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Effect of Multi Stitched Locations on High Speed Crushing of Composite Tubular Structures

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Abstract

The present paper experimentally investigates progressive energy absorption of fibre-reinforced polymer (FRP) composite tubular structures under high speed loading conditions. Various multi stitched locations are studied to find a correlation between single and multi-locations of stitches and energy absorption capabilities of composite absorbers. The through-thickness reinforcements are applied into locations of 10mm, 20mm, 30mm, 10-20m, 10-30mm, 20-30mm, 10-20-30mm and 10-15-20-25-30-35mm from top of the tubes. It is shown that multi-stitched location can cause several increase of crushing load and consequently increase of energy absorption of composite tube absorbers. The idea would be expanded to other designs which are followed by increase of stitched locations and reduction of the distance between stitches to improve the mean force with a smooth and progressive pattern of crushing load.

Keywords: A. Polymer-matrix composites (PMCs); B. Crack; C. Progressive; D. Crush; E. Multi-stitches;

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1. Introduction

The energy absorption capability of composite materials offers an exceptional combination of reduced structural weight and improved vehicle safety by higher or at least equivalent crash resistance compared with metallic structures. Crash resistance covers the energy absorbing capability of crushing structural parts as well as the demand to supply a protective shell around vehicle occupants. The basic principle of occupant crash protection has been used in the automotive field since the early 1950s, and crash safety has meanwhile become a well-established car design requirement. In aeronautics, the first structural design requirements for better crash protection were studied for military helicopters and light fixed-wing aircraft in the form of the aircraft crash survival design guide [1-5].

In all previous researches several variables related to the energy absorption of composite thin-walled structural components have been investigated. Regarding crushing behaviour of composite tubular structures, their suitability is determined not only by the usual design parameters, such as geometry, layups and strain rate sensitivity [6-8] but by their progressive failure mechanisms.

One of the most important parameter which has a significant effect on the crushing process is interlaminar and intralmaniar fracture toughness. Various researches have studied the crack propagation and all alternative ways to control the failure within the structure of composite absorbers. The most important of these works can be summarised as below:

Zhou et al [9] studied crashworthiness characteristics of rectangular tubes made from a carbon-fibre reinforced hybrid-polymeric matrix (CHMC) composite using quasi-static and impact crush tests. Their results showed that the load carrying capacity and total energy absorption tend to increase with greater polyurea thickness and lower elapsed reaction curing time of the epoxy although this is typically a function of the loading rate.

Solaimurugan et al. [10-11] investigated the effect of stitching, fibre orientation and stacking sequence on G_{IC}, SEA, and also progressively crushing of glass/polyester composite cylindrical shells under axial compression. According to their results the axial fibres placed close to the outer surface of tube led to more petal formation and stable crushing process, while axial fibres close to inner surface tube cause higher energy absorption. The energy absorption capability in the form of circumferential delamination increases for higher values of Mode-I fracture toughness. They also showed that through the thickness reinforcement improves the Mode-I interlaminar fracture toughness which results in improvement of energy absorption of cylindrical tube.

Ghasemnejad and Hadavinia [12] reviewed off-axis crashworthy behaviour of woven GFRP composite box structures. They found two fracture mechanisms of bundle fracture and delamination crack propagation in Mode-II for all composite boxes at various off-axis loading. Due to crack propagation in mixed-Mode I/II and more friction and bending resistance at one side of composite box which firstly contacted the crushing platen, the amount of SEA at off-axis loading of 10° was the maximum in comparison with other off-axis crushing loadings. Ghasemnejad et al. [13] have also studied the effects of delamination failure of hybrid composite box structures on their crashworthy behaviour. According to their results it was found the hybrid laminate designs which showed higher fracture toughness in Mode-I and Mode-II delamination tests, will absorb more energy as a hybrid composite box in crushing process. In another work by author [14] the effect of delamination failure of stitched composite box structures in their crashworthy behaviour were studied and their performances were compared with non-stitched ones. The combination of unidirectional CFRP and GFRP composite materials with lay up of $[C_{90}/G_0]_7$ were used to laminate the composite boxes. This laminate design showed the highest energy absorption capability in our previous study of authors. Delamination study in Mode-I with the same lay-up was carried out to investigate the effect of delamination crack growth on energy absorption of natural stitched composite box structures. The double cantilever beam (DCB) standard test methods were chosen for delamination studies. It was shown that stitching can significantly increase the interlaminar fracture toughness and consequently energy absorbing capability of composite materials and structures.

In engineering application generally the loading classification are static, fatigue, high speed loading and impact. These loads are categorised according to the rise time of the load. For static loading this time is three times greater than the fundamental period of the mechanical system. Fatigue loading occurs when the 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 of fundamental periods of the mechanical system [15-16].

In all previous researches several variables related to the energy absorption of composite thin-walled structural components have been investigated. Apart from all these parameters, multi-location stitching is another factor which significantly influences the energy absorption of composite tubular structures under high speed loading. This paper experimentally aims to study the relation between locations of stitches and energy absorption capabilities of composite absorbers.

2. Valuation criteria for crushing behaviour

There are many important variables which must be considered in the study of energy absorption capabilities. These include material; manufacturing method; microstructure; geometry of specimen, including any crush initiator used; and rate of crushing speed. One of the most important parameters is the specific energy absorption (SEA) performance of collapsing or crushing specimens or structural parts. This value is related to the absorbed energy compared to the mass of the absorber or structure. In this case, it is an important criterion for lightweight designs. Another important factor in the study of energy management capabilities is the shape of the force-crush distance curve. One measure which is used to characterise the shape of the curve is called crush-force efficiency (CFE). This value relates the average crush force (F_m) to the maximum force (F_{max}) of the crush characteristic.

3. Crushing failure mechanisms

Catastrophic and progressive failures are two main failure mechanisms of composite tube structures (see Figure 1). A progressive crushing is introduced at one end of the specimen using a bevelled trigger mechanism and then it progresses through the specimen without significant damage past this crush front. For a catastrophic failure the initial maximum force is very high and drops rapidly, therefore the average force is low.

In this work all composite tubes were fabricated by glass/epoxy material (ρ = 2000 kg/m^3) using hand lay-up techniques with a symmetric twelve-ply quasi-isotropic laminate of $[-45/45/0/90/0/90]_S$. Once the tubes had been laid-up, they were placed between pre-cut aluminium plates to keep them flat during the curing process. The plates were pre-treated with a mould cleaner to remove grease and debris and a monocoat wax was applied to prevent escaped epoxy from the prepreg bonding to the metal plates. The plates were then covered in non-stick polymer sheets to further decrease the chance of epoxy bonding to the plates. The plates were placed on either side of the uncured composite, then covered top and bottom with three sheets of ‘breather cloth’ and placed inside a heat resistant polymer bag. The breather cloth has the appearance of cotton wool and allows air to circulate around the bag preventing the formation of air pockets. The bagging material was cut from a roll and was opened at either end. A high temperature, double-sided epoxy tape was used to seal the ends. Once sealed, an air suction valve is inserted through the bag and a pipe connected the valve to a vacuum pump. The vacuum pump was used to evacuate the bag, with the aid of the breather cloth. This has the effect of pressing the aluminium plates tightly together and forcing the plies of prepreg together, allowing good adhesion between the plies and eliminating air that could cause voids in the composite. The pressure gauge was inserted via a second valve to monitor the pressure in the bag. This can be used to ensure the correct pressure is applied to the bag (following the manufacture’s guidelines). The pressure gauge was also used to measure any pressure drop in the vacuum bag once the pump had been switched off and hence to check if the bag was properly sealed. All absorbers were also stitched by glass fibre yarns to reinforce the tubes through the thickness (see Figures 2 & 3). Four specimens were tested for each design to find the standard deviation of experimental results. The crushing stroke and total length of specimens were chosen based on the capacity of our machine with maximum crush distance of 50mm. This research has concentrated on force displacement results which consequently give the amount of energy absorption capability of designed absorbers. Since there are various factors such as geometry, layup, strain rate and loading direction affecting failure mechanisms of FRP composite absorbers we have decided to set other variables constant and only study effect of stitching on the specific energy absorption capabilities of composite absorbers.

4. Results and Discussions

4.1. High speed axial crushing vs off-axis crushing process

The high speed crushing rate of 2 mm/sec was chosen for this study to investigate the structural integrity of GFRP composite tubes against axial and off-axis loading. Various angels of 5, 10, 20 and 30 degrees were selected for off-axis loading. There was no stitching for this part since the loading condition was the only variable. Our results indicated that by increasing of loading angle, the mean crushing force and also energy absorption capability of all tested tubes decreases. This phenomenon was in contrast with our previous researches since the off-axis angel of 10 showed the highest amount of energy absorption among all other angles (see Figure 4). The amount of F_m in axial test was 100 kN in comparison with all other mean forces as shown in Figure 5.

The crushing failure modes of axial and angle 5 were close to brittle fracture which is a combination of lamina bending and transverse shearing modes. In both of these crushed specimens various mechanisms such as bundle fracture and lamina bending were observed (see Figure 6). On the other hand, the transverse shearing mode was found for off-axis angle of 10 which was characterised by a wedge-shaped laminate cross section with multiple short interlaminar and longitudinal cracks. The catastrophic failure with unsymmetrical damaged areas was finally observed for angles of 20 and 30 mm (see Figure 7).

4.2. High speed crushing of single and multi-stitched tubes

In the second part of this research effect of single and multi-stitched locations on the crushing behaviour of composite tubes under axial high speed load is investigated. All GFRP composite tubes were stitched at different locations according to the planned design explained in Figure 3. The progressive crushing was initiated for all tested specimens at the beginning of process. This behaviour was shown after elastic deformation and rapid straight rise of load in force displacement diagrams. The main central crack in the middle of wall of all tubes behaves as mode I interlaminar crack propagation which has been extensively studied in the previous researches of authors [12-13]. This main crack initiates progressive growth until it reaches to the stitched area. Here, there is a significant change in the force-displacement diagram which is followed by a rapid increase and then a quick drop to the lower level of load. This change can cause increase of crushing load and consequently increase of specific energy absorption. This phenomenon was consistently observed for all single stitched composite tubes (see Figure 8). The mean force (F_m) did not increase for single stitch of 20mm in comparison with 30mm stitch which was around 105 kN (see Figure 9 and 10). The observed crushing mode for these composite tubes was lamina bending which was shaped with long interlaminar, intralaminar, and parallel to fibre cracks. This mechanism causes the formation of continuous fronds which spread inwards and outwards.

The scenario was different for the multi-stitched tubes which showed two rapid increases within the graphs. Both of these two increases can improve the mean crushing force and energy absorption of absorbers. However, this behaviour can be varied in different cases since high speed rate can overcome the resistance of through the thickness yarns and consequently causes minor effect on crushing process. Figure 11 shows the crushed view of specimens with no significant difference in the crushing process. The force-displacement diagrams of simple, single and multi-stitched tubes are shown in Figures 12-13. As it is shown in Figures 12 and 14, the crushing force has increased at the stitched locations. This behaviour is clearly highlighted in design of 10-20-30mm and 10-15-20-25-30-35mm which showed several increase of load during crushing process. This idea would be expanded to other designs followed by increase of stitched locations and reduction of the distance between them to create a smooth and progressive force history. The behaviour can increase the overall mean crushing force which is the ideal performance of composite absorbers. The presented technique is beneficial in terms of weight saving since we still use unidirectional FRP composites with the improved structural integrity. Furthermore, the specific crushing stress (SCS) which is a function of the materials properties, geometric and physical parameters of the composite materials was calculated for various designs of stitched tubes. Composite tube with stitched locations of 10-20-30-40 showed the highest value of SCS in comparison with others (see Figure 15). Our results have also been compared to our previous work [14] which was carried out on composite box structures. These results clearly showed that tubular structures have significantly absorbed higher energy in comparison with box absorbers (see Figure 16).

5. Conclusions

In this study, the energy absorption capabilities due to crushing behaviour in composite tubes under high speed rate of 2 mm/sec have been studied. Axial and off-axis crush testing have been carried out at lateral off-axis angles of 5°, 10°, 20° and 30°, and stitching through thickness at single and multiple locations of 10mm, 20mm, 30mm and 30mm were performed to study the improvement of mean crush force.

Our experimental results showed that axial load has better energy absorption rather than off-axis which is in contrast with composite box absorbers. This is due to geometry of the tubes and also longitudinal cracks have direct effect on the amount of energy absorption of the tubes, which is obtained at axial process. The crushing behaviour of the tubes was closely studied and more controllable stability was involved at axial loading and off-axis crushing of 5°. They showed uniform and progressive crushing failure modes and also the failure mechanism associated with composite tubes were circumferential delamination, axial cracks, lamina bending and bundle fracturing. However, catastrophic failure modes at 20° and 30° inclined angles caused more side damage, with unstable behaviours. The main reason for this catastrophic failure in this case is the sudden propagation and the initiation angle with bending moment of the axial cracks through the side of the tube length. This shows that the inclined angle of the composite tubes have a significant role on progressive crushing.

In axial crushing, yarn stitching through the thickness at different locations was introduced, and illustrated a steady mean crush load which was obtained for the stitched specimens.

Stitching at a right position can provide specific energy absorption values than the standard non-stitched composite tubes; this is an important factor to consider achieving better specific energy absorption values (see Table 1). Stitching at location of 30mm, multi-stitched locations of 10-20-30mm and 10-15-20-25-30-35 provided the highest energy absorption capabilities with increase of average crush load tolerance which indicates a stable crashworthy behaviour respectively. The present study has established sufficient information on the effect of single and multi-location stitching on high speed crushing of composite tubes, and the positive effects of yarn stitching through thickness was found both on local and average crushing load.

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Table 1. Comparison of mean crushing force (Fm) and specific energy absorption (SEA) of all tested specimen.

Stitched locations	**F_m (kN)**	**SEA (kJ/kg)**	**Failure Mode**
Axial - Standard	100 ± 2	40	LB
10mm	90 ± 2	36	LB
20mm	100 ± 2	40	LB
30mm	105 ± 2	42	BF
10-20mm	95 ± 2	38	LB
10-30mm	95 ± 2	38	LB
20-30mm	95 ± 2	38	BF
10-20-30mm	105 ± 2	42	LB
10-15-20-25-30-35mm	105 ± 2	42	BF

LB = Lamina Bending, BF = Brittle Fracture

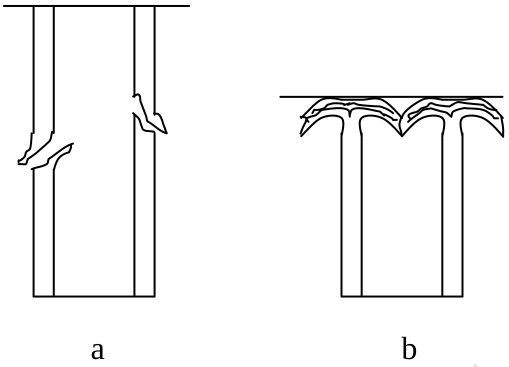


Fig. 1. (a) Catastrophic crushing failure (b) progressive crushing failure.

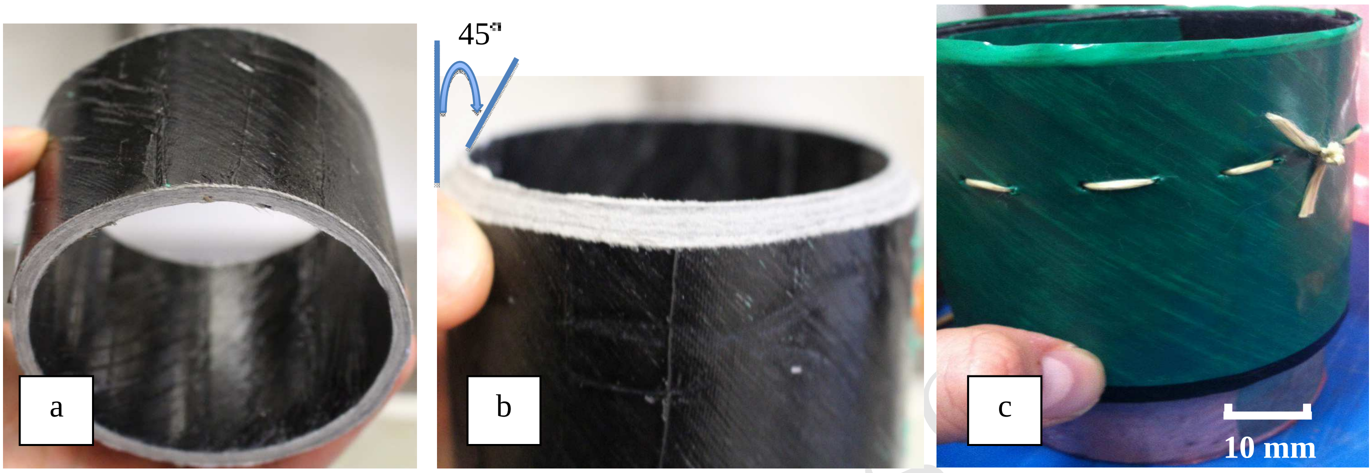


Fig. 2. a) Composite crushing tube, b) bevelled trigger mechanism, and c) stitching technique.

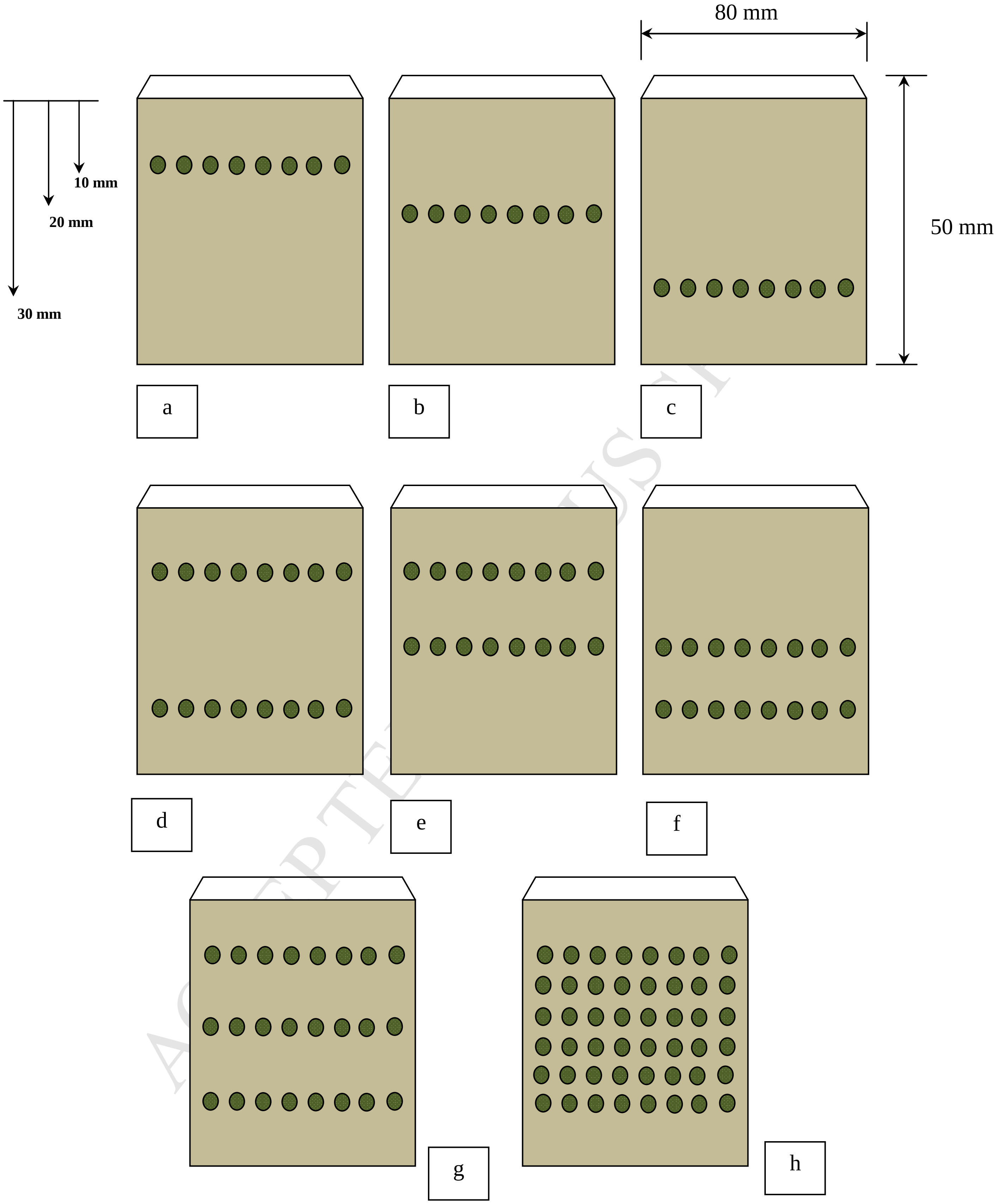


Fig. 3. Various designs of single and multi-location stitches within composite box structures.

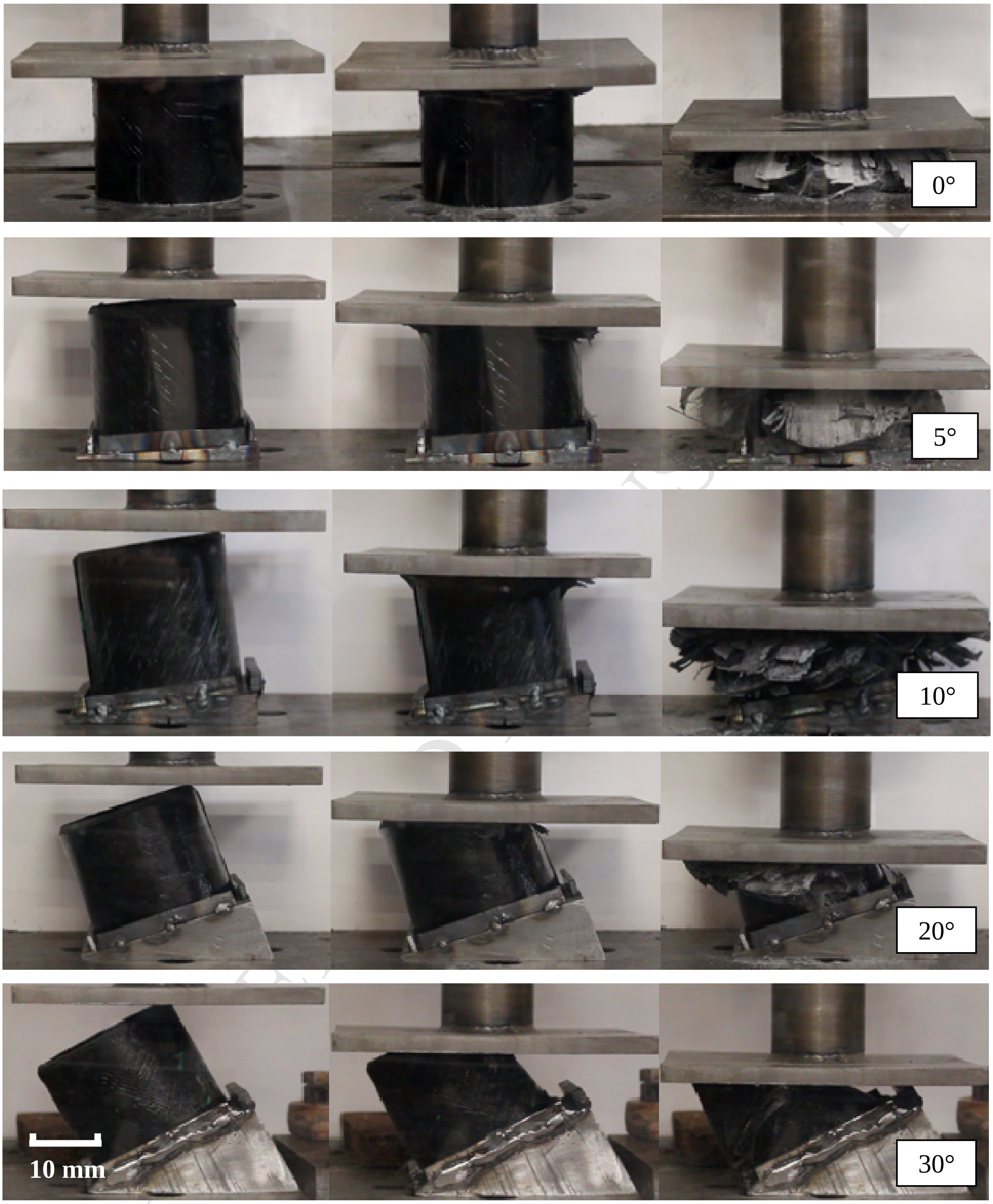


Fig. 4. Various stages of high speed crushing a) axial, b) 5°, c) 10°, d) 20° and e) 30°.

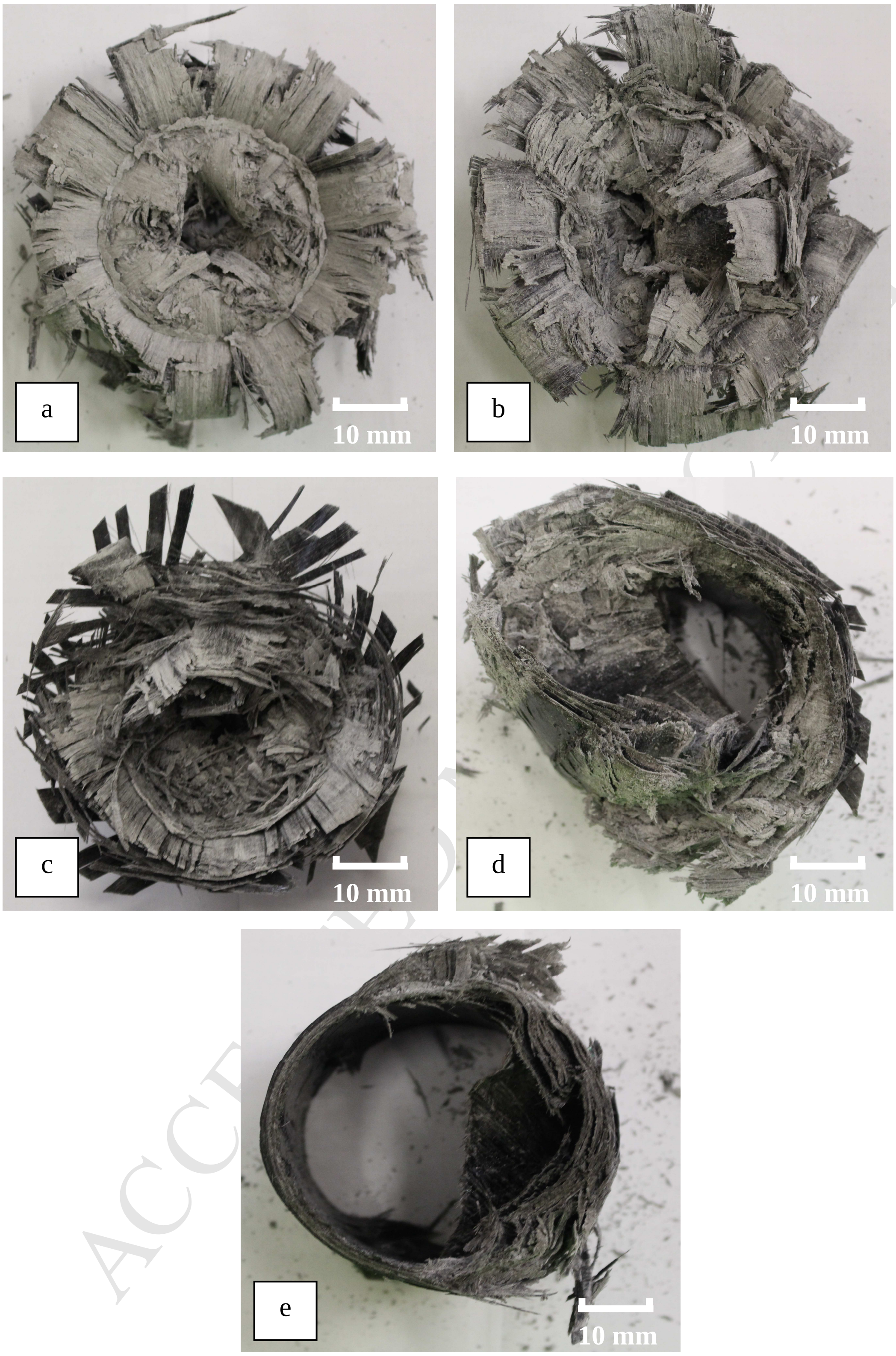


Fig. 5. Plane view of crushed specimens a) axial, b) 5°, c) 10°, d) 20° and e) 30°.

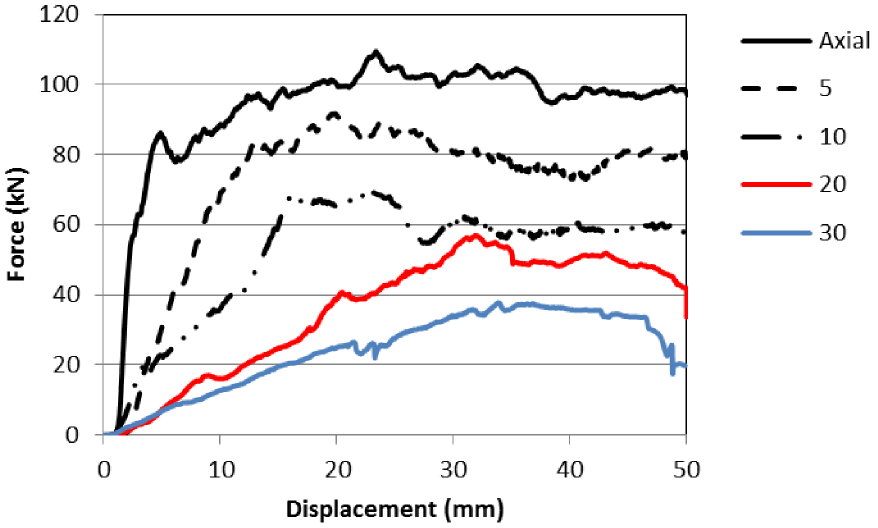


Fig. 6. Comparison between force – displacement graphs of axial and off-axis high speed crushing load.

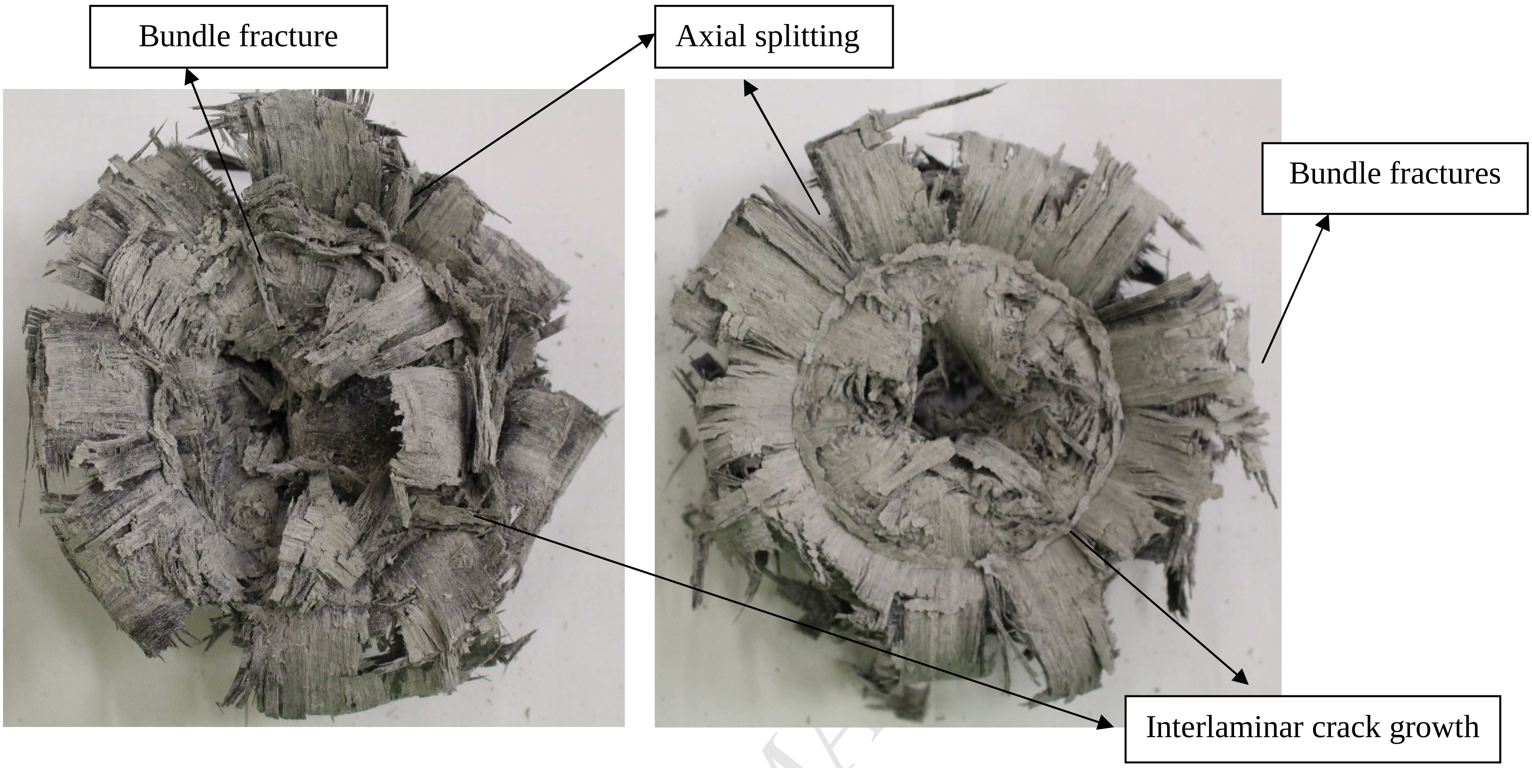


Fig. 7. Brittle fracture crushing mode for axial and 5 degrees angle.

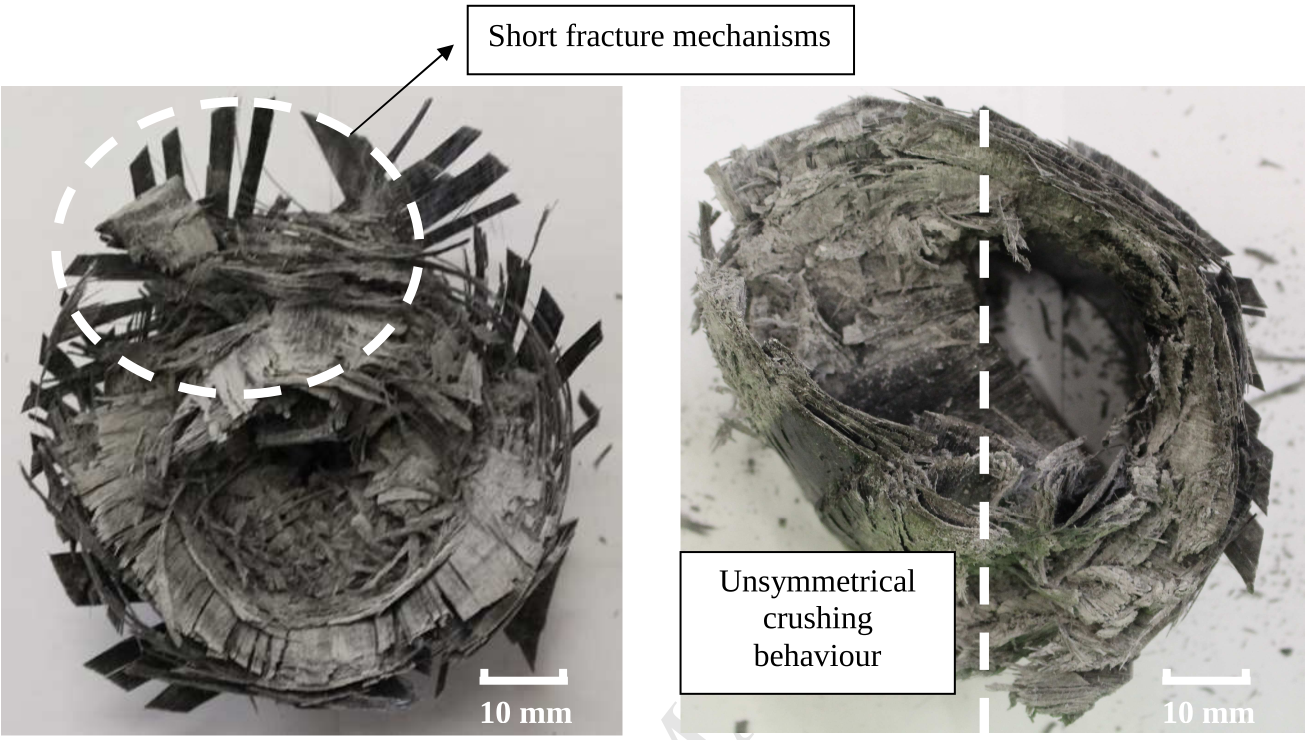


Fig. 8. a) Transverse shearing mode vs b) catastrophic crushing failure.

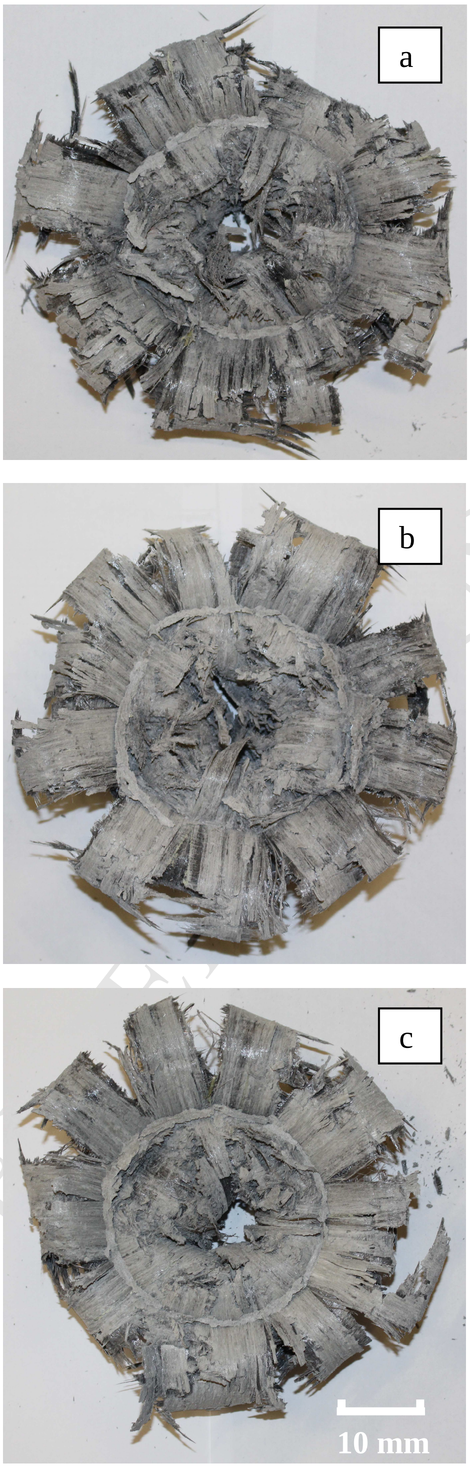


Fig. 9. Plane view of crushed specimens with single stitches a) 10mm, b) 20mm and c) 30mm from top of the tubes.

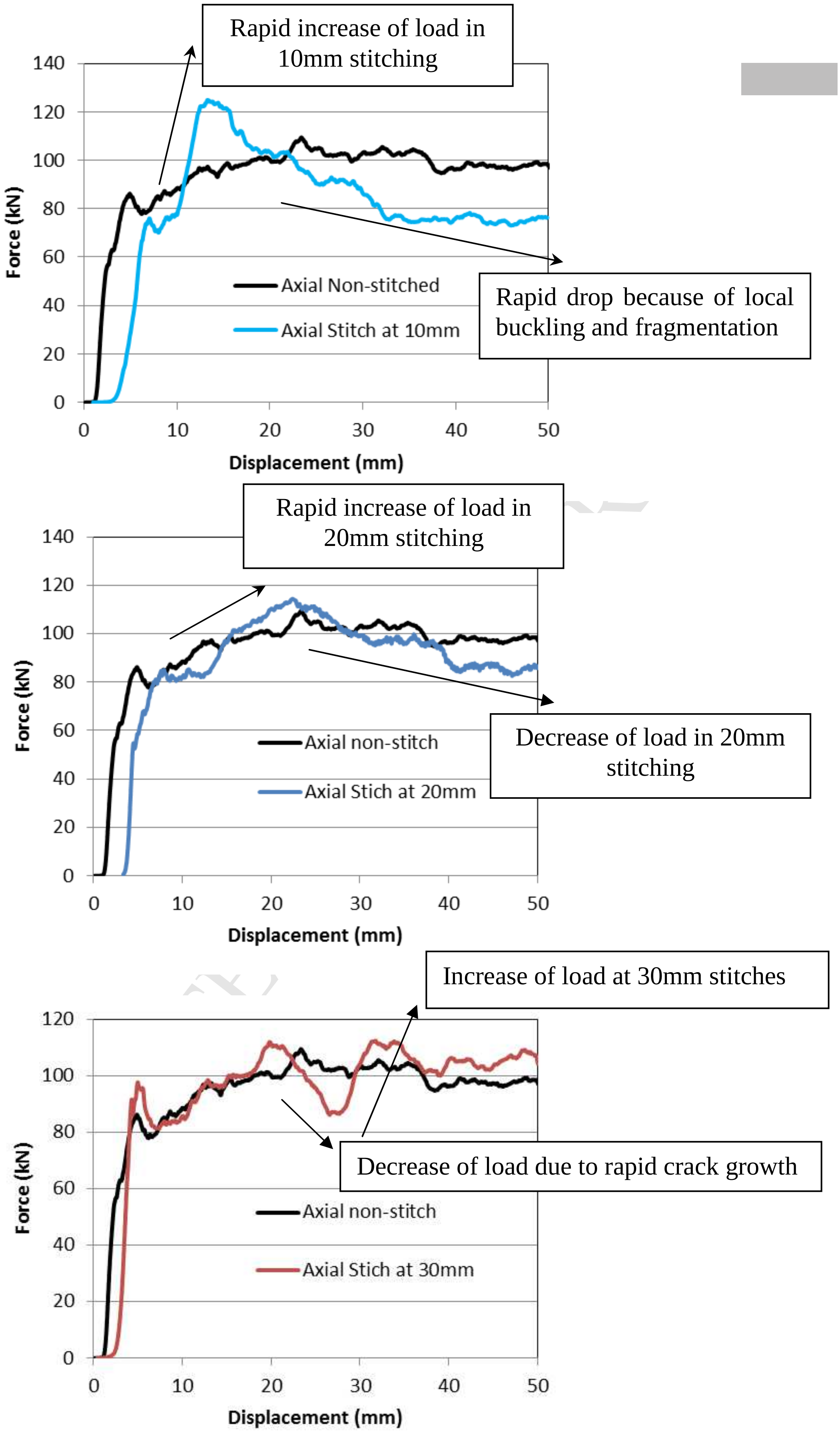


Fig. 10. Comparison between force – displacement graphs of simple and a) 10mm, b) 20mm and c) 30mm single stitched tubes under high speed crushing load.

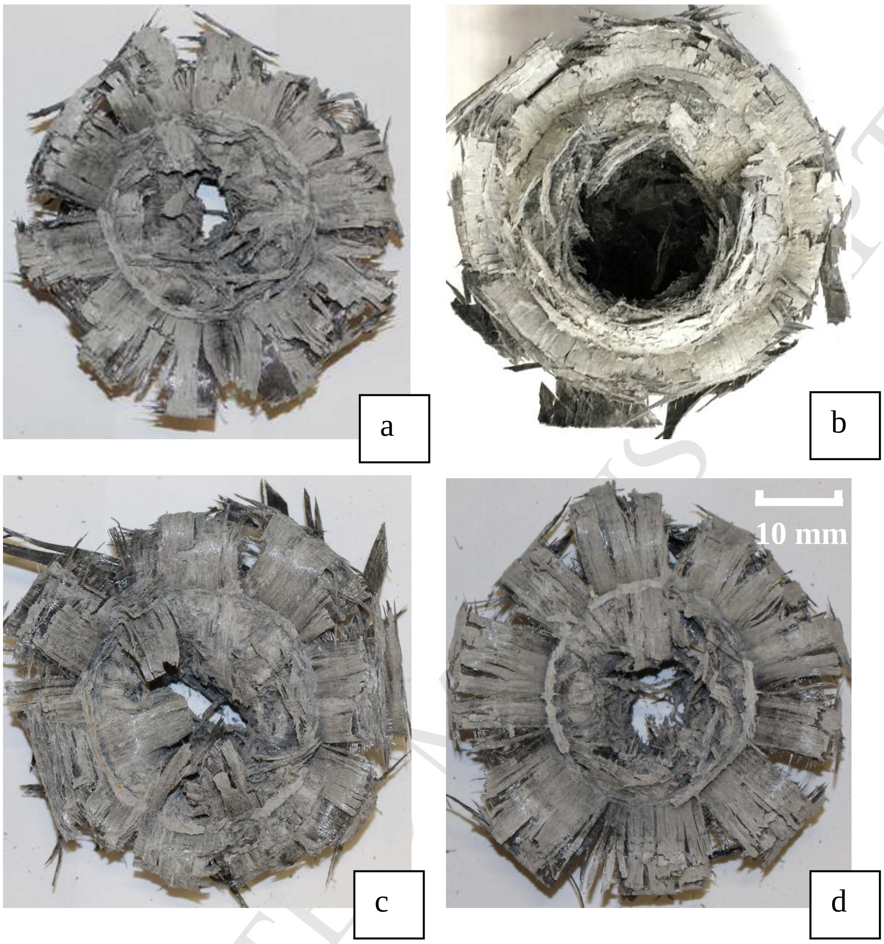


Fig. 11. Crushed view of multi-location stitched composite tubes, a) 10 – 20mm, b) 20 – 30mm, c) 10 – 30mm & d) 10 – 20 – 30mm.

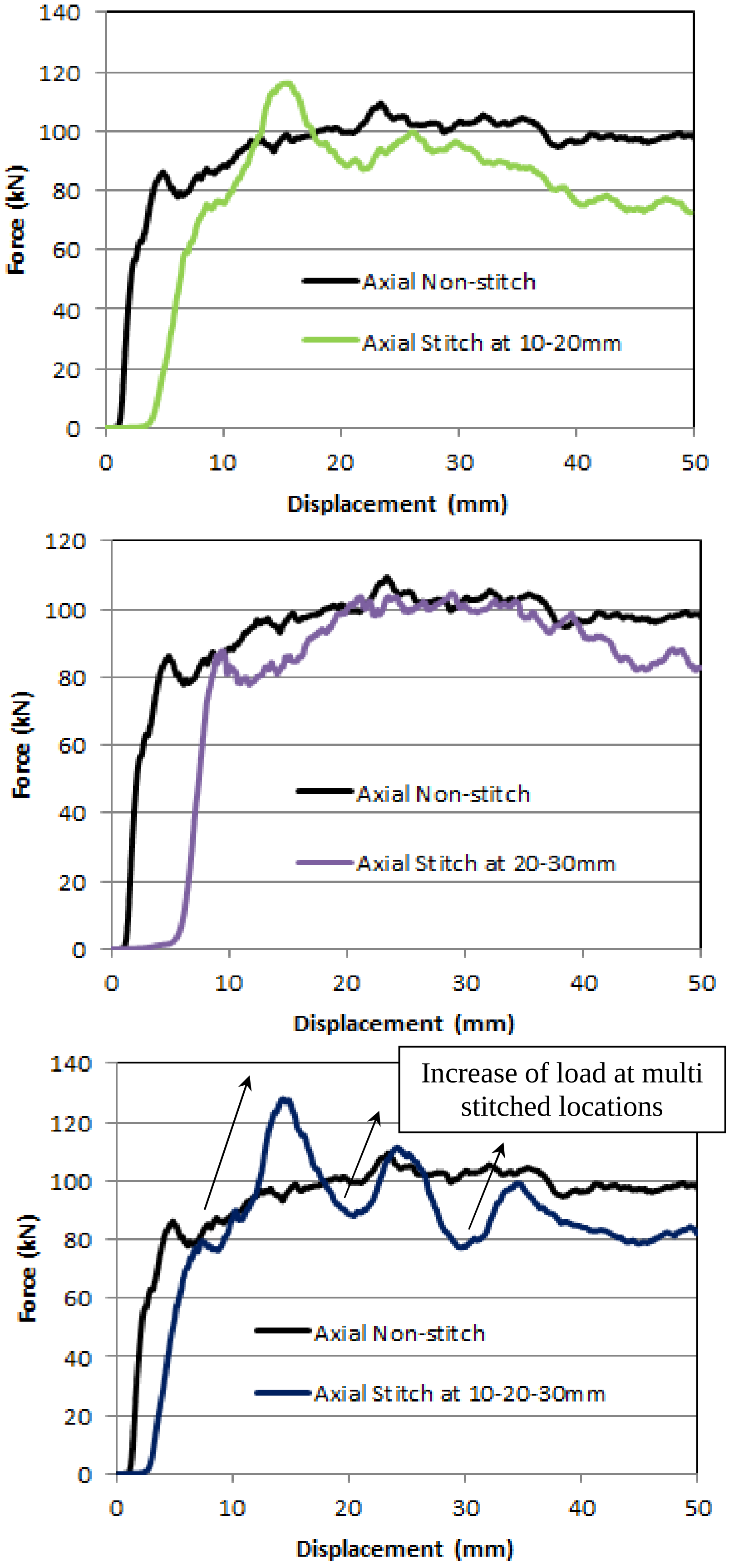


Fig. 12. Comparison between force – displacement graphs of simple and a) 10-20mm, b) 20-30mm and c) 10- 20-30mm multi-location stitched tubes under high speed crushing load.

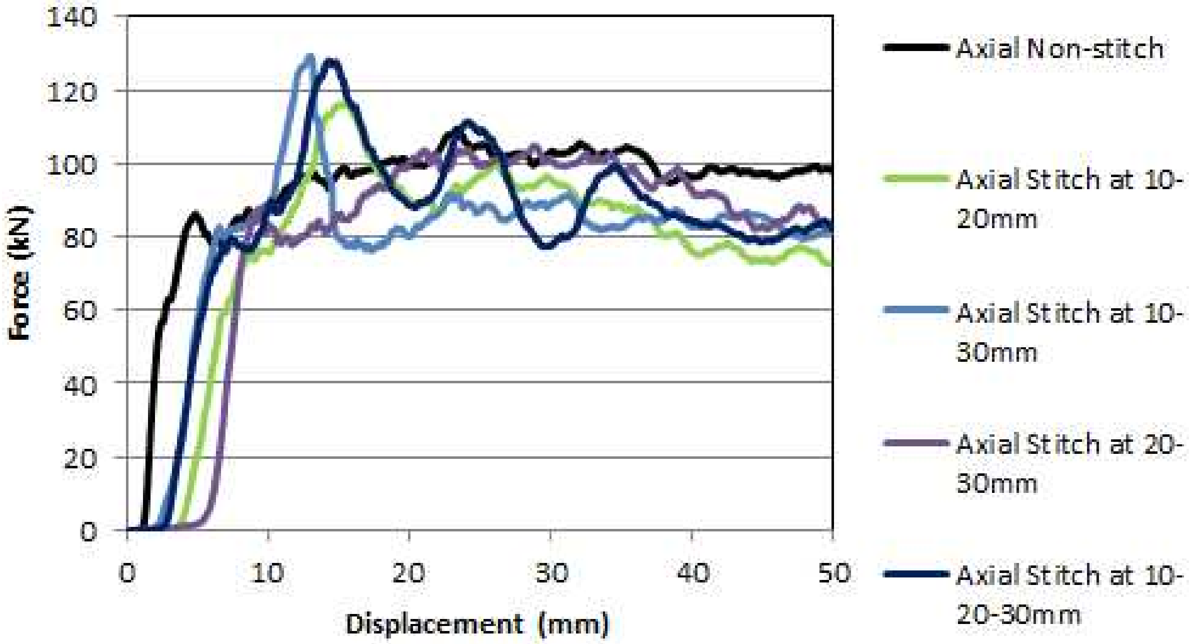
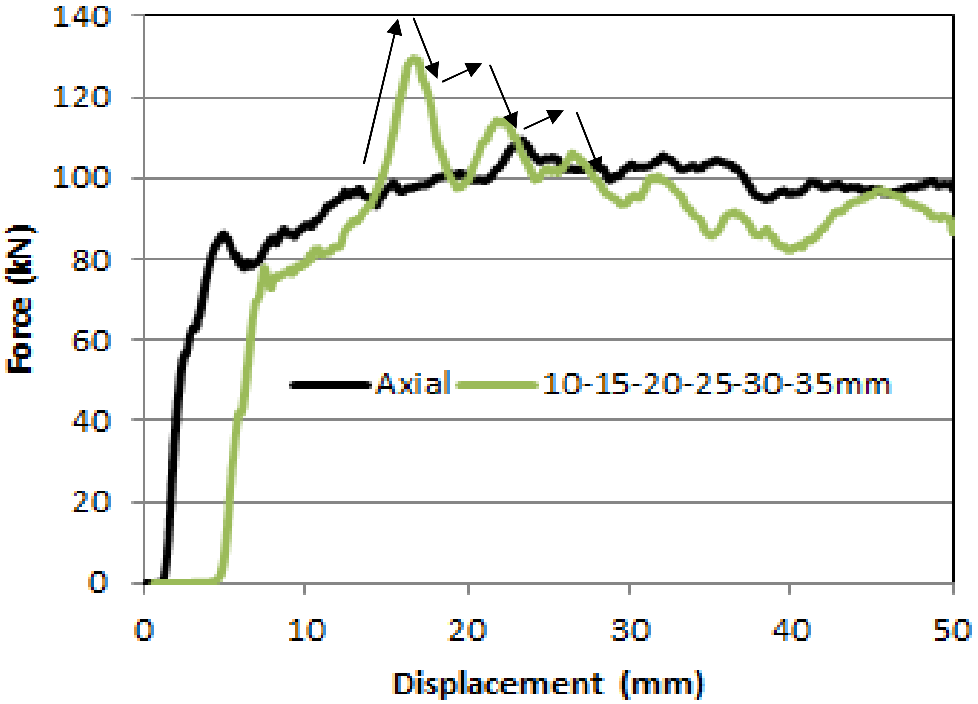


Fig. 13. Comparison between force – displacement graphs of simple and a) 10-20mm, b) 10-30mm, c) 20-30mm and 10-20-30mm multi-location stitched tubes under high speed crushing load.



a

b

Fig. 14. Comparison between a) force – displacement graphs of simple and 10-15-20-25-30-35mm, multi-location stitched tubes under high speed crushing load and b) plane view of crushed specimen.

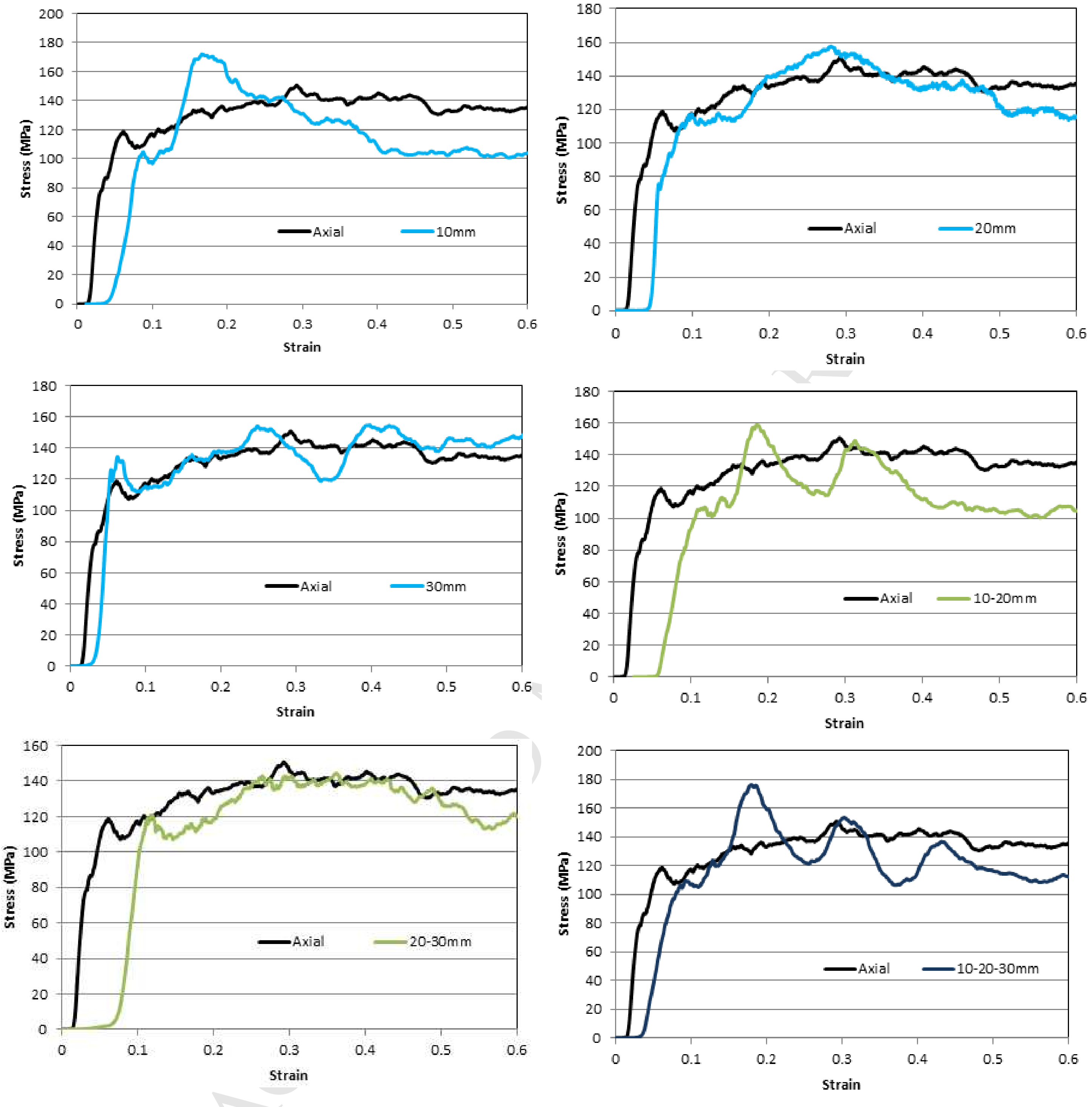


Fig. 15. Comparison of specific crushing stress between non-stitched and multi-stitched location tubes, SCS-Non-Stitched = 43.1, kJ/kg, SCS-10 = 38 kJ/kg, SCS-20 = 43 kJ/kg, SCS-30 = 45.2 kJ/kg, SCS-10-20 = 40.9 kJ/kg, SCS-20-30 = 40.9 kJ/kg and SCS-10-20-30 = 45.2 kJ/kg.

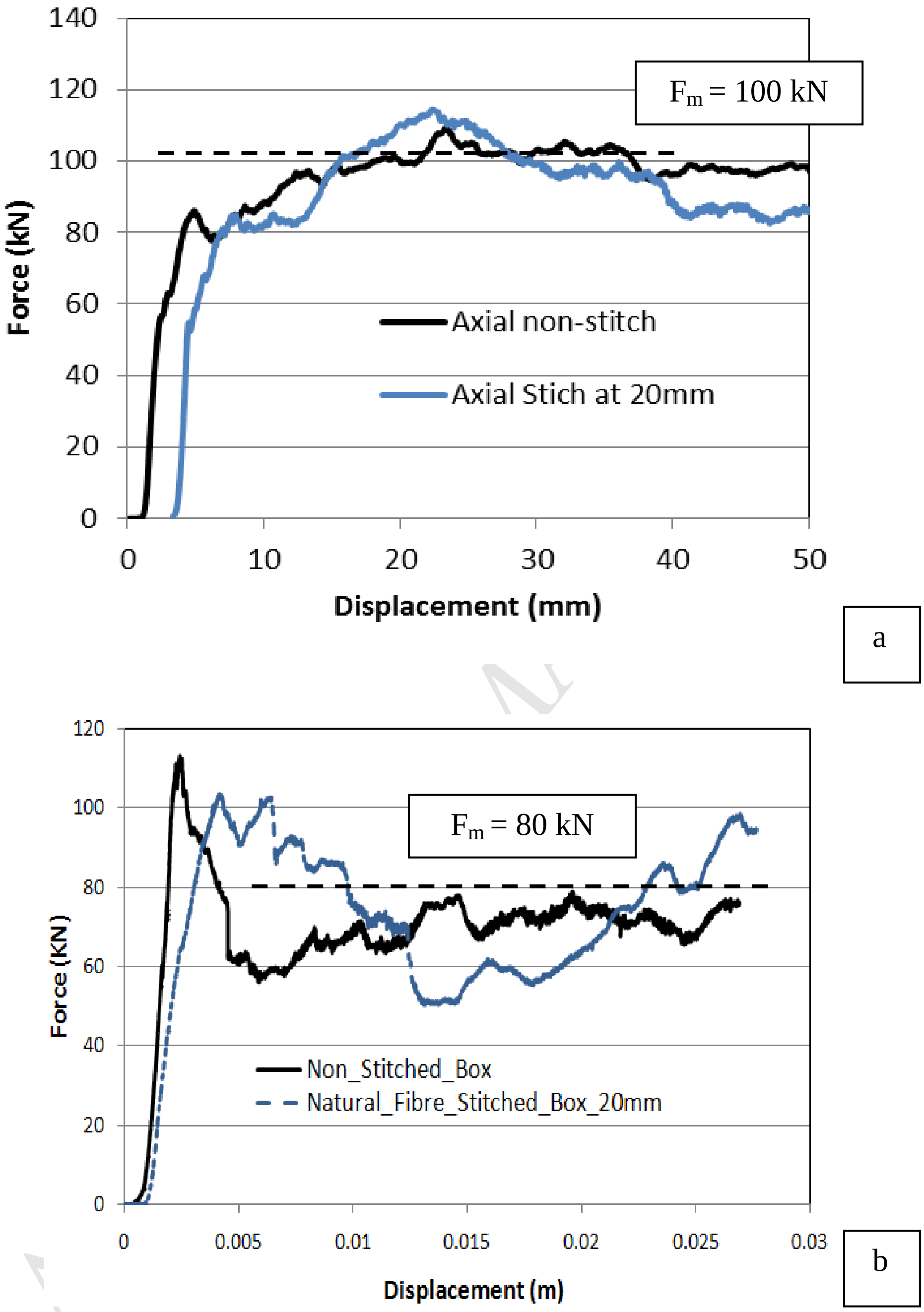


Fig. 16. Comparison between force-displacement of composite a) tube (F_m = 100 kN) and b) box (F_m = 80 kN) absorbers [14].

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