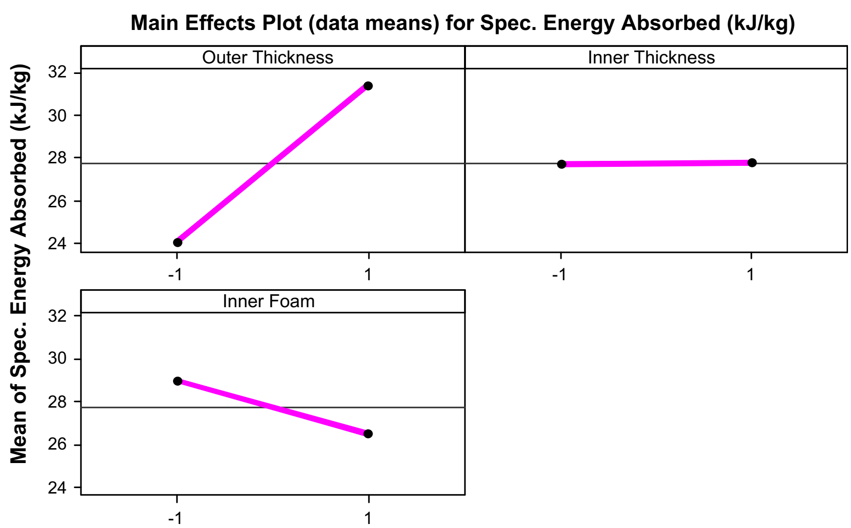

Fig. 18. Influence of design variables on specific energy absorption.

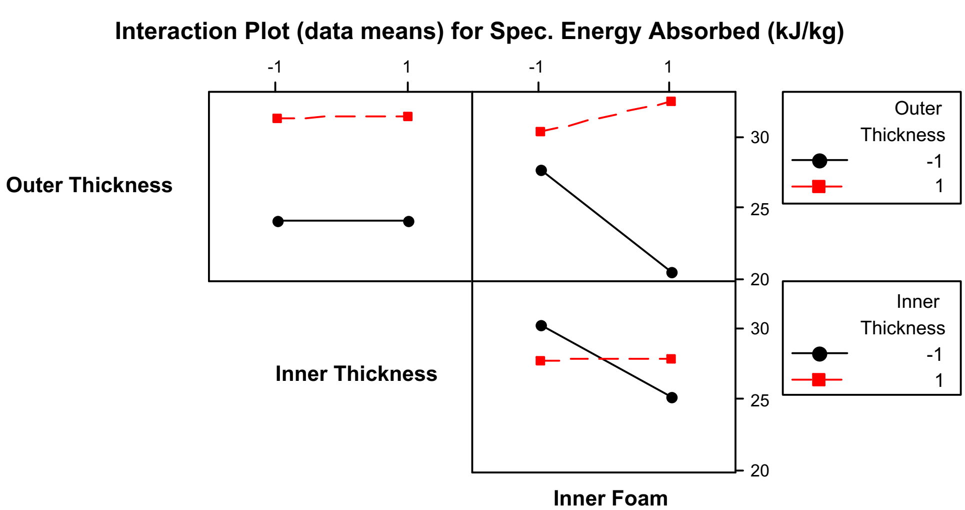

Fig. 19. Influence of interaction between design variables on specific energy absorption.

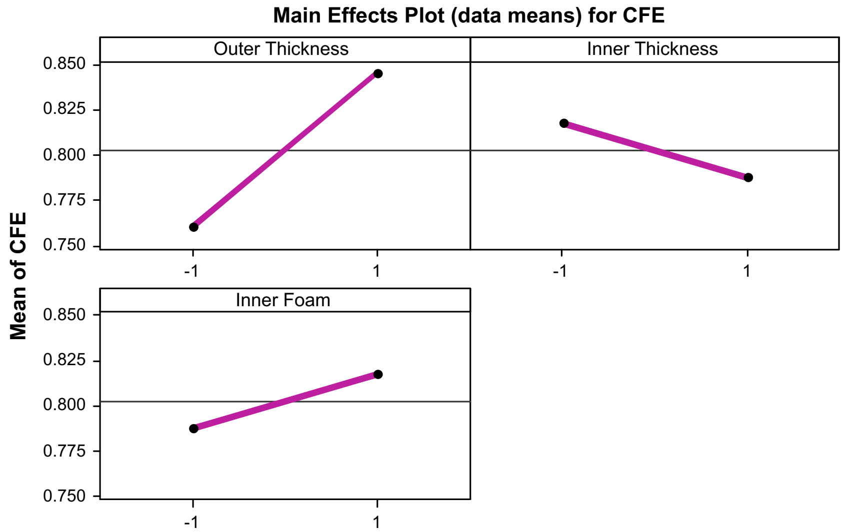

Fig. 20. Influence of design variables on crush force efficiency.

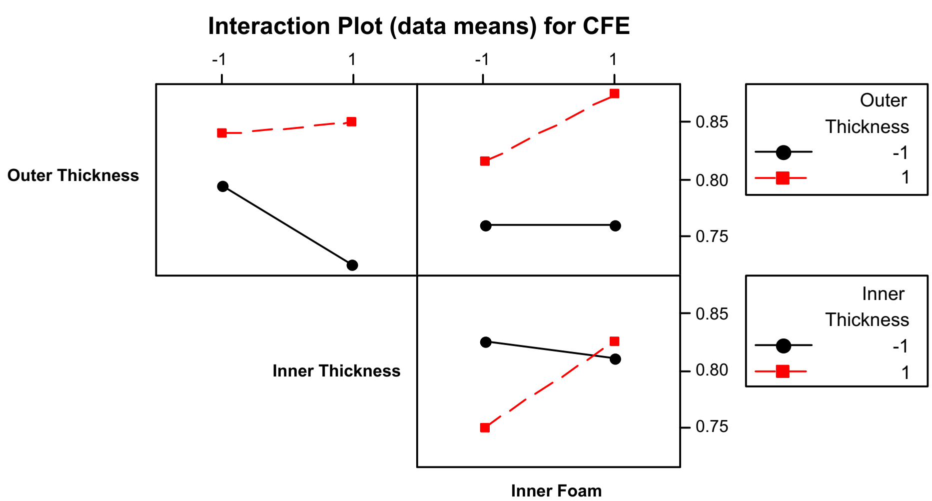

Fig. 21. Influence of interaction between design variables on crush force efficiency.

- Elastic compression of the composite material.
- Permanent plastic deformation of the core (foam).
- Densification formation of the foam due to compression.

The total energy absorbed can be given by:

$$E_{total} = E_{mc} + E_{debond} + E_{fiber} + E_{core} + E_{splaying} + E_{fragmentation} + E_{lost} \quad (1)$$

where E_{total} is the total energy input into the system by the servo-hydraulic machine, E_{mc} is the energy required to crack the polymer resin matrix, E_{debond} is the energy required to debond the fiber from the matrix, E_{fiber} is the energy required to fracture the fibers, E_{core} is the energy absorbed by the core as it gets compressed, $E_{splaying}$ and $E_{fragmentation}$ are the main energy absorption mechanism, respectively. These energies are responsible for the fragmentation and splaying of the composite tubes. Finally, some energy is lost (E_{lost}) as heat due to friction and due to noise.

3.3. Comparison between performance parameters

3.3.1. Total energy absorbed

The total energy absorbed can be defined as the area under the force–displacement curve (Eq. (2)). It is a function of the sample geometry, material and loading rate. Numerical integration was carried out to calculate the energy absorbed as given by the numerical equation.

$$E_{ABSORBED} = \int_0^{d_{max}} P(l)dl \quad (2)$$

$$E_{ABSORBED} = E_{TOTAL} - E_{LOST} = \sum E_i = \sum (P_i * 0.5 * (d_{i+1} - d_{i-1})) \quad (3)$$

where P_i is the current instantaneous applied load and d_i is the current displacement value. The summary and comparison of the total energy absorbed is given in Table 2 and Fig. 15 respectively. It was evident from these results that an increase in the composite mass would increase the energy absorption capabilities, i.e. the energy absorbed increased by nearly three folds as shown in Fig. 14.

3.3.2. Specific energy absorption (E_{SEA})

To compare different geometry or material of specimens in terms of energy absorption capabilities, it is necessary to normalize the total energy absorbed with respect to per unit of crushed mass of the specimen. This is termed as specific energy and has the units of kJ/kg (see Eq. (4)). The higher the value of this specific energy, the more efficient the specimen is in terms of energy absorption on a mass basis. The summary of the specific energy absorbed by

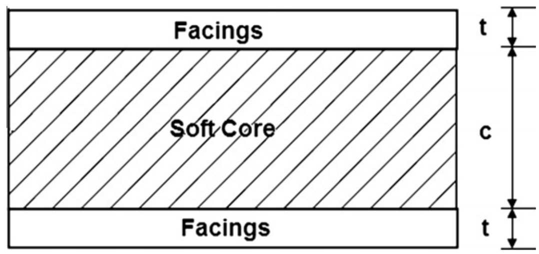

Fig. 22. Sandwich column representation.

each specimen is given in Table 2 and a direct comparison is shown in Fig. 16. From these results, it is found that the specimens O8I4-CaCb and O8I8-CaCb have the highest specific energy, i.e. ~32 kJ/kg. In comparison, the specific energy absorbed by the control sample was about 10.3 kJ/kg.

$$E_{SEA} = \frac{\int_0^{d_{\max}} P(l)\, dl}{m_{crushed}} \tag{4}$$

3.3.3. Crush force efficiency (CFE)

The average and peak loads are important parameters as they are directly related to the deceleration that will be experienced by the vehicle occupants. The best way to quantify this is by defining a ratio between the mean load to the peak load (see Eq. (5)). This ratio is defined as crush force efficiency (CFE). If the ratio is close to unity, the absorber is crushing at a value close to the peak load, hence minimizing the changes in deceleration as desired. On the other hand, if this ratio is away from unity, there are rapid changes in the deceleration and this could have an adverse effect to the occupant and must be considered in the design of a vehicle [2]. The summary and comparison of the CFE is given in Table 2 and Fig. 17, respectively. In general, all specimens displayed better CFE if compared to their metallic counterpart [24,25].

$$CFE = \frac{P_{mean}}{P_{\max}} \tag{5}$$

$$P_{mean} = \frac{\int_0^{d_{\max}} P(l)\, dl}{d_{\max}} \tag{6}$$

3.4. Statistical analysis

In this study, the thickness of the outer tube, the thickness of the inner tube and the insertion of foam into the inner tube were taken as the variables. It is important to understand the role of

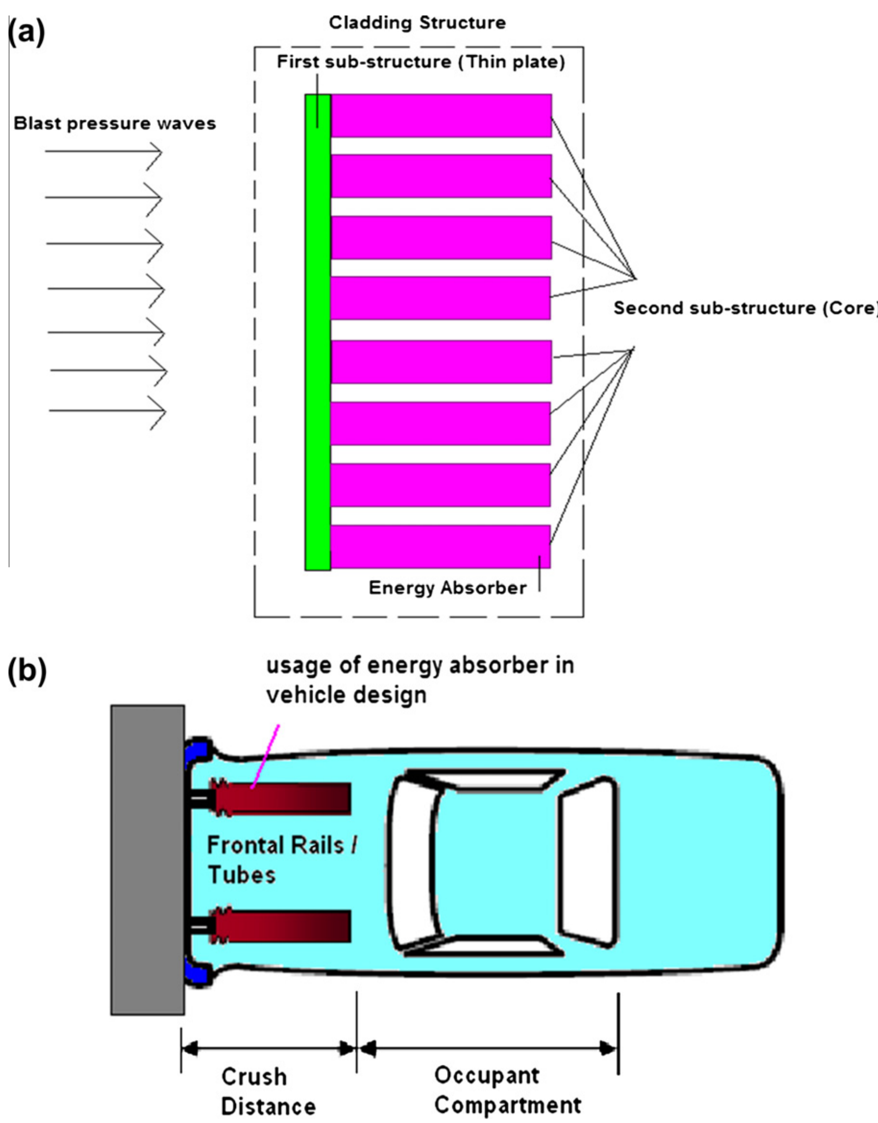

Fig. 23. Applications of energy absorber design (a) as cladding structure (b) as longitudinal tubes in vehicles.

these variables on the performance parameters. Hence basic analysis of variance was done on the specific energy absorption and crush force efficiency to understand the effects of these three variables on both these responses. Figs. 18 and 19 show the main effects and interaction plot respectively for the specific energy absorption, whereas Figs. 20 and 21 depict the main effects and interaction plot respectively for the crush force efficiency. These figures are coded, meaning the lower value (−1) corresponds to the smaller thickness, whereas the higher value (+1), corresponds to the larger thickness. For the inner foam, the lower value corresponds to no inner foam filling, whereas the upper value corresponds to inner foam filling.

From Fig. 18, it can be seen that as the outer thickness increases, so will the specific energy absorption ($\boldsymbol{E_{SEA}}$). This figure also shows that the inner tube thickness does not contribute towards the increase or decrease of $\boldsymbol{E_{SEA}}$. The inner foam filling on the other hand decreases the energy absorption. In general, the outer tube thickness is the most prominent factor. Fig. 19 which describes the interaction between factors depicts that there is no interaction between the inner and outer tube thickness. Nonetheless the same cannot be said for the interaction between the outer tube thickness and the inner foam filling. When the outer tube thickness is at its highest level, the interaction is positive, but when the outer tube thickness is at its lowest thickness, this interaction becomes negative. This is probably associated with the formation and interaction between micro-cracks within the specimen during crushing of the tubes. Finally, the interaction between the inner tube wall thickness and inner foam filling is similar to that of the outer tube wall. For the crush force efficiency (Figs. 20 and 21), the interactions between the factors are positive when the higher design values were used. For the lower design values, these interactions become negative.

3.5. Design to avoid buckling failure

Based on literature review, the sandwich panels used for energy absorption studies consist of traditional design of sandwich columns. These columns had a soft shear deformable core with top and bottom facings as shown in Fig. 22. In general buckling is predicted by using the Euler buckling formula as given in Eq. (7). Based on this formula, fundamentally the critical load increases with an increase in the moment of inertia (I). Hence in principle, when designing, one would increase the moment of inertia to avoid buckling and this is can be done by increasing the core thickness since it is lightweight. However in a study conducted by Tarlochan et al. [22] using composite sandwich panels, the critical load did not increase significantly with the increase in the moment of inertia. This observation was attributed to the overall decreased in the overall Young's Modulus of the structure based on the rule of mixture as given in Eq. (8). Hence to design sandwich "columns" effectively for energy absorption, the issue of buckling has to be resolved. This could be achieved by strengthening the facing which is made from composite materials. Hence, a deviation from a typical composite sandwich column as shown in Fig. 22 has to be made. One plausible way of overcoming buckling is to provide a continuous facing enclosing the core material. The facings, tied in a continuous manner, would support each other from buckling as shown by Tarlochan et al. [27]. A similar idea was used in this study to overcome buckling effect by enclosing the core with cylindrical facings (tubes). This internal tubular structure would also serve to enhance the energy absorption capabilities of the composite.

$$P_{cr} = \frac{\pi^2 EI}{L_e^2} \tag{7}$$

$$E_{eff} = \upsilon_f E_{facing} + \upsilon_c E_{core} \tag{8}$$

4. Conclusions

In this study, the crushing response of composite sandwich structures under quasi-static compressive loads was investigated. The aim of the study presented here was to design and fabricate tubular sandwich structures that have potential as energy absorber devices. The following conclusions can be drawn from this work:

1. All of the specimens collapsed under compressive loading in a brittle manner demonstrating progressive folding patterns.
2. The potential of composite material and polymeric foam material as energy absorbers was explored quantitatively.
3. Specimens O8I8-CaCb showed the highest specific energy absorption as well as crush force efficiency while specimens O4I4-CaCb exhibited the lowest specific energy absorption and crush force efficiency.
4. The energy dissipated that is related to the collapse mode can be associated with any of the following failure characteristics:
   - Splaying and fragmentation of the composite skins (both inner and outer).
   - Bending of the fronds and composite lamina bundle.
   - Sliding of the internal (inner tubular structure) and external (outer tubular structure) against the crosshead.
   - Elastic compression of the composite material.
   - Densification formation and permanent deformation of the core (foam) due to compression.
   - Transverse shearing of the mid length specimen outer wall (as observed).
5. In general, as the number of plies increases, there is an improvement in the performance parameters.

The present work has demonstrated the potential of using tubular sandwich composite structures as energy absorber devices for cladding structures and also for crashworthiness application in vehicle design as shown in Fig. 23.

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