International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:10, No:10, 2016

Effect of Stitching Pattern on Composite Tubular Structures Subjected to Quasi-Static Crushing

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Abstract**—**Extensive experimental investigation on the effect of stitching pattern on tubular composite structures was conducted. The effect of stitching reinforcement through thickness on using glass flux yarn on energy absorption of fiber-reinforced polymer (FRP) was investigated under high speed loading conditions at axial loading. Keeping the mass of the structure at 125 grams and applying different pattern of stitching at various locations in theory enables better energy absorption, and also enables the control over the behaviour of force-crush distance curve. The study consists of simple non-stitch absorber comparison with single and multi-location stitching behaviour and its effect on energy absorption capabilities. The locations of reinforcements are 10 mm, 20 mm, 30 mm, 10-20 mm, 10-30 mm, 20-30 mm, 10-20-30 mm and 10-15-20-25-30-35 mm from the top of the specimen. The effect of through the thickness reinforcements has shown increase in energy absorption capabilities and crushing load. The significance of this is that as the stitching locations are closer, the crushing load increases and consequently energy absorption capabilities are also increased. The implementation of this idea would improve the mean force by applying stitching and controlling the behaviour of force-crush distance curve.

Keywords**—**Through-thickness, stitching, reinforcement, Tulbular composite structures, energy absorption.

I. Introduction

THE ability of a structure providing protection for occupants by absorbing the implied energy in a case of an impact is known as crashworthiness of a structure. Energy absorption of initial impact enables reduction of overall main body structure damage and provides greater passenger safety. Weight reduction and high energy absorption is the key factor in aerospace and automotive applications. Energy absorption of structural absorbers is obtained through a stable load pattern caused by controlled failure mechanisms and various modes. In composite absorbers, due to anisotropic behaviour, the overall energy absorption capabilities depends on several factors including, lay ups, structure geometry, curing and strain rate sensitivity. Composites due to high stiffness-to-weight and strength-to-weight ratios enable high performance comparable with traditional materials such as aluminum. Other characteristics including corrosion resistance, fatigue, non-conductivity, and low coefficient of thermal expansion have also influenced composites popularity. FRP composites are used in thin-wall structures due to high-energy absorption capabilities in axial loading through membrane [1]-[7].

In prior to FRP composites, researchers focused on metal tubes axial crushing behaviour with failure of plastic deformation due to progressive fold formation [8]. To improve crashworthiness, increase in mass volume influences energy absorption, although some researchers increased the wall thickness [9], [10]. Furthermore, Cheng et al. had introduced foam filled aluminum braided stainless steel tube for better energy absorption [11]. Other researchers studied metals in inner core of sacrificial cladding structure [12]–[14]. However, due to material, manufacturing and maintenance expenses, and also heavier structure, this is not sufficient in aerospace and automotive industries [15], [16]. Alternatively, composite materials because of high specific energy absorption (SEA), low weight and low cost in maintenance, have relative advantages [17], [18].

In passenger carrying application such as aerospace and automotive, weight is an important factor. Metal improvisations are no longer relevant due to fuel consumption, and CO_2 emission. FRP consequently has been studied extensively due to characteristics of being lighter and stronger compared to metals [19], [20]. After vast investigations researchers concluded that a well-engineered FRP composite could absorb more energy than metals [21]–[23]. Composite materials, glass FRP, and carbon FRP encounter for instance fractures in axial crushing to absorb energy unlike metals as exhibited in metal tubing undergo plastic deformation [24], [25]. Savona and Hogg [26] stated failure modes of Mode I and Mode II fracture, absorbed majority of implied energy, during frond bending and fiber fracture with friction at crushed fronds and within [27].

Many researchers studied the parameters of composite tubes crushing that influence crashworthiness performance [17], [28]. Progressive crushing process yields higher energy absorption, dominated by mechanical properties of fiber orientations, laminate stacking sequence, fiber and resin, fiber, and resin volume fractions, and geometry of the tube [17], [28]. However, altering the geometry of composite structures, for the same parameters with different levels of the SEA is observed [24]. Thronton and Edwards [29] and Thronton et al. [30] investigated and concluded that better energy absorption capabilities are observed in circular cross sectional composite tubes compared to square and rectangular cross sectional composite tubes.

In reinforcement of composite structures, stitching through the thickness increases local energy absorption. Solaimurugan and Velmurugan [31], [32] studied composite cylindrical

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shells with various stacking sequence, fiber orientation and stitching on progressive crushing of glass/polyester under axial compression. The authors concluded that stitching improves energy absorption thorough Mode-I interlaminar fracture toughness. In allocation of axial fiber, the behavior at outer surface of the tube causes more petals, that leads to stable crushing, whereas axial fibers allocated to inner surface causes increase in energy absorption. Circumferential delamination improves energy absorption capability by increasing Mode-I fracture toughness.

Ghasemnejad and Hadavinia [33] and Ghafari-Namini and Ghasemnejad [34] experimentally investigated the effects of stitching through thickness on delamination failure of composite box structures with a hybrid combination of unidirectional CFRP and GFRP composite materials with $[C_{90}/G_0]_7$ orientations. The crashworthiness of the stitched thin-structure was compared with a non-stitch specimen. The author concluded that the design performance exceeded the expectation of previous methods used, and showed the highest energy absorption. Delamination study of Mode-I with the same lay-up was carried to investigate the influence of natural stitched on delamination crack growth and energy absorption. Standard test method of double cantilever beam (DCB) was used for this study. The significance of increase in interlaminar fracture toughness and energy absorption capabilities in thin-structure composite was obtained from the results by using stitching through the thickness.

In the previous researches in regards to energy absorption of composite thin-walled structural components, all parameters were subjected to increase of energy absorption capabilities. In this research, as well as increasing the energy absorption capability in a controllable manor, the ability of controlling the force-crush distance curve is also the aim to achieve through multi-location stitching subjected to high speed crushing load. Multi-location stitching can introduce a pattern of local increase in energy absorption and overall SEA. This paper experimentally aims to investigate the influence of stitching pattern on energy absorption capabilities and also controlling and optimising the force-crush distance curve.

II. Crushing Behaviour Criteria

In the study of energy absorption capabilities of composite tubes, many important factors are considered. These factors can each influence the ability of energy absorption, these include, material, crush initiator, specimen's geometry, manufacturing method, microstructure, rate of crushing. The overall performance is dependent on SEA of crushing, collapsing or structural parts. This value relates the structural mass of the absorber to energy absorption capabilities. The point of reference in this case is based on improvement in SEA and local energy absorption for lightweight designs. In addition, the study of the shape of force-crush distance curve, in regards to safety factor and also energy management capabilities, is considered. After the initial impact if the curve increases, consequently shows more energy absorption, this indicates a safety factor for passengers, if there is a drop after the initial impact this indicates that the energy has transferred onto the main body structure, which means the implemented energy is transferred to the passengers. One measure to characterise the behaviour of the curve is known as crush-force efficiency (CFE). This value in crush characteristic relates the average crush force (F_m) to the maximum force (F_{max}).

III. Analysis of Crushing Mechanism

In composite tube structures, stable and unstable crushing behaviours are the two failure mechanisms considered; these are also and most commonly known as catastrophic and progressive failures (see Fig. 1). Catastrophic failure is distinguished by a relative small initial peak load followed by sudden drop in energy absorption, therefore the average force is low and the specimen is no longer capable of sustaining a notable compression load. Conversely, progressive failure is distinguished by an increase in load after the initial peak load, and it is still capable of sustaining a significant compression load. In progressive crushing failure mode, high-energy absorption is obtained, which is thus the main goal of crashworthy structures, it is also important to analyse the associated failure mechanisms.

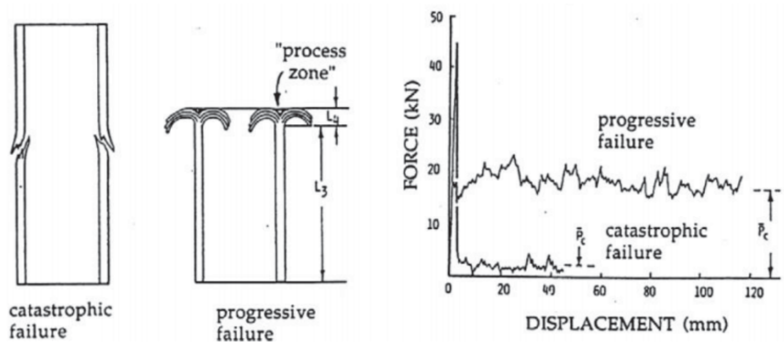

Fig. 1 Failure mechanism of composite tubular structures, progressive and catastrophic

In regards to this research, all composite tubes were fabricated within the same conditions from glass/epoxy material (ρ = 2000 kg/m^3) using hand lay-up techniques. The laminate design was [-45/45/0/90/0/90]S to create a symmetric twelve-ply quasi-isotropic laminate. The curing process of this consists of experimental studies based on optimum performance of the tubes. The laminates that were laid-up onto the mould with 74 mm outer diameter were sealed up using non-stick polymer sheets to eliminate 'resin escape' this enables minimal room for the prepreg epoxy to escape to. To increase pressure acting on the uncured laminates during the curing process, a mould sleeve with the same size at 80mm in diameter was added. The mould was placed onto a precut aluminum covered in 'breather cloth', which eliminates air pockets formation by allowing air circulation, then positioned inside a heat resistant polymer bag. A suction valve was inserted into the bag connected to a vacuum pump. The bag was open on either sides and was fully sealed with double-sided epoxy tape. This adds more pressure onto the laminates and extracts the air inside of the bag, forcing the plies to cure in high pressure tightly together. Using a pressure gauge, the pressure inside of the bag was monitored.

All absorbers were stitched through the thickness by glass fiber yarns to control the behaviour of force-crush distance curve and to reinforce the tubes subsequently increasing energy absorption capabilities (see Fig. 2). Four specimens were tested for each design to find the standard deviation of experimental results. Based on the criteria of thin-structures, the design parameters were chosen closely to the testing machinery at 80 mm in length and width and 3 mm in thickness with total weigh of 125 grams, with maximum displacement (crush distance) of 50 mm. This research focused on force displacement that illustrates the energy absorption capabilities from for the designed absorbers. All parameters were kept constant including geometry, layup, strain rate, and loading direction affecting failure mechanisms of FRP composite absorbers with one variable of stitching locations, in order to study the effect of it on SEA capabilities of composite absorbers.

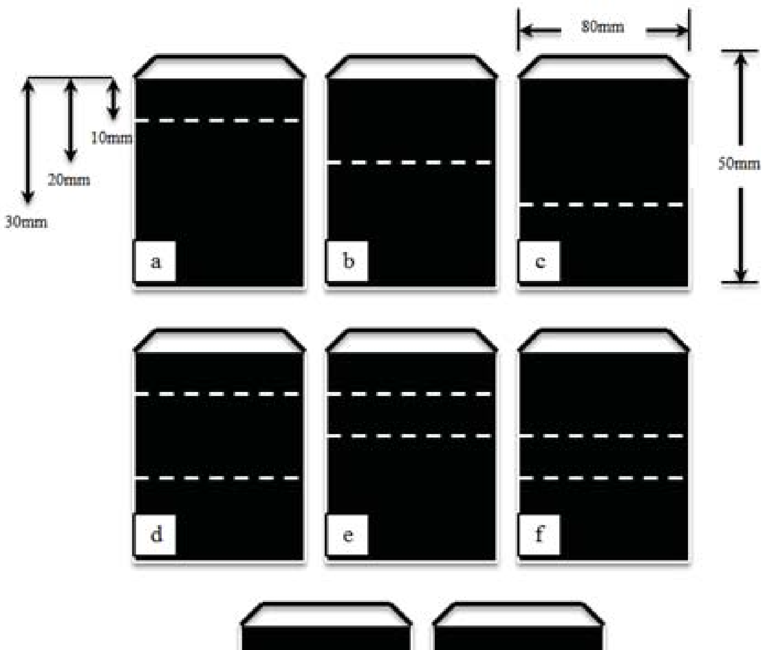

Fig. 2 Various stitching design combinations of single and multi-location within composite tube structures

IV. Analysis of Crushing Behaviour

The effect of single and multi-stitched locations was examined experimentally on crashworthiness of the designed absorbers. The behaviour of GFRP composite tubes subjected to high-speed quasi-static loading was different with the stitched locations variables. The design parameters were illustrated in Fig. 2 from a to h. All absorbers had progressive crushing behaviour with elastic deformation and rapid and sudden increase of load in force displacement diagrams. The main central crack in midsection of the tubes indicates a behaviour of mode I interlaminar crack propagation that were extensively studied by authors of [33], [34]. The crushing process initiates progressively until it reaches the stitching area where a significant increase takes place in force-displacement diagram that indicates subsequent increase of SEA, with a prompt drop in load right after passing the stitching location. This significant increase in load was observed in all single stitched composite tubes (see Fig. 3). There is no significant increase in mean force (F_m) itself in stitching location of 20 mm compared to 30 mm with 105 kN mean force. The crushing mode for single stitched absorbers were mainly lamina bending with long interlaminar, intralaminar, and parallel to fiber cracks, which causes fronds to form a continuous inward and outwards shape.

In multi-stitching effect, the scenario was different and showed depending on the design two or more sudden increase in load. This improved mean crushing force and energy absorption of the designed absorbers. Fig. 4 illustrates the results from multi-stitched locations compared to simple non-stitched absorber and it indicates multi-stitching has increased crushing force. The behaviour in design of 10-20-30 mm and 10-15-20-25-30-35 mm (see Figs. 4 and 5) has shown multi-increase points in load during crushing process that resulted in higher energy absorption compared to non-stitched or single stitch locations in overall and in mean force (F_m).

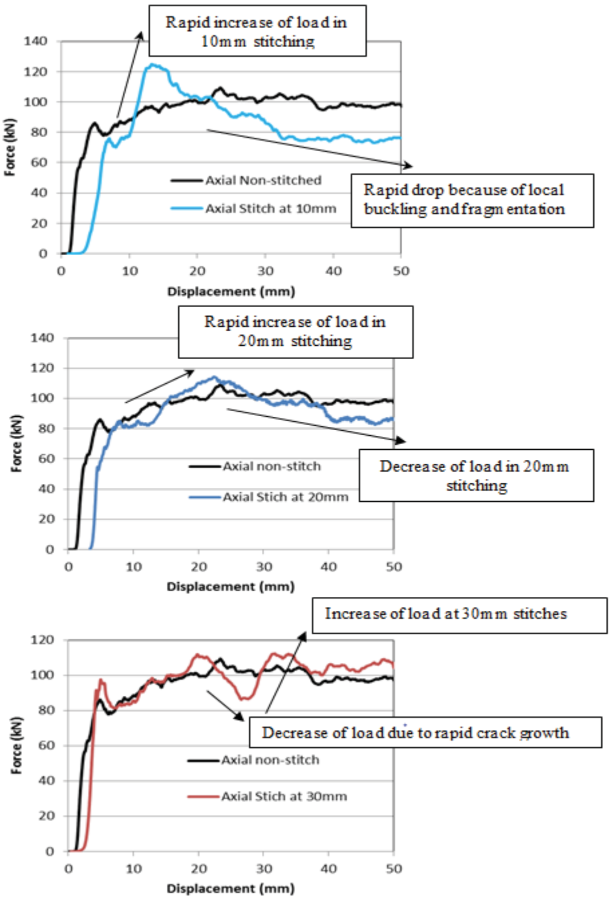

Fig. 3 Force displacement graph comparison between non-stiched absorber and 10 mm, 20 mm, and 30 mm single stitched absorber

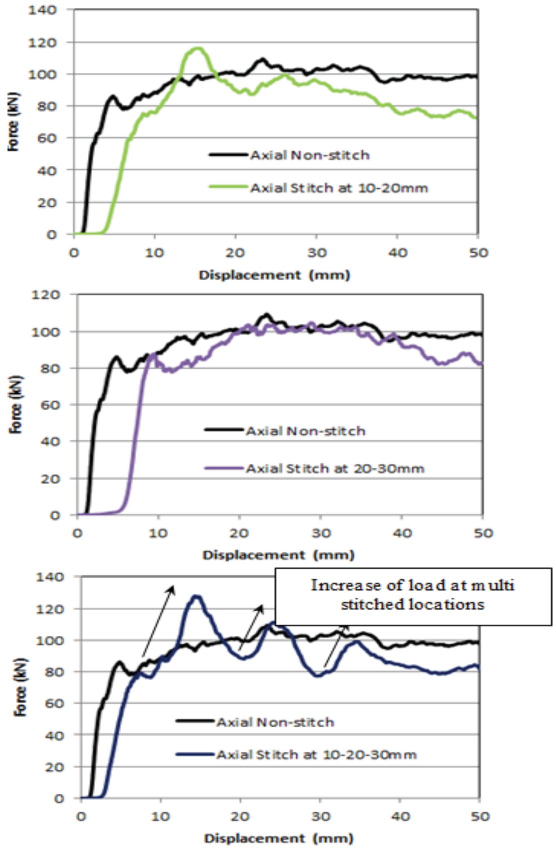

Fig. 4 Force displacement graph comparison between non-stiched absorber and 10-20 mm, 20-30 mm, and 10-20-30 mm multi-stitched absorber

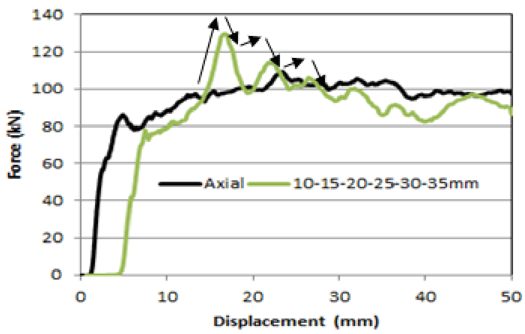

Fig. 5 Force displacement graph comparison between non-stitched absorber and 10-15-20-25-30-35 mm multi-stitched absorbers

V. Conclusion

In this study, high-speed rate of 2 mm/sec was considered for testing GFRP composite tubes for energy absorption capabilities subjected to axial quasi-static loading. Stitching through thickness was chosen as reinforcement and multi-stitching was also introduced to control the behaviour of force-crush distance curve. The pattern of the stitching as illustrated in Fig. 2 are 10 mm, 20 mm, 30 mm from the top of the absorber as single stitching then 10-20 mm, 10-30 mm, 20-30 mm, 10-20-30 mm and 10-15-20-25-30-35 mm were introduced as multi-stitching locations to improve mean crush force.

The experimental results have shown that by introducing stitching through thickness using natural flux yarn at various locations can increase mean crush load. At single stitching location, a significant increase is observed followed by a sudden drop in load, whereas in multi-stitching this rapid increase becomes more progressive and steady. This enables the control of the force-crush distance curve to behave at a certain standard in regards to crashworthiness and also the purpose of the application intended to be used for. This increases the SEA values of 10-20-30 mm, and 10-15-20-25-30-35 absorbers give the maximum energy absorption capabilities with increase of average crush load tolerance that indicates a stable crashworthy behavior, respectively. The study established a positive effect of yarn stitching through thickness at multi-location on both local and average crushing load.

The idea of multi-stitching at various locations can be implemented into other applications followed by reduction of spaces between the stitching points to increase energy absorption and create an increase in overall mean crushing force. This is the optimum behaviour of composite absorbers. This is beneficial in weight saving techniques using unidirectional FRP composites with minimal added weight into the absorbers itself. By stitching through thickness, the weights of the absorbers were the same at 125 grams.

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