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Experimental Assessment of Collapse Behavior and Energy Absorption of Composite and Hybrid Composite Square Tube Subjected to Oblique Loads

[1], Lim Keng Teek, [2], Rizal bin Zahari, [3], Faizal bin Mustapha,
[4], Mohamed Thariq bin Hameed Sultan
[1, 2, 3, 4] Department of Aerospace Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.

ABSTRACT

Composite tubes have been effectively employed as energy absorber devices mainly in automobile as well as airplane in this era. This research paper compared the energy absorption and crushing behavior of composite materials and hybrid composite square tube subjected to quasi-static oblique loads with various angles. Overall the study highlights the advantages of using hybrid composite material as best energy absorbers. The oblique loadwasrealized experimentallybyapplyingaloadviathe inclined modified compression plates to the specimens. When the structures are subjected to the axial and oblique quasi-static loading, the deformation modes, such as progressive collapse, axi-symmetrical or diamond deformation mode were observed at 0 degree to 5 degree. As the angle increase beyond 10degree bending force was identified and became significant. Results show that the axially compressed tubes give better energy absorption against the tubes that subjected to high oblique loading under quasi-static conditions. Hybrid composite square tube from C-glass fiber and Kevlar exhibited good energy absorption capability.

KEYWORDS: *Energy absorption capabilities; Hybrid composite; Oblique loading;Quasi-static; Square tube.*

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I. INTRODUCTION

Hybrid composite materials which consist of two or more high performance reinforcements are combined. Hybrid composite materials have been widely used in aerospace industry and automobile industry. For example, the aircraft is made of many combination composite materials. These composite materials have the benefits of light weight saving, high stiffness, strong characteristic, thermal and corrosion resistance as well as many other integration purposes. High attention was given to produce hybrid composite tubes and testing the materials crushing behavior and energy absorption. The crush behavior of a square column subjected to oblique loads, which is undergoing both axial and bending collapses, is studied and analyzed in this research paper.

Axial collapse and bending collapse are the type of failure modes occur at the crushing behavior of thin-walled structures. The collapse modes have been previously studied by the means of numerical method, analytical method and empirical point of view. Mahmood HF et al. [1] had carried out analytical studies of axial collapses of the rectangular columns. Tani M. [2]and Okubo Y. [3] had dealt with hat type sections for thin-walled structures. Wierzbicki T. had experimented the dynamic axial crushing of tubes on both rectangular columns [4] and square columns [5]. RecepGümrük [6] worked on the quasi-static axial crash response of a top-hat section. Besides that, White MD [7] had also studied the crushing of top-hat as well as double-hat thin walled structures. Alexander [8] has first studied on the energy absorption behavior of circular tubes under axial loading. He found that the approximation theory of the process had a good agreement with the experimental results.G.M. Nagel and D.P. Thambiratnam [9] experimented on dynamic simulation and energy absorption of tapered thin-walled tubes under oblique impact loading. They concluded that due to a change in the failure mode when the angle of applied load increases, the mean load and energy absorption decrease significantly.Reyes et al. [10] had done several studies on thin-walled aluminum extrusions subjected to oblique loading. They analyzed the crashworthiness of aluminum extrusions by experimental and numerical approaches. They also carried out the quasi-static experiments and also numerical simulations on empty and foam-filled circular [11] and square aluminum tubes [12,13].

Han and Park [14] examined the crush behavior of square columns of mild steel subjected to oblique loads. Different angles were tested and he found that at a critical load angle, a transition will take place where the axial collapse mode will change to bending collapse mode. In their experiments, the oblique load was realized by impacting the column at a declined rigid wall with no friction. Qingwu Cheng et al. [15] studied the energy absorption of aluminum foam filled braided stainless steel tubes. They found out that the response of the aluminum foam filled braided tube can be adjusted based upon aluminum foam density and the preload applied to the energy absorbing structure. A.A.S. Abosbaia et al. [16] worked on the effect of segmentation on the crushing behavior, energy absorption and failure mechanism of composite tubes and the result was that a change in segmentation sequence affects the crush loads significantly.

Moreover, Elfetori F. Abdewi et al. [17] investigated the effect of corrugation geometry on the crushing behavior, energy absorption, failure mechanism, and failure mode of woven roving glass fiber or epoxy laminated composite tube. They found that the radial corrugated tubes have presented an effective and stable energy absorption phenomenon under axial compression loading conditions.Farley G. L [18] and Bannerman, D.C et al. [19] studied the crushing modes of composite and aluminum structures. They identified that the local buckling of the tube that collapsed axially resulted in progressive folding. There was an initial linear elastic increment behavior that end at peak load before dropping and followed by series of oscillations about a mean loading.

As far as the author's concerns, there has no literature available on the comparison of the hybridcomposite and composite square tube under quasi-static loadings. Therefore, the purpose of this study is to use the experimental approaches to determine the absorption energy of the composite tube subjected to obliqueloads and compare the performances of different composite materials under compression force. The performances of the composite tubes in terms of the effect of different crush angles and collapse behaviors were also compared.

II. MATERIALS AND METHODS

The experimental works were carried out to investigate the deformation and energy absorption characteristics of the composite square tubes by using specially design inclined jigs. The jigs are designed and manufactured in order give 0°, 5°, 10°, 15° and 20° [20] inclined forces to perform the quasi-static oblique loading experiments. The inclined jig's angle, θ is shown in Figure 1 below. The deformation modes of the tubular structure subjected to oblique quasi-static loading and their energy absorption characteristics with respect to the load angles are determined and compared. The data were collected and presented in this paper.

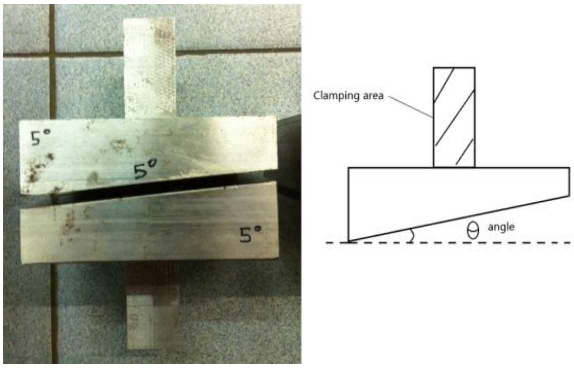

Figure 1: The jig's inclined angle, θ.

1.1 Test setup

The composite square tubes are modeled by using a square steel bar with outer dimensions of 25mm x 25mm. The composite sheets are wrapped around the square bar and applied with epoxy resin and hardener. The composite tubes are fabrication in 7 layers each with the composite orientation as shown in Figure 2. The ratio of epoxy resin to hardener is 2:1. Fabrication process of the hybrid tube and the test procedure are as follow:

2.1.1 The composite sheets are cut into desired dimension before fabricated into square shape. The tube section is oriented at 0/90 with respect to the tube axis to give maximum load results.
2.1.2 The steel bar is applied with the mold release wax and wrapped with a layer of transparent plastic so that after curing process, the specimen is easy to remove from the mold.
2.1.3 After applying the resin, the specimen is left for curing about a week to make sure that it is completely

cured and dried. When the specimen is cured, it is removed from the mold.

2.1.4 After removing from the mold, the tube is cut into 25mm x 25mm x 60mm length of desired testing specimens. Figure 2 shows the processes of the fabrications and the finished tube prior to test.

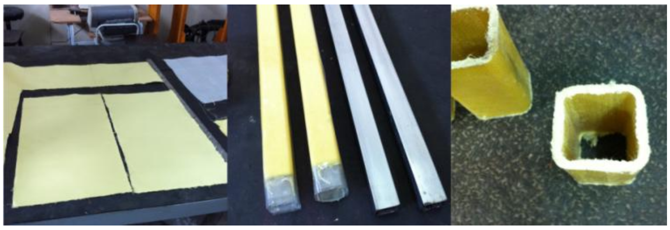

Figure 2: Process of preparing the specimens.

2.1.5 The steps are repeated by using different materials i.e. 200g/sqmC-glass, 600g/sqm C-glass, Kevlar-29 and hybrid of 600g/sqm C-glass with Kevlar-29 to produce the composite square tubes.

2.1.6 The compression test is carried out and computerized by using Instron 3382 100kN tensile/compressive machine.

2.1.7 The test is run atthe quasi-static cross head speed of 5mm/min [21]. When the compression test is started, no further modification is added until one test is successfully ended.

2.1.8 Peak load and the force-displacement curve are recorded with the computer connected to Intron 3382 machine.

2.1.9 To minimize the error, each angle is run for 5 times and the average values are obtained. Each materials are also tested the obtained the energy absorption characteristic.

2.1.10 Setup of the machine as shown in Figure 3 below.

Figure 3: Setup of quasi-static compression test for axially loading (left) and oblique loading (right) with INSTRON 3382 machine.

1.2 Properties of C-glass 200g/sqm, 600g/sqm and Kevlar-29 composite materials.

Three different types of composite materials have been used to fabricate the hybrid tube, i.e. 200g/sqm C-type fiberglass, 600g/sqm C-glass and Kevlar-29. The properties for the 200g/sqm density C-glass are listed as follow:

- Thickness : 0.2 mm
- Weave Type : Plain
- Density (warp) : 7g/25mm
- Density (weft) : 6.5g/25mm
- Weight : 200 +/- 8% g/sqm

For C-glass of 600g/sqm, the material characteristics are as follow:

- Thickness : 0.6 mm
- Weave Type : Plain
- Density (warp) : 21g/25mm
- Density (weft) : 19.5g/25mm
- Weight : 600 +/- 8% g/sqm

For Kevlar-29, the material characteristics are as follow:

- Thickness : 0.2 mm
- Weave Type : Plain
- Density (warp) : 5g/25mm
- Density (weft) : 5g/25mm
- Weight : 200 +/- 8% g/sqm

Figure 4below shows the materials orientation of the hybrid tube.

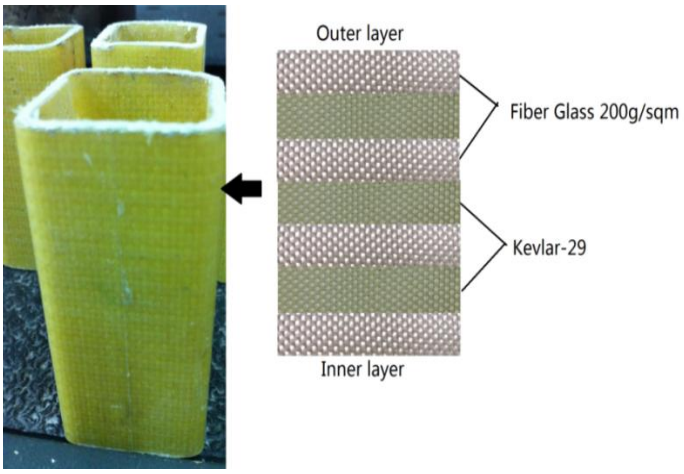

Figure 4: Hybrid of C-glass/Kevlar-29 composite tube.

1.3 Terminology

1.3.1 Energy absorption

Composite materials have a considerable potential of absorbing kinetic energy during crush. The energy absorption capability offers a unique combination of reduced structural weight and improved the vehicle safety. A good crash resistant covers the energy absorbing capability of crushing structural parts as well as providing a protective shell to the payloads in the transport. For the specimens tested, the collapse process was terminated once the process became unstable or bottomed-out. Hence, the energy absorption, E_a, indicates the stable limit of a structure and allows comparisons to be made on different designs.The force–displacement curve for oblique crushing of composite tube can be obtained with computer software connected to the Instron 3382 while test is running. Inordertohaveabetter understanding ofthe experiment results someparametersare defined inthefollowing. The totalenergyabsorption E_t, whichdescribestheenergy absorption capacityofeachof the specimens,isdefinedasthe integration of the force vs. deformation curve:

$$E_t = \int_0^S F(u)du,$$

Where: F(u) = The crushing force as a function of crush distance u,

S = Displacement before the end point.

1.3.2 Specific energy absorption (SEA)

The specific energy absorption (SEA), E_s, which is defined as the energy absorbed per unit mass. SEA provides a way of comparing energy absorption capacity of structures with different masses and is given by:

$$E_s = \frac{E_t}{m}$$

Where: m = Total mass of the specimen undergoes deformation.

1.3.3 Mean load

The mean load is defined as $F_m = E_a/\delta_f$, which is an indication of the energy-absorbing ability of a structure, when compared to the permanent axial displacement required to absorb that energy.

1.3.4 Maximum load/Peak load

The maximum load is the maximum value, P_{max}, give the indication of the force required to initiate failure of the structure and hence begin the energy absorption process. The maximum load should be within the tolerance limit for the payload.

Experimental Results

1.4 Force-Displacement Curves of 200g/sqm C-glass Tube

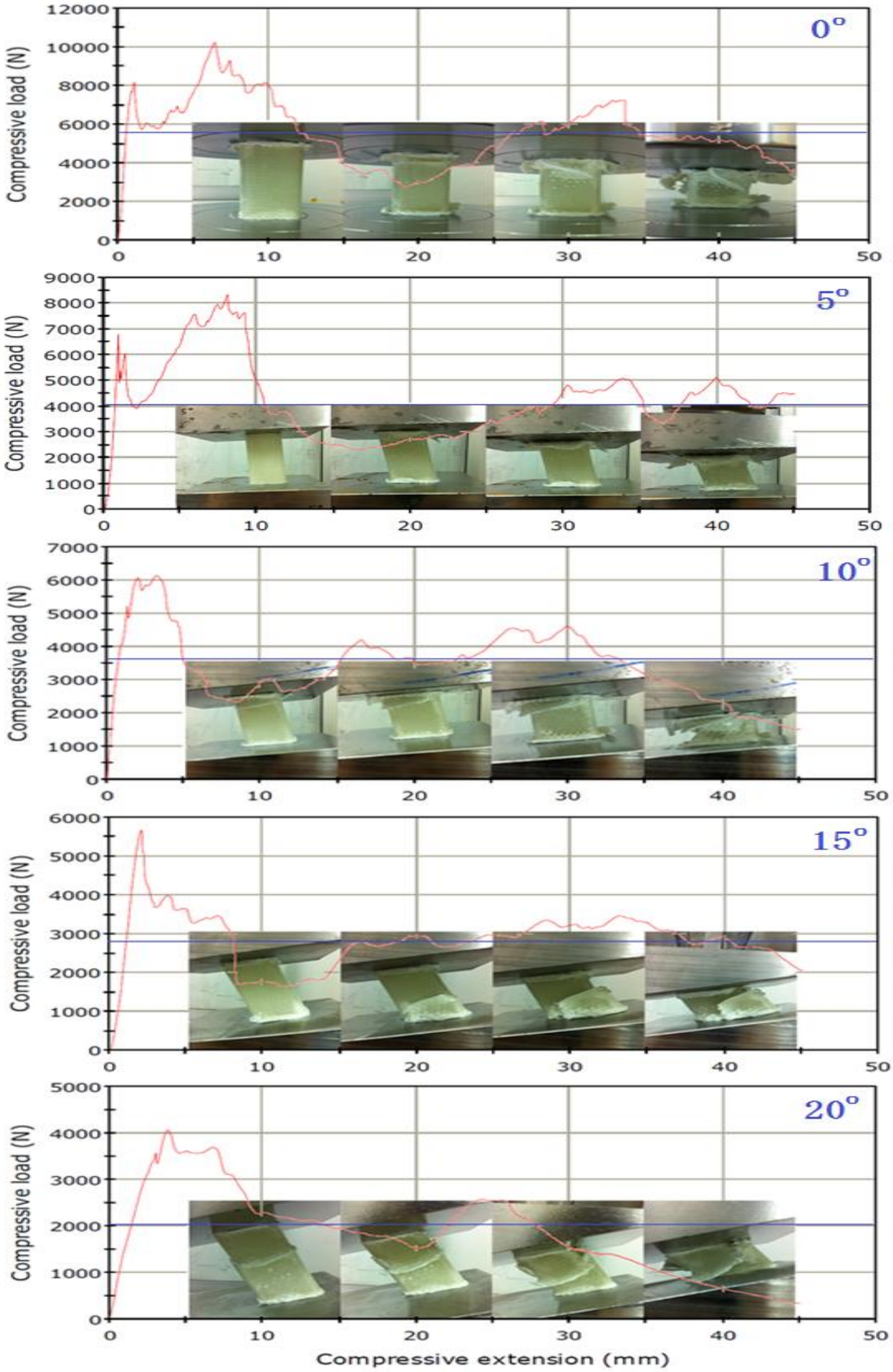

Figure 5: Force-displacement curve of 200g/sqm C-glass material at different angles.

The failure of the composite appears to affect the stability of the tube as well as reduce the peak load and the energy absorption during the crushing process as shown in Figure 5. At 0 degree of inclination, the fracture behavior of the material can be observed at the top of the tube when subjected to the axial loading. When the compression continues, more cracks can be seen on the top, bottom and wall of the tube. Since glass/epoxy is a brittle material, the tube tends to disintegrate to small pieces when the loadings continue.For 5 degree of inclination, the collapse behavior of 200g/m^2 C-glass tube is similar with that at 0 angles. The fracture of the materials can be observed at the top and the bottom of the tube. This is caused by the shearing force to the fiberglass structure. The fiberglass shatters at top and collapses progressively more significant at top of the tube which can be observed at the end of test. Cracks occurred at the corners of the square tube and progressed along the edge of the tube when it is compressed.At 10 degree of inclination, the shearing effects start to be more significant. When the tube is compressed at this angle, the material starts shearing off at the top of the tube. As the loading progress, the shearing fractures become more obvious from top of the tube.At 15 degree, the crushing mode shows the transverse shearing the both end of the tube initially. When the load continues to the extension at 20mm, a shearing occurs at the lower part of the tube. This behavior is first observed at the inclined angle of 10degrees. Shearing forces due to the inclined compression load shear of the corner of the square tube and crack the wall at the lower part of the fiberglass tube. Lamina bending can be observed at the top of the tube at the end of the test.

At 20 degree of inclination angle of quasi-static loading, the failure mode explained the same behavior as 10 and 15 degree. All the tubes exhibited plastic deformation when the loadings are applied. Transverse shearing and fracture of the structure occurred at the center of the tube. The 200g/m^2 C-glass tube is not stable to handle oblique loadings, hence, when higher inclined angle will shear off the structures and reduce the peak loads and also the energy absorption capability. Shearing crash mode nominated the failure mode in this fiberglass that subjected to oblique loadings. Figure 6 shows the peak loadings and mean loadings of the C-glass material tested. The peak load and mean exhibited linear relationship to angle.

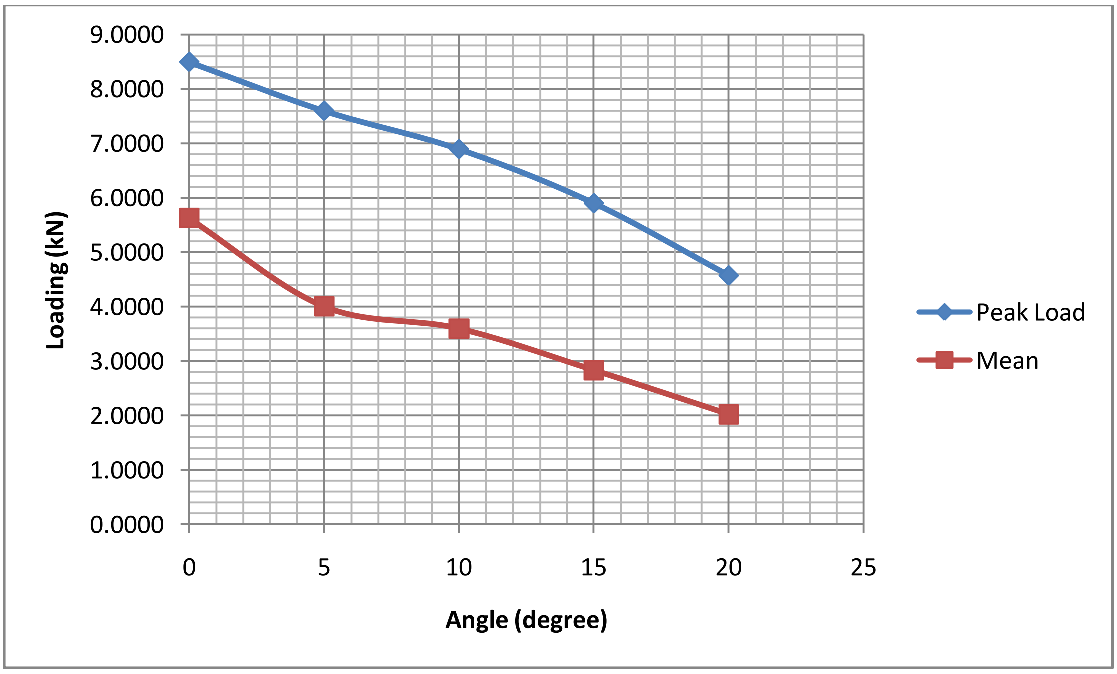

Figure 6: Comparison of Peak loads and mean loads of 200g/sqm C-glass.

1.5 Force-Displacement Curves of 600g/sqm C-glass Tube

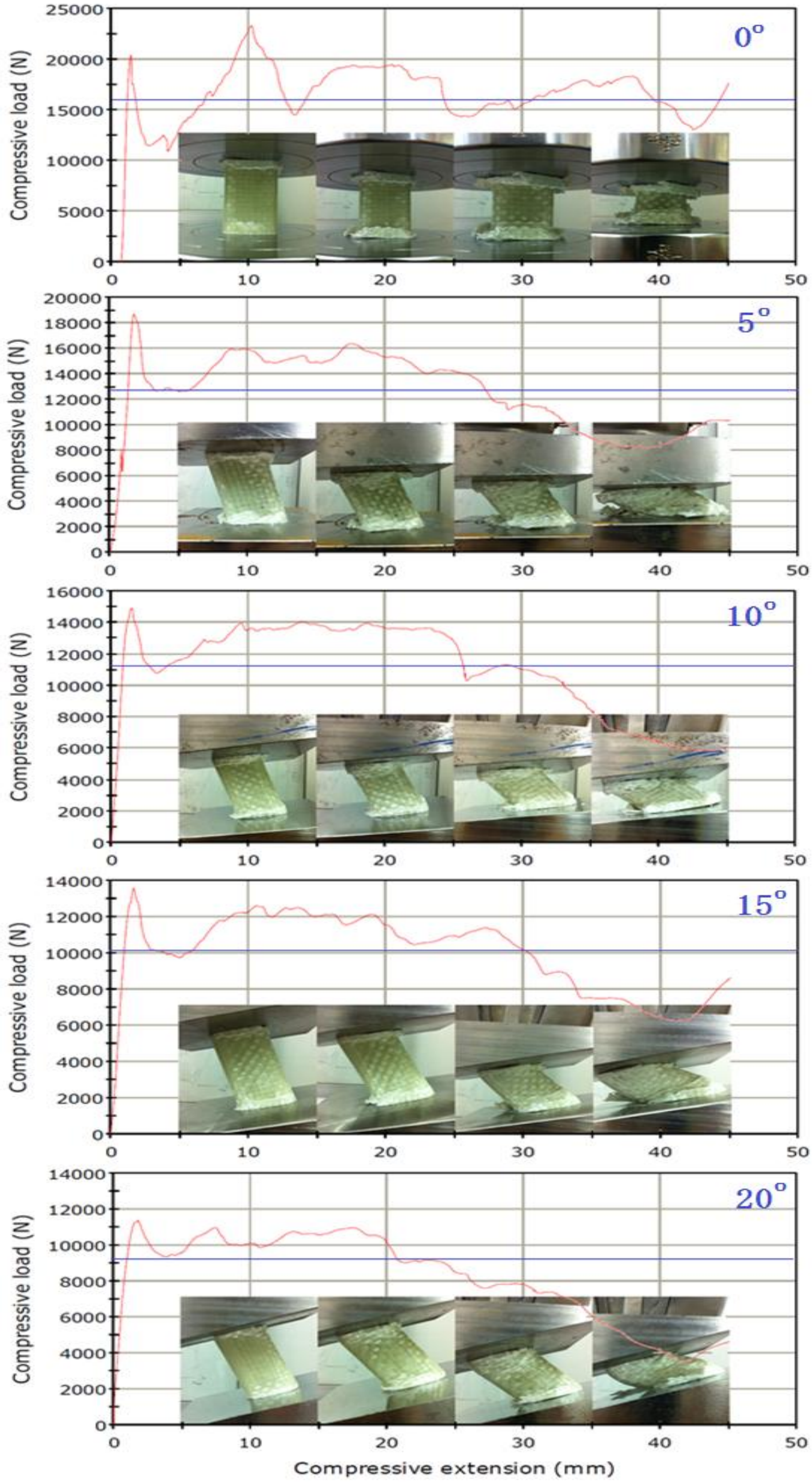

Figure 7: Force-displacement curve of 600g/sqm C-glass material at different angles.

Figure 7 shows the Load-displacement curves of the C-glass composite tubes subjected to 0, 5, 10, 15 and 20 degree. At 0 and 5 degree of inclined angle, the failure behavior of the 600g/sqm fiberglass displayed the brittle fracture when axial force was applied. The initial failure reduced the peak load and the energy absorption during the crushing process. The crushing behavior showed transverse shearing and plastic deformation. As the loading continues, the fracture propagated and became more significant at both end of the tube. These failure modes are similar to that of 200g/sqm fiberglass tested previously, except that the failure point occurred at higher loading forces.

At 10 degree inclination, the tube shows progressive collapses at both end of the tube. There is not shearing off fracture detected on the wall of the tube. This is due to the thicker wall of the tube compare to 200g/sqm fiberglass. The tube continued to break into pieces as the loading force extends. Local bucking is observed at the ends of the tube. It is observed that the failure mode of the crashed tube includes transverse shearing, lamina bending and bending of the tube. Delamination of the tube caused the structure ability to absorb energy significantly reduced. At 20 degree oblique loading, fracture of the structure can be observed at the beginning when the load is applied at both end of the tube. When the loading continue, the cracks also propagated through the entire wall of the tube. Figure 8 show the recorded peak load and mean load for 600g/sqm C-type fiberglass square tube in compression tests.

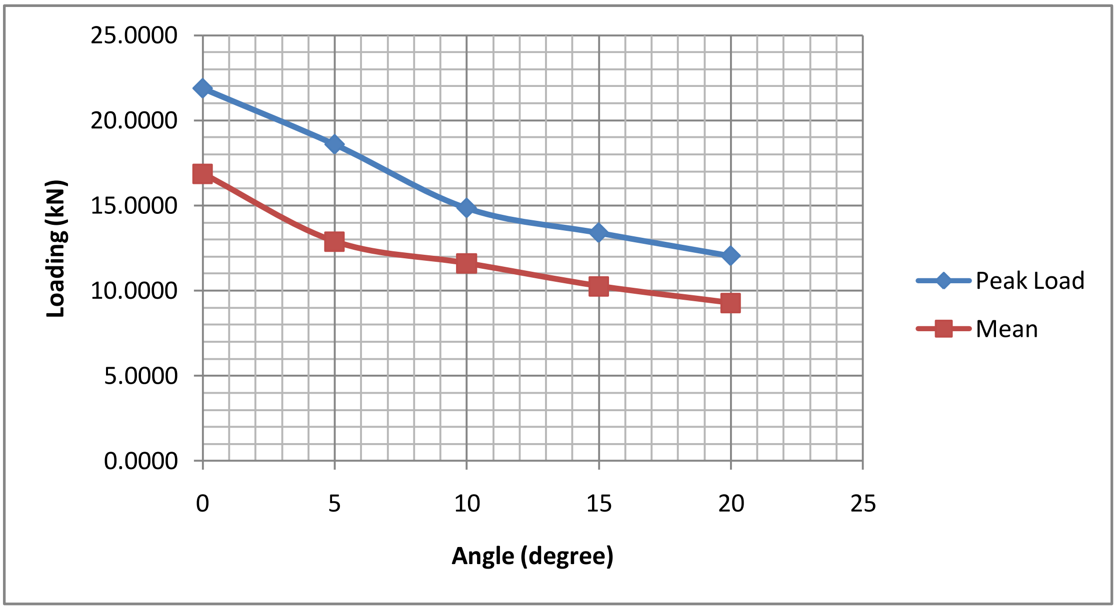

Figure 8: Comparison of Peak loads and mean loads of 600g/sqm C-glass.

Displacement Curves of Kevlar-29 Tube

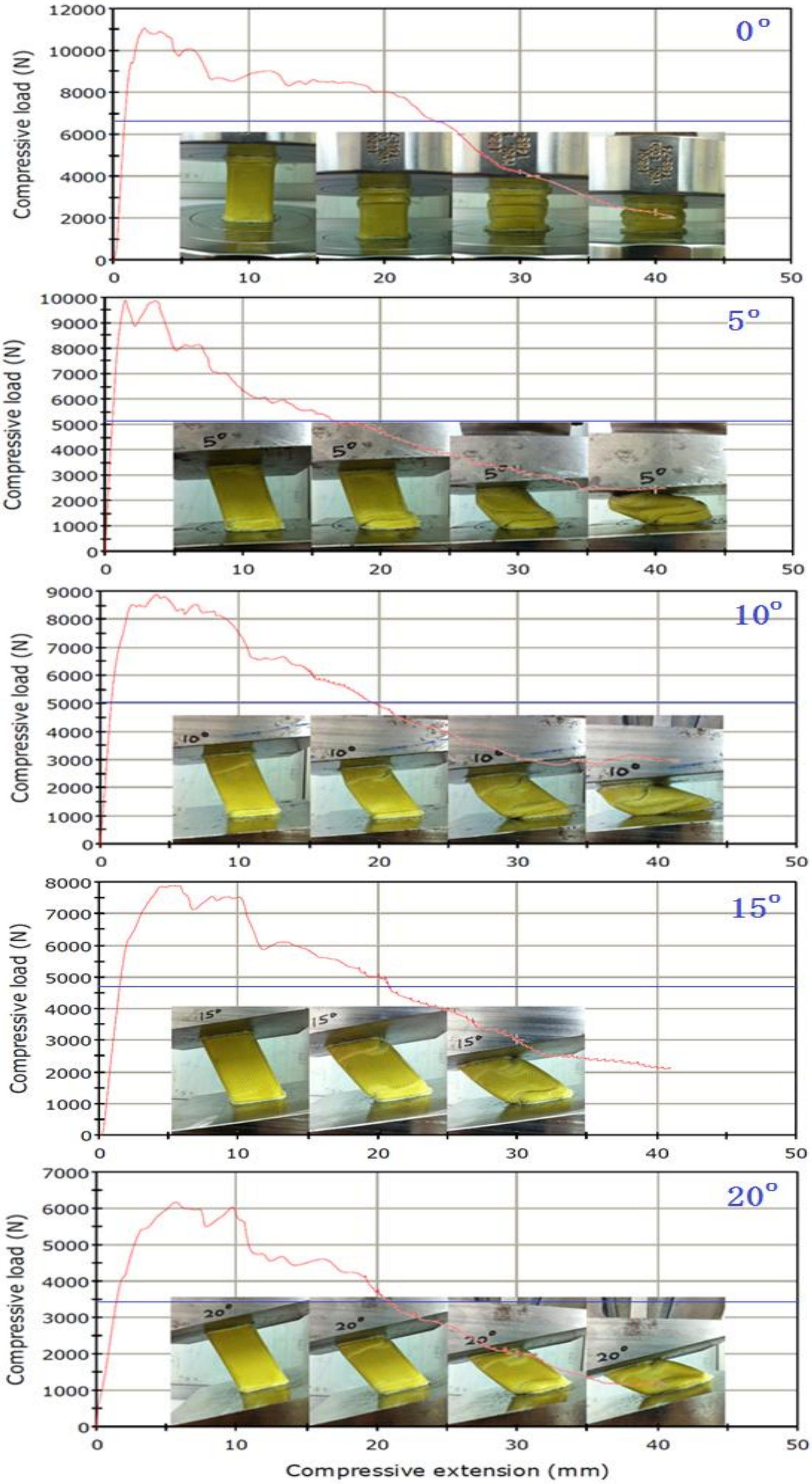

Figure 9: Force-displacement curve of Kevlar-29 composite tube at different angles.

For pure Kevlar-29 square tube under axially crushing, the tube shows the progressive collapse which can be observed at 0 degree compression in Figure 9. Unlike fiberglass, it does not disintegrate due its flexible properties. Kevlar-29 shows a very clear asymmetrical collapse of local buckling starting from the top of the tube and propagates to the entire tube when loading force continues. Instead of folding, the Kevlar-29 does not break into small pieces. It experienced lamina bending and local buckling at the end of the tube. Therefore, there is no sharp drop of the loads like one exhibited by fiberglass. For inclined angle of 5 degree, the tube also displayed progressive folding but it is distorted a little to side due to the applied oblique load.

At the inclination of 10 degree, the tube does not exhibit progressive folding behavior but bucking at the side of the tube at both end of the tube. It is asymmetrical collapse mode. At 15 and 20 degree of inclination, the crushing behavior of the tube showed the similar deformation which is displayed by the loading at 10 degree. At higher inclined angle loadings, the bending effect start to take place instead of the axial folding effect. Figure 10 shows the peak load and mean against angles of Kevlar-29 composite square tubes subjected to oblique loadings.

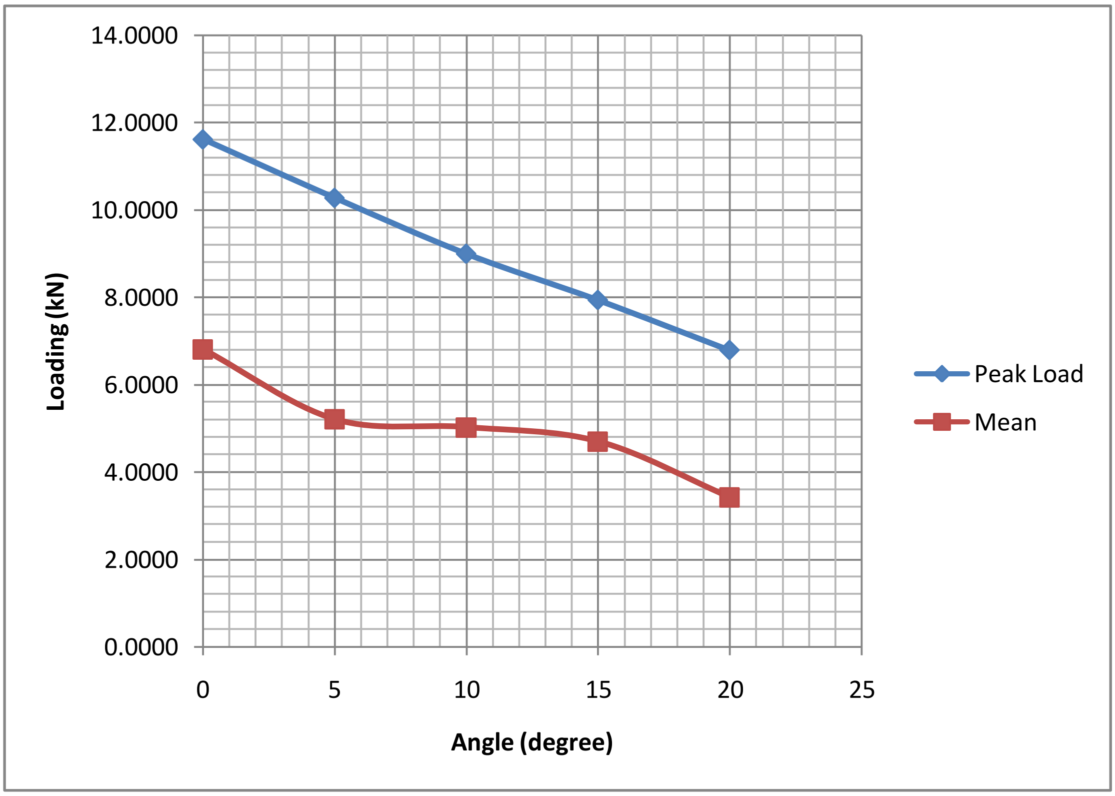

Figure 10: Comparison of Peak loads and mean loads of Kevlar-29.

Force-Displacement Curves of Hybrid Composite Tube

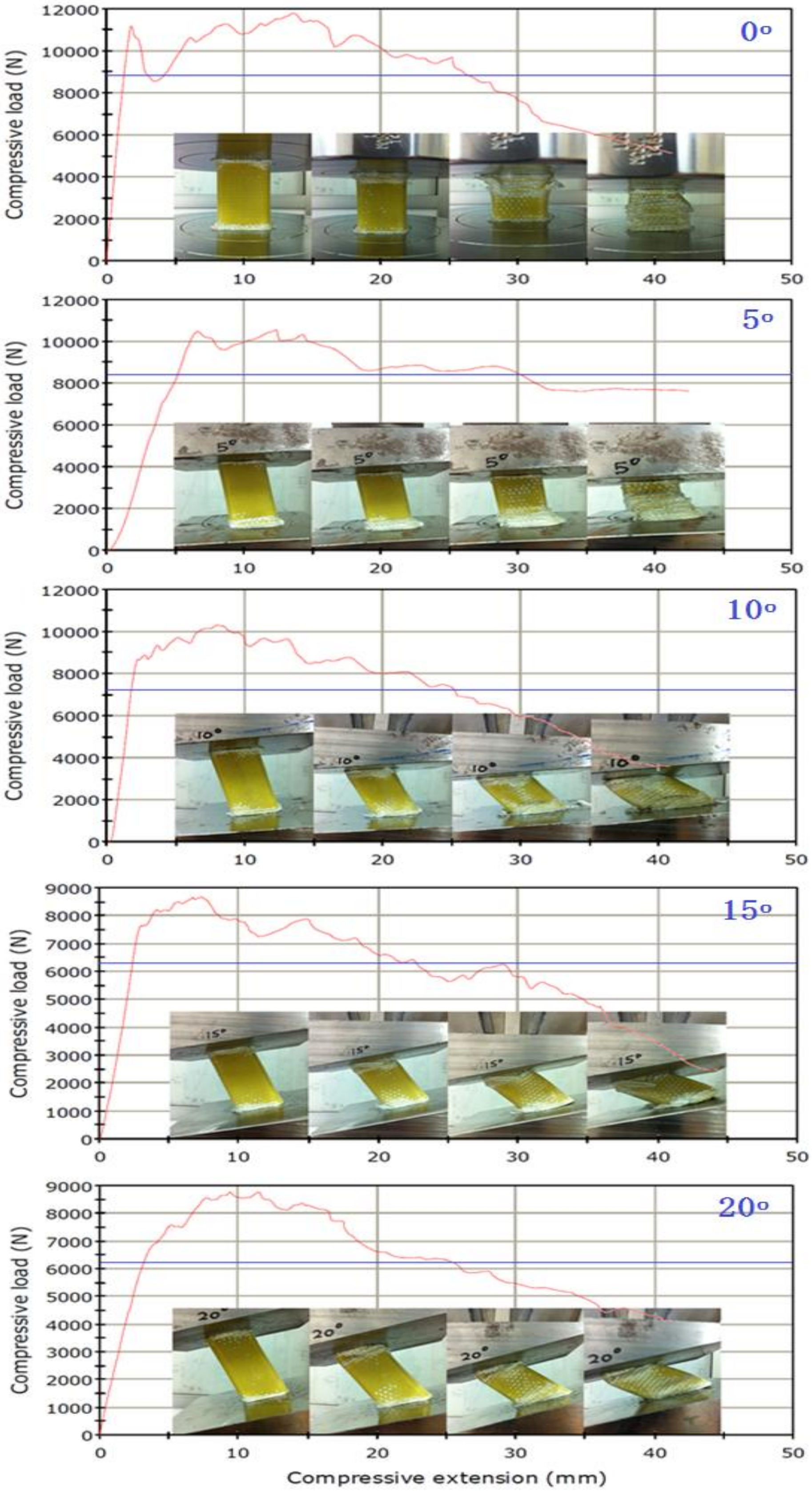

Figure 11: Force-displacement curve of hybrid composite at different angles.

For hybrid composite as shown in Figure 11, it is expected that the combination crushing behavior of both type of the materials i.e. fiberglass and Kevlar-29. At the 0 angle of loading, which is equal to axial loading, the fracture is observed at both end of the tube which is caused by the disintegration of fiberglass, but the specimen does not shear of from the main wall of the tube as loading is applied and compressed the tube. When the loading is extended, the crack can be seen at a side of the hybrid tube. The crushing behaviors of the tube are also showing progressive folding with asymmetrical pattern at the same time. For inclined angle of 5 degree, the tube crushes similar to that of axial load except that there is some distortion due to the angle loadings. The outer layer of fiberglass material is being distorted because of its brittle nature compare to Kevlar. When the compression continues, the tube experienced progressive folding from the bottom of the tube. The energy absorption capability decreases steadily compare with pure fiberglass and Kevlar tube.

When the inclined angle increases to 10 degree, the bending force becomes significant than the axial force. When the compressive force is applied to the tube, the fiberglass lamination cracked. The tube is deformed and bended but does not fracture off due to the higher strength of Kevlar and also its flexibility. At 15 degree, the crushing behavior of the tube is same as the one at 10 degree inclination. At 20 degree of inclined loading, the tube is also showing the bending at a side of the tube at both top and bottom part which is observed at Figure 11. The bending force is taking place in this angle for the deformation of the tube. The result posted similarity as pure Kevlar-29 tube under same compression condition. For hybrid composite tube of C-glass and Kevlar-29, the average peak loads and mean decrease linearly against angle as displayed in Figure 12 for hybrid composite materials.

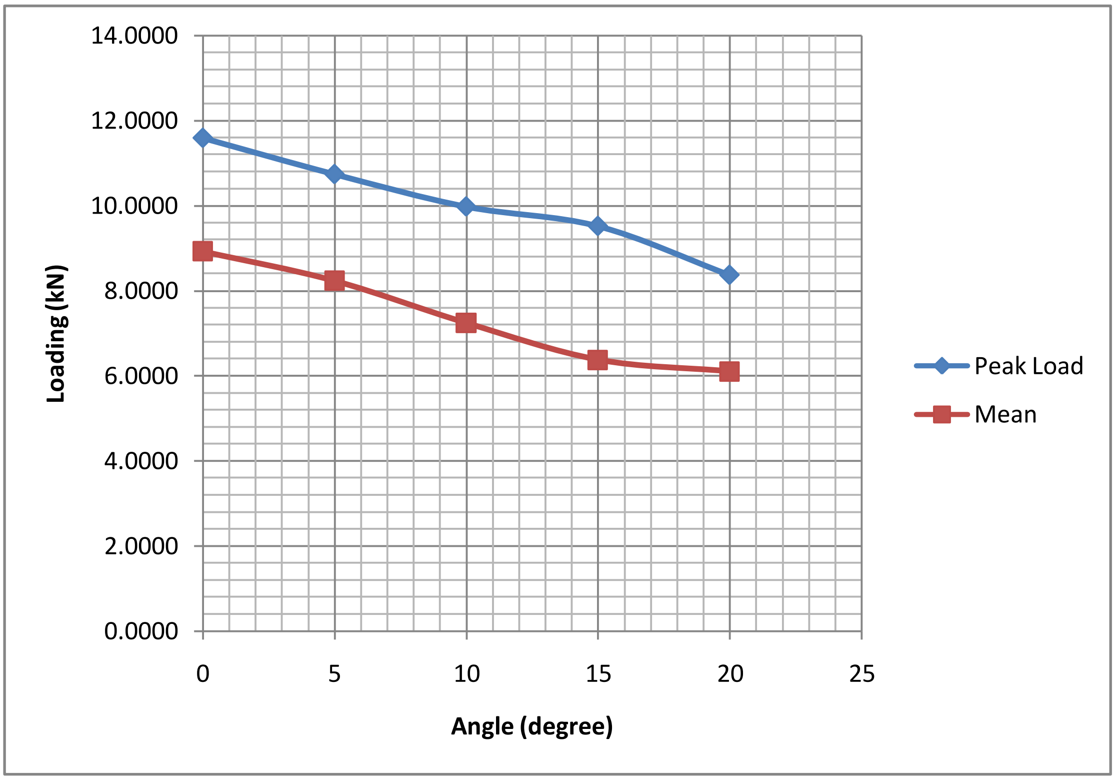

Figure 12: Comparison of Peak loads and mean loads of hybrid composite.

Comparison of Specific Energy Absorptions of The Materials

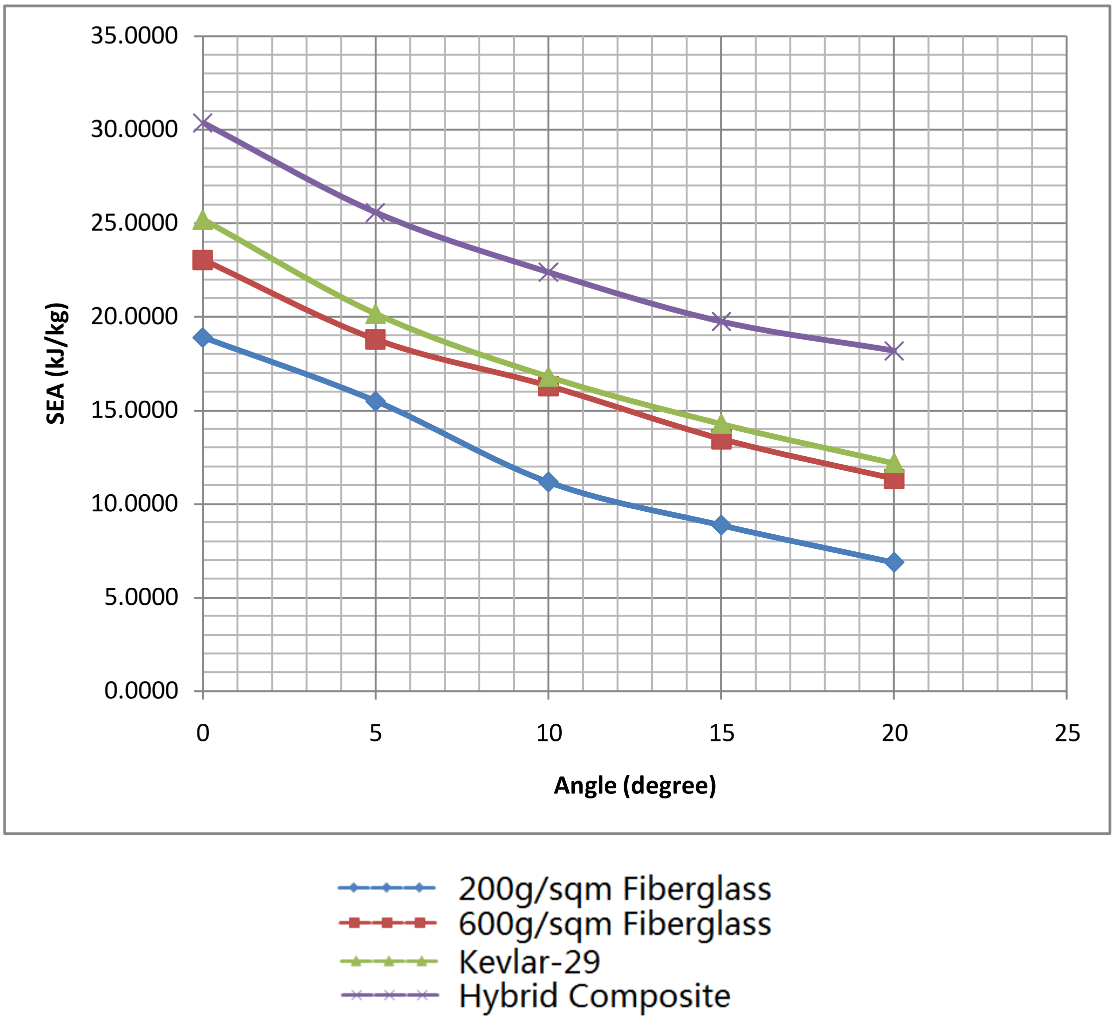

Figure 13: Specific energy absorption (SEA) versus angle.

The Figure 13 above shows the comparison of specific energy absorption (SEA) against inclined angle for all materials tested under oblique loadings. For all materials, they show the linear relationship of energy absorption and inclination angle. When the inclination increases, the energy absorption capability per kilogram of the materials reduce. This is due to the structure of the material is more stable to handle axial loading than the bending forces. From the average results calculated above, hybrid composite of C-glass and Kevlar-29 has the highest SEA compares to second highest is pure Kevlar-29 while 600g/m^2 C-glass has higher SEA than 200g/m^2 C-glass for all oblique angle.

At 0^o, the average SEA for hybrid composite is 30.3587kJ/kg. While for Kevlar-29 is 25.1984 kJ/kg followed by 600g/m^2 C-glass, 23.0434 kJ/kg and 200g/m^{2}C-glass 18.8933 kJ/kg. For the inclination of 5^o, the SEA for hybrid composite recorded a reading of 25.5652kJ/kg. For Kevlar-29, the SEA is 20.1587kJ/kg. For 600g/m^2 and 200g/m^2 C-glass materials, the SEA is 18.7892kJ/kg and 15.4852kJ/kg respectively. For the hybrid composite, the average SEA recorded at 10, 15 and 20 ^{o} of inclination are 22.3696kJ/kg, 19.7332kJ/kg and 18.1753 kJ/kg respectively. They exhibited the highest energy absorbed per kilogram for all corresponding angles. While for pure Kevlar-29 tubes, the energy absorbed are 16.7999kJ/kg, 14.2791kJ/kg and 12.1792kJ/kg for the loading angles of 10, 15 and 20 ^{o} respectively. Kevlar-29 material has the second highest energy absorption capability per unit mass among all the materials tested. 600g/m^2 C-glass type material energy absorption capability per unit mass is lower than that of hybrid and Kevlar composite materials. At 10^o, 15^o and 20^o, the average energy absorbed per unit mass are 16.3076kJ/kg, 13/4715kJ/kg and 11.3444kJ/kg respectively. Last but not least, 200g/m^2 C-glass type material recorded the lowest energy absorption capability per unit mass. The readings are 11.1642kJ/kg at 10^o inclination, 8.8587kJ/kg at 15^o and only 6.8703kJ/kg at 20^o of inclination.

III. CONCLUSION

Thecomposites and hybrid composite square tubes were fabricated and tested. For each angle of inclination,five sampleshad beenexperimented and recorded to obtain the average values and increase accuracy of the results. The collapse modes have been identified and the peak loads and specific energy absorption characteristics of the structures had been calculated and analyzed.

In conclusion, hybrid composites have the highest energy absorption per unit mass while Kevlar-29 material is at the second highest. It shows promising results compare to other type of pure composite materials. On the other hand, C-glass material has the lowest energy absorbed per unit mass and the 200g/sqm type is lower compare to 600g/sqm C-glass when subjected to oblique loading forces.The failure mechanism of the composite as well as hybrid composite tubes have been investigated and discussed. The tube is structurally not stable when subjected to oblique loadings. When the angle of inclination increases, the effectiveness of the tube to absorb energy will reduce. If the angle is increased further higher, the bending force starts to take place and causing the tube to bend, buckling, disintegrate and etc. Hence, the energy absorbed is greatly reduced. Hybrid composite gives the best stability in term of the crashing behavior and has better energy absorbing capability against other type of composite material tested.

IV. ACKNOWLEDGEMENT

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