The Effect of Cone Angle on Composite Tubes Subjected to Axial Loading

Haidar F. AL-Qrimli[1*], Karam S. Khalid[2] and Fadhil A. Mahdi[3]

[1]*Department of Mechanical Engineering, Curtin University, Sarawak, CDT 250 98009, Miri, Malaysia.*
[2]*Department of Mechanical Engineering, College University Ibra, South, Oman.*
[3]*Department of Electrical Engineering, University of Baghdad, Iraq.*

Authors' contributions

This work was carried out in collaboration between all authors. Author HFA-Q designed the study, conducted the experimental tests, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript and managed literature searches. Authors KSK and FAM managed the analyses of the study and literature searches. All authors read and approved the final manuscript.

Original Research Article

ABSTRACT

An experimental study of natural fiber cones that were compressed is discussed in this work. One of the main objectives is to comprehend the deformation and its corresponding mechanism of composites under axial loadings. The results from this work included load-displacement plots, initial and maximum failures, and average failure loads, all of which will help us determine parameters associated with crashworthiness. This led us to conclude that geometry is influential upon energy absorption. The highest value of specific energy absorption was determined to be 0.276 kJ/kg, which was from a cone lacking sharp angles, rendering it suitable as parts of automobiles.

Corresponding author: E-mail: haidar.fa@curtin.edu.my; halqrimli@yahoo.com;

1. INTRODUCTION

Composites are fast being recognized in the field of engineering and manufacturing due to its unique properties, such as high specific strength and specific modulus. Certain applications require electrical properties as well. These properties render composites quite attractive, and a potential substitute of metal. Currently, composites are ubiquitous, and can be found being used for sports, vehicles, and power, mostly due to properties such as excellent corrosion resistance, high strength-to-weight ratio, high impact resistance properties, and design flexibility, all of which require T high-quality, durable, and cost-effective products. Quite a number of researchers pointed out that composite material have been classified in many ways, depending on its corresponding ideas and concepts [1-5].

Neutral fibers are present all over the globe, and are primarily utilized to make ropes and bags. The composites that are made up of natural fibers are regarded as cellulose micro fibrils that are dispersed within an amorphous matrix of lignin and hemicelluloses. The applications in which natural fiber composite are now used include door inner panels, seatbacks, and roof inner panels. Natural fiber composite provide higher acoustic damping than glass or carbon fiber composites, and are therefore more suitable for noise attenuation, which is an increasingly important requirement in interior automotive applications. Natural fibers are cheaper than glass and carbon fibers [2]. It is also cheaper than other industrial fibers such as carbon fibers.

From previous investigations, it was determined that the idea of composites is workable on a macro scale [6-8]. Some of the potential application area of composites is aviation, where reduced weights are beneficial towards speed and payload. Currently, a large variety of composite components are used in aircrafts. [9-11] determined that automotive parts represent an immense market for composites. Both the volume of the automotive market and the potential automotive usage for composite materials is quite huge. Moreover, hand layup, a simple and classic composite fabrication process, is especially suitable in the manufacturing of major components such as the hull of a boat. This process involves glass or any other form of reinforcement being placed in an open mold, followed by resin being poured, or in some cases sprayed, onto the glass. The hand lay-up method results in significant reduction of surface roughness as opposed to the filament winding process. It is also a better process due to its low requirement of specific cutting pressure and resulting reduced surface roughness. Any presence of entrapped air can be eliminated with squeegees or rollers [12,13]. Some common matrix resins include room-temperature curing polyester and epoxies. Curing is a process that is helped along by the introduction of catalysts or accelerator within the resin, which acts to harden the composite without the presence of any external heat. In [14], Mertens proposed several composite automobile parts that are currently in production, and many others are being planned, such as suspension springs, space frames, body panels, and entire assemblies. Elgalai et al. [15] made a quasi-static axial compressive load to examine the crushing behavior of composite corrugated tubes, and they used two types of composite material for the test; carbon fiber/epoxy in filament form and glass fiber/epoxy in woven roving. Their work involved the analysis of the influence of the corrugation angle, and they discovered that corrugated tubes are especially susceptible to value fluctuations. The results showed that CFRE-40 absorbs the most energy, which led them to conclude that energy absorption is susceptible to angles. In addition, for the glass fiber/epoxy composite tubes, they found consistent trends with the variation in the specific crushing energy absorbed. They also studied the effect of fiber type, and found that carbon fiber/epoxy possess the highest load-absorbing capacity. Lee et al. [16] experimentally investigated the energy absorption characteristics of thin-walled square tubes that are under quasi-static axial loading for the purpose of coming up with the optimal structural configuration of vehicles that provides maximum safety to occupants in the event of a collision. The result of the static collapse test showed that the amount of energy absorption and mean collapse load of the thin-walled tubes is increasing, and it depends on the thickness-to-width ratio. Jose et al. [17] fabricated tubes of circular and square cross sections, and they use polyester resin and plain weave E-glass with fibers oriented at 0/90º and steel molds to fabricate specimens for a quasi-static compression test. The results showed that under similar conditions, tubes of circular cross-section provide the best results. Giovanni and his team [18] conducted impact tests via a series of quasi-static tests to get information on the laminate's strength, which lead them to conclude that the energy absorbed by the specimens can be calculated from the load–displacement curve.

From the literature, the authors confirmed that most researchers used circular or square geometries as an energy absorber, and there are no attempts to try other geometries. Furthermore, natural fibers are not used. This study considers utilizing both. The most important factor that should be taken into account when designing an automobile is the safety of the passengers in the event of a crush or a collision. When evaluating the crashworthiness recital of energy absorber devices, attention should be directed to the instantaneous crush behavior, such as crush force efficiency (CFE), crushed strain (CS), and failure modes at different stages of the crushing process and energy absorption capabilities [19,20]. This study investigated and fabricated two geometries (cone with non-sharp angle and cone with sharp angle), with a total of 12 specimens. Experimental tests have been performed, and the load-displacement curves were obtained. At the end of the study, the crashworthiness parameters were calculated.

2. FABRICATION OF TUBES AND MATERIALS

This section discusses the materials and mandrels being used in this work. Coconut fibers were used to fabricate the specimens, as shown in Fig. 1. Coconut is a fruit and is ubiquitous, and can be sun-dried, which in our case, took two days. The fibers were extracted by hammering the dry natural piece using heavy metals, until it breaks into small pieces; the resulting fibers are called coir. Coir is made up of two types, pasty, which is derived from young coconuts. These are somewhat superior and lighter in color as opposed to its more mature counterparts. These

fibers are often used to make yarns, which will in turn be used to manufacture mats, sacking, rope, and twine. In the rope industry, ashen coir fiber can sometimes be cheaper. Russet fiber, which is another type of coir, is from established coconuts, and it tends to be more stiff and unyielding. Coir fiber can be observed in Fig. 1.

The mandrel used to examine the behavior of natural fiber was cone-shaped, as shown in Fig. 2. The mandrel was made from Aluminum. The mandrel has a 60 mm radius and is 120 mm in height.

The coir coconut fiber was immersed with epoxy. After preparing the mixture, the coconut fiber was handled in aluminum mandrels. The process began by placing the coconut fiber into the mandrel from its narrow side. Then, epoxy was added again on the fiber for well mixing. The mixture was left for eight hours to dry; then, the specimen was extracted by knocking it out from an upper angle. It should be pointed out that the knocking was done very gently using a wooden pole to avoid breaking the specimens.

3. CRUSHING TEST

After being fabricated, the cone specimens with sharp and non-sharp upper angles were examined under a quasi-static test. The machine used in the crushing test was a computer-controlled servo-hydraulic INSTRON machine, system ID (4469 H2005), made in England. Fig. 3 shows the machine being used. It is connected to a computer, which saves the results of the crushing test.

Fig. 1. Natural coconut and coir coconut

Fig. 2. Aluminum conical mandrel

Fig. 3. The test machine used

The specimens were subjected to a quasi-static load at a speed of 50 mm/minute; the crushing distance was set on 100 mm to examine each part of the specimens. The specimen was positioned on the inactive lower platen with the beveled end up. The crosshead was subsequently lowered in anticipation of the upper platen (touching the upper side of the specimen). If the machine cross head did not attach a shelf to the specimen, the machine will not respond to the order of crush. This setting ensures the accuracy of the outcomes. Then, the cross head was set to move down. The load and displacement data were collected from the computer that was connected to the INSTRON machine using a thumb drive. It should be mentioned that the number of specimens was 12,

and the results shown in this study are the average of those specimens.

4. RESULTS AND DISCUSSION

4.1 Load Displacement Curves

The Load-displacement plot is divided into two primary zones; the first is the elastic region, also known as the pre-crushing stage of the specimen, where initial failure will be detected (P_i). At the end of the first zone, the plastic zone began, and it is regarded as the second zone, also known as the post-crushing stage. The load displacement plot shows the maximum load (P_{max}), average load (P_{av}), and the displacement of the failure [3]. From here, the other

354

crashworthiness parameters can be also calculated.

4.1.1 Cone specimen with non-upper sharp angle

Fig. 4 shows the load-displacement curve of the cone with a non-sharp angle. The load increased with increasing displacement until the initial crushing, with load and displacement values of 158.5 kN and 9.03 mm, respectively. The structure of the cone specimen shows huge resistance to the load subjected by the machine. After the initial failure load, the structure started to break. After this, parts of the specimen begin to collapse, until the remaining structures are completely crushed.

4.1.2 Cone specimen with upper sharp angle

The behavior of cone specimen with an upper sharp angle under the quasi-static load with a speed of 50 mm/min can be explained in the plot, which is shown in Fig. 5. The curve started to rise until the load reached the value of 153 kN. Meanwhile, the displacement increased to 36.4 mm. Equivalent response is seen on the cone specimen with a non-sharp angle, the cone with an upper sharp angle began failing by cracking in the middle of the specimen, and suddenly, half of the specimen fell away with a loud snapping sound. The crushing stopped before the whole structure collapsed.
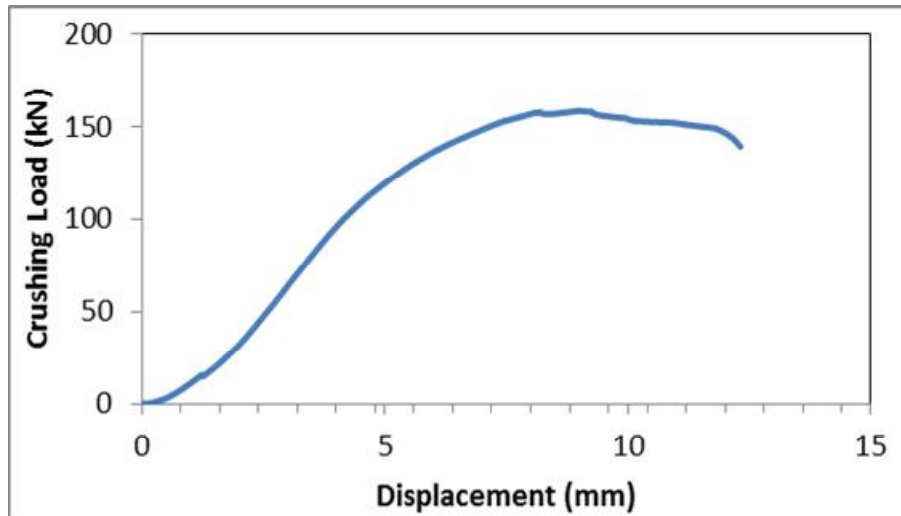

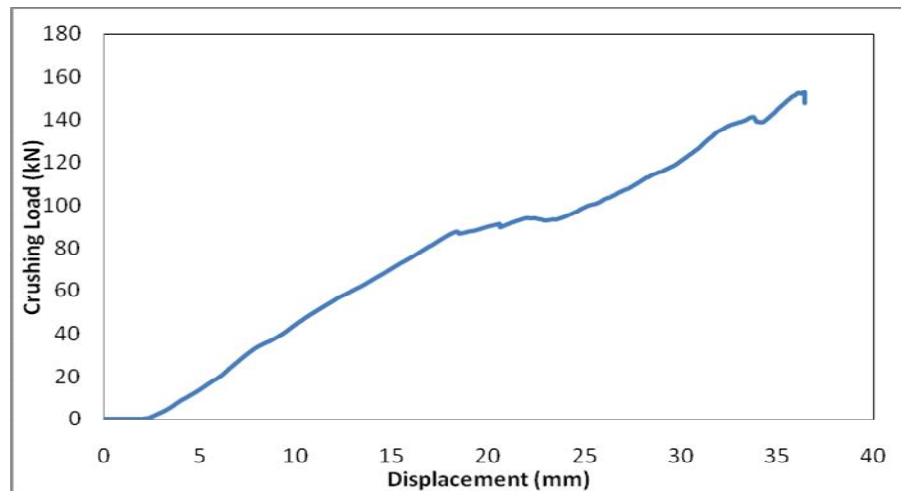**Fig. 4. Load displacement curve for cone with non-sharp angle**

Fig. 5. Load displacement curve for cone with sharp angle

4.2 Crash Worthiness Parameters

4.2.1 Initial and maximum failure load (p_i, p_{max})

The initial failure load was determined to be the border of the elastic-plastic zone, and is also definable as the point where the load drops as the linear elasticity increases [3]. It will also be prudent to determine the region of temporary deformation, which is the pre-crushing zone (elastic) and the permanent deformation region of the structure called the post-crushing zone (plastic). For this work, the cone geometry gives similar values for the both initial and maximum failure load, which is indicative of the ultimate crushing for the structure. The cone, with a non-upper sharp angle, produce pi and P_{max} with a value of 158.5 kN more than the cone with sharp angle, where the value is 153 kN, as shown in Fig. 6.

4.2.2 Average failure load (p_{av})

The failure load, (P_{av}), is an imperative part of crashworthiness parameter in the context of the crushing energy absorbed by the structure. As shown in Fig. 7, the cone specimen with a non-sharp angle (a) produce a large value of P_{avr} that is superior to the cone specimen with a sharp angle (b).
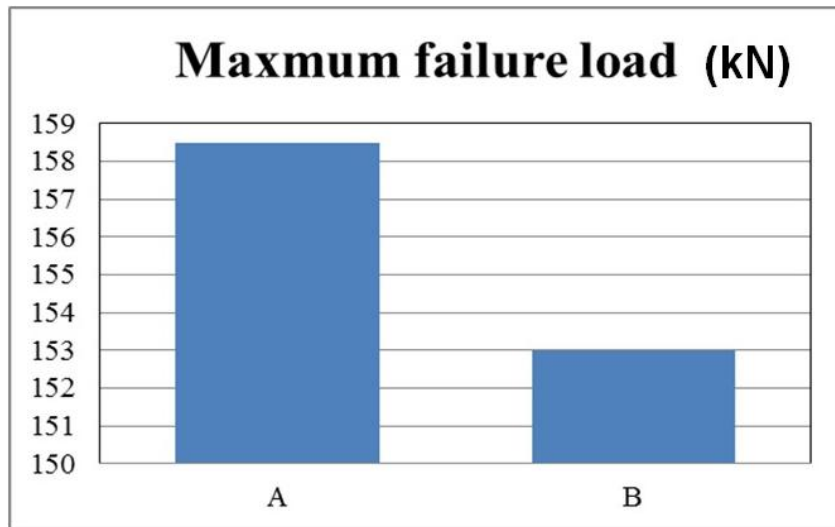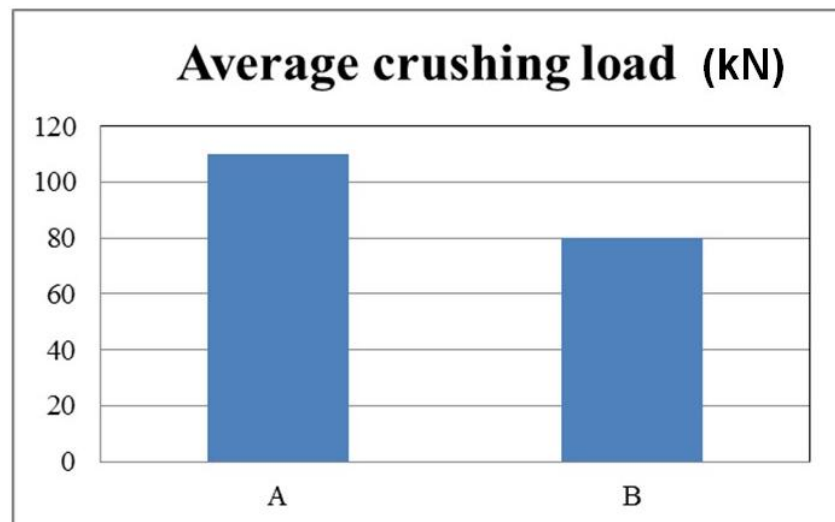

Fig. 6. Maximum failure load P_{max}

Fig. 7. Average failure load P_{avr}

4.2.3 Load ratio (p$_r$)

The main purpose of using the load ratio parameter is because it is imperative that the failure modes along the crushing failure are analyzed. The load ratio (P$_r$) is the ratio between the initial failure load (P$_i$) and the maximum failure load (P$_{max}$), which is shown in the equation P$_r$= P$_i$ / P$_{max}$. When the initial failure load has similar values to the maximum failure load, it means that the load ratio is equal to 1, and the structure is initially crushed in a limited catastrophic failure mode. Furthermore, if the load ratio (P$_r$) is less than 1, then a matrix failure mode will be observed in the initial crushing stage of the specimen. For this research, the work the load ratio is equal to 1 for the two cone specimens, because the initial and maximum failure loads are similar.

4.2.4 Total energy absorbed (tea) (kj)

The area under the load-displacement plot is the total energy absorbed (TEA), and is calculated from: TEA = ∫P$_{av}$ d$_s$ ≡ P$_{av}$ (d$_f$ – d$_i$), where the P$_{av}$ is the mean crushing load, d$_f$ is the final crushing distance, and di is the initial crushing distance. The SI unit for TEA is kJ [3]. The area under the load-displacement plot is divided into two regions, the first one is pre-crushing, which can be calculated by finding the area under the triangle, and the area will then be ½ multiplied by p$_i$ and d$_i$, where the SI units is kN.m (kJ). The energy absorbed in the second (post-crushing) region can be calculated from the equation, where the factors are obtained from the tables

shown previously, and the total energy absorbed can be calculated by finding the simulation of energy absorbed in the two regions (pre and post crushing). The cone specimen with non-sharp angle (a) produce tea with a value 0.3644 kJ more than the value produced the by cone angle with a sharp angle (b), with a value of 0.12kJ, as shown in Fig. 8.

4.2.5 Specific energy absorption (sea)

The specific energy absorption (SEA) is crucial to the design of parts that require weight reduction, such as land or aerial vehicles. SEA is the energy absorbed per the mass of the specimen, and its unit is kJ/kg. It can be calculated from the equation: (SEA= TEA/mass). The SEA for cone with non-sharp angle is much better than the cone with a sharp angle, as shown in Fig. 9.

4.2.6 Volumetric energy absorption (vea)

The volumetric energy absorption (VEA) is an indispensable restriction for the energy absorbing structure design. The VEA is the percentage flanked by the total energy absorption to the volume of the specimen. The SI unit is kg/m^3 and VEA can be obtained from the equation (VEA = TEA / V). The formula for the volume of the cone is V=1/3*π*r^2*h, where r is the radius of the base circle and h is the height of the cone. The cone with non-sharp upper angle produced a value of VEA of 967.2 kJ/m^3, which is the highest value of the cone with a sharp angle, as shown in Fig. 10.
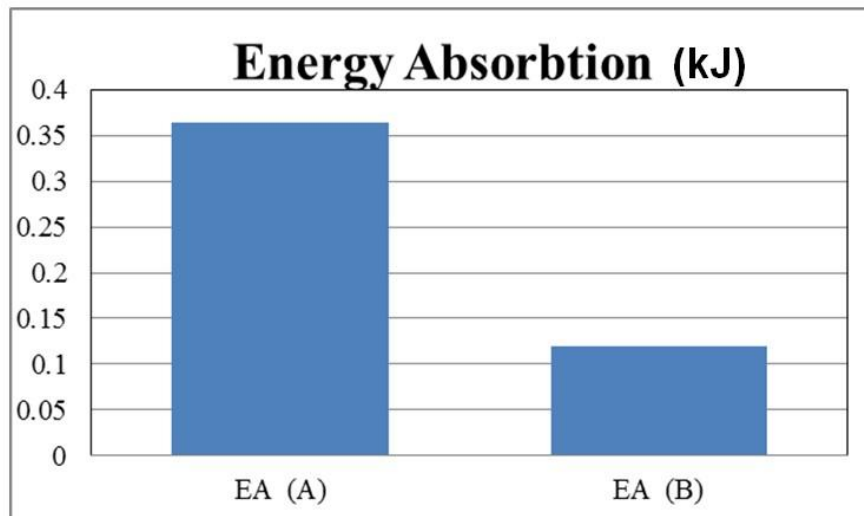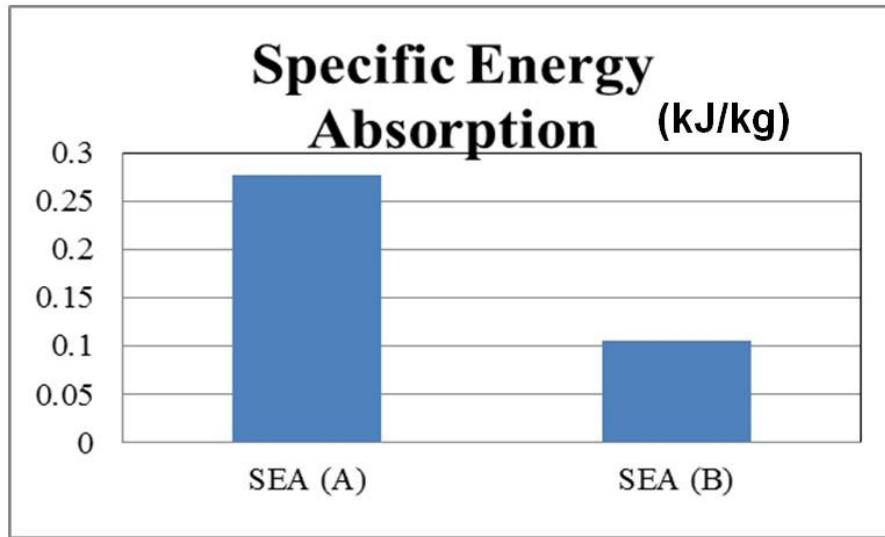

Fig. 8. Energy absorption
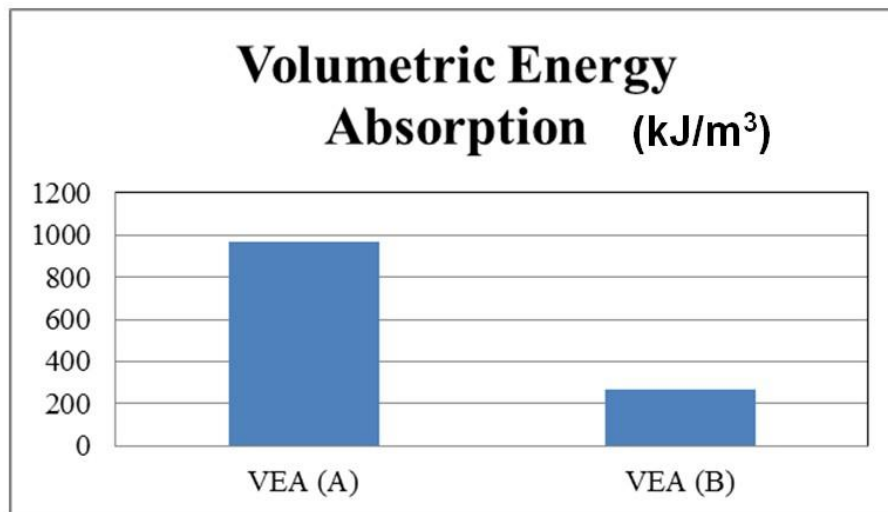
Fig. 9. Specific energy absorption SEA

Fig. 10. Volumetric energy absorption VEA

4.2.7 Crush force efficiency (cfe)

CFE is imperative vis-à-vis the performance evaluation of a structure in the event of a collapse/crush. It is also flanked by the average crushing load (P_{av}) and the maximum crushing load (P_{max}), derived from: (CFE= $P_{av / P_{max}}$). As shown in Fig. 11, the CFE for the cone (a) is higher than similar factors with cone (b).

4.2.8 Crush strain relation (C)

The crushing strain relation (C) allows an independent harmonized evaluation of the structural response from the material elastic

properties [3]. The higher the value of the C parameter, the higher the magnitude of energy absorbed by the structure, and the more optimal the design of the structure. Crushing strain relation is the percentage flanked by the crushing lengths to the total length of the specimens (C = (d_f-d_i) / h), where (d_f-d_i) are the final and the beginning of the crushing distance respectively, and h is the crushing distance. Fig. 12 illustrate the CSR for the two cones (a) and (b), it is obvious that the cone with non-upper sharp angle (a) has the highest value of CSR compared to the cone with an upper sharp angle (b).
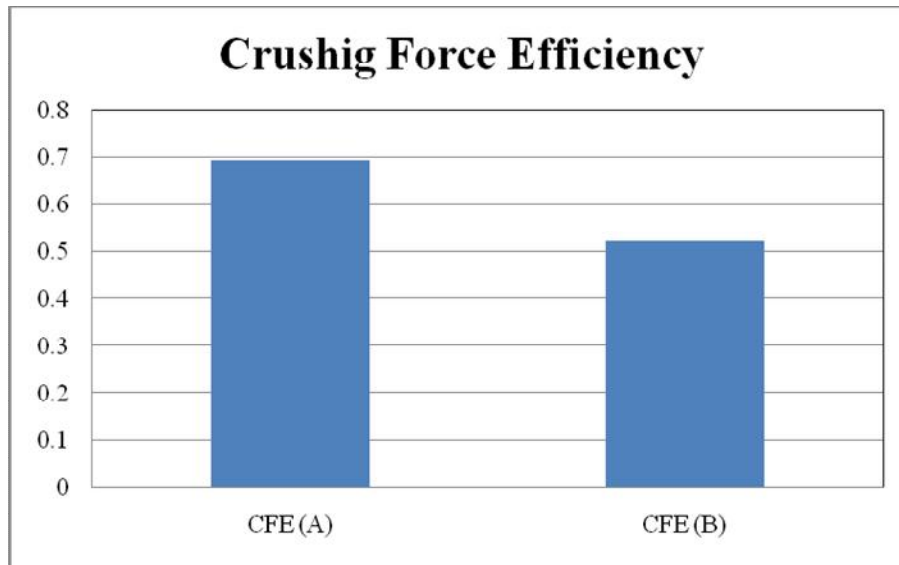
Crushig Force Efficiency

Fig. 11. Crushing force efficiency CFE

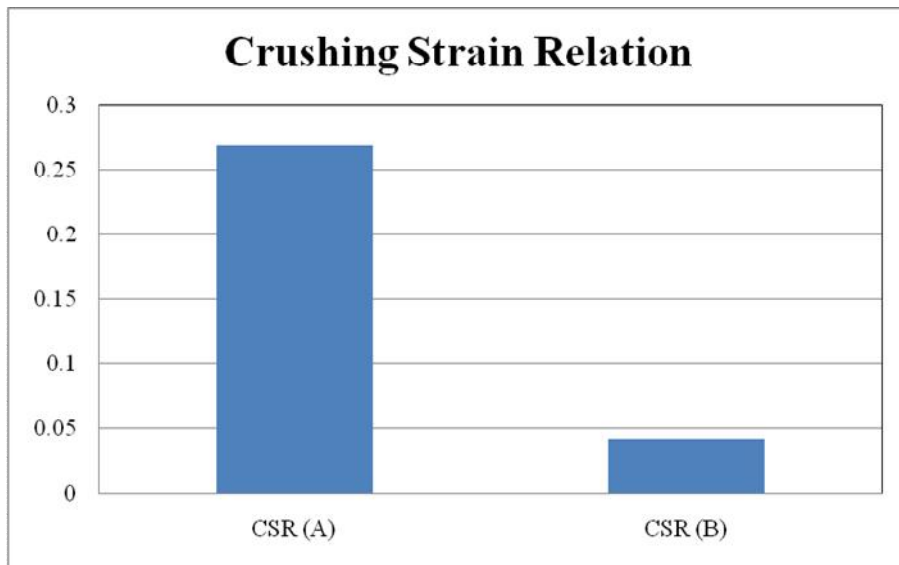## Crushing Strain Relation

Fig. 12. Crushing strain relation CSR

4.3 Failure Modes

There are some basic mechanical failure modes in the composite tubes after the initial elastic deformation, as it can be seen clearly in the Appendix. Matrix deformation and cracking occurs in all the specimens, and it is the first form of failure, which is an effective way of increasing the toughness of composites tubes and the total energy absorbed in the event of fracture. During the fracture process, the fibers may become separated from the matrix via cracks running parallel to the fibers; an event called debonding. In this process, the secondary bonds between the fibers and the matrix are broken. This occurs when the fibers are strong and the interface is weak. Delamination cracks occurs due to high shear stress in the matrix adjacent to the crack tip, as shown in Fig. 13. The crack may branch off and start running at the interface parallel to the plane of the plies. Fiber breakage will eventually occur when complete separations of the laminate occur, as shown in Fig. 13.
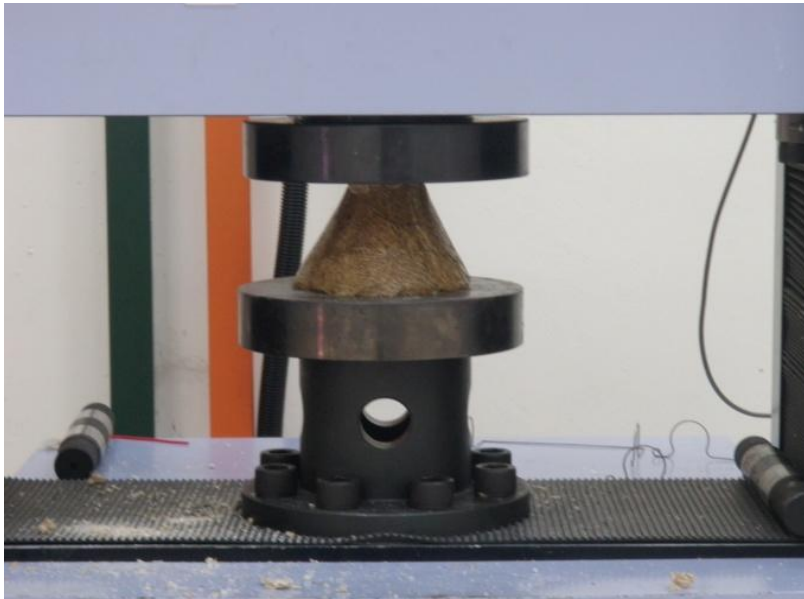
Fig. 13. Cracking failure

5. CONCLUSION

Specimens with two different geometries were fabricated (cone with non-sharp angle and cone with sharp angle). Cone with non-sharp angle (A) is the best at absorbing energy among all tubes, as mentioned in the previous section. Cones with non-sharp angle (A) also demonstrated better values of the initial failure load, maximum failure load, and crash force efficiency.

Based on the results that of this research, increasing the ability of the energy absorption depend on the specimen's geometry. The cone specimen, with a non-sharp angle (A), produced the highest value of energy absorption, specific energy absorption, and volumetric energy absorption, with recorded values of 0.344 kJ, 0.276kJ/kg, and 967.2 m^3, respectively. The specific energy absorption is crucial in reducing the weight of the automobile parts and optimizes fuel consumption.

ACKNOWLEDGEMENTS

COMPETING INTERESTS

Authors have declared that no competing interests exist.
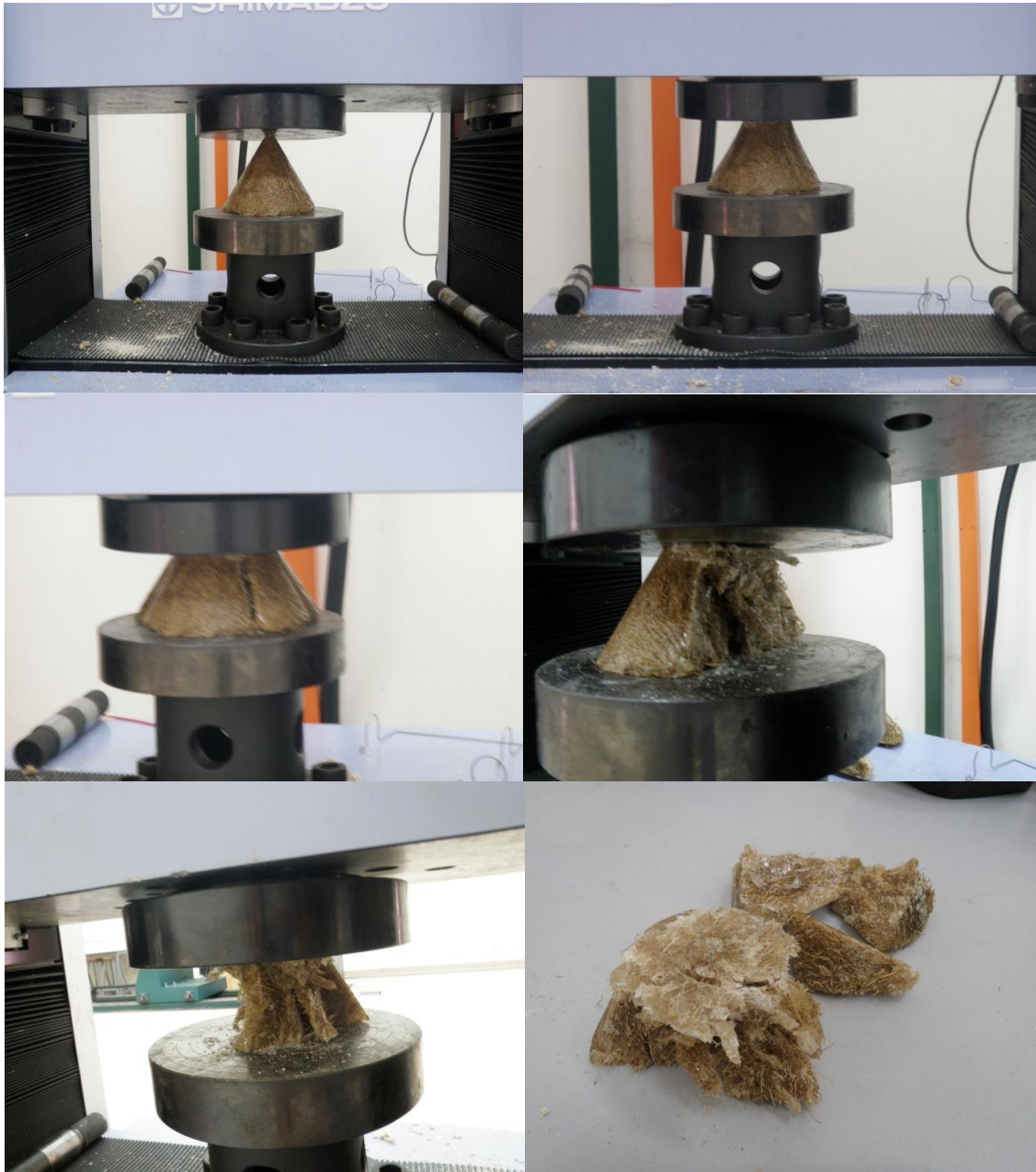
REFERENCES

1. Rafic Younes, Ali Hallal, Farouk Fardoun, Fadi Hajj Chehade, Comparative review study on elastic properties modeling for unidirectional composite materials, composites and their properties. Published by In Tech, Rijeka, Croatia. 2012;391-408.

2. Mallick PK. Fiber reinforced composites materials, manufacturing, and design, 3rd ed. Taylor and Francis Group. 2007;640. ISBN 9780849342059.

3. Fadhil Abbas Mahdi Al-Qrimli. The effect of composite tubes subjected to axial loading comparing with the number of layers and geometry. Australian Journal of Basic and Applied Sciences. 2011;5(11):607-616. ISSN 1991-8178.

4. Alexander E. Bogdanovich, Mehmet Karahan, Stepan V. Lomov, Ignaas Verpoest. Quasi-static tensile behavior and damage of carbon/epoxy composite reinforced with 3D non-crimp orthogonal woven fabric, Mechanics of Materials. 2013;62:14–31.

5. Darshil U. Shah, Peter J. Schubel, Mike J. Clifford, Peter Licence. Fatigue life evaluation of aligned plant fibre composites through S–N curves and constant-life diagrams. Composites Science and Technology. 2013;74:139–149.

6. Derek Hull, Cahn RW, Davis EA, Ward IM. An introduction to composite materials (Cambridge solid state science series), printed in Great Britain at the university press, Cambridge; 1990. ISBN 0 521 239911111 5.

7. Tao Yin, Min Zhi Rong, Jingshen Wu, Haibin Chen, Ming Qiu Zhang. Healing of impact damage in woven glass fabric reinforced epoxy composites. J Applied Science and Manufacturing. 2008;39:1479-1487.

8. Daniel, Denial Gay, Suong V. Hoa, Stephen W. Tsai, composite materials design and applications.CRC Press printed in united state of America; 2003. No. 1-58716-084-6.

9. Hakim S. Sultan Aljibori, Haidar F. Al-Qrimli, Rahizar Ramli, E. Mahdi, Faris Tarlochan, Chong WP. A comparative analysis of experimental and numerical investigations of composite tubes under axial and lateral loading. Australian Journal of Basic and Applied Sciences. 2010;48:3077-3085. ISSN 1991-8178.

10. Liang S, Gning PB, Guillaumat L, A comparative study of fatigue behaviour of flax/epoxy and glass/epoxy composites. Compos Sci Technol. 2012;72(5):535–43.

11. Saiphon Charoenphan. A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy (Engineering Mechanics), Computer Methods for Modeling the Progressive Damage of Composite Material Plates and Tubes, At the University Of Wisconsin-Madison. 2002;1-185.

12. Andrew Makeev. Interlaminar shear fatigue behavior of glass/epoxy and carbon/epoxy composites. Composites Science and Technology. 2013;80:93-100.

13. Mahdi E, Hamouda AMS, Sahari BB, Khalid YA. Effect of hybridization on crushing behavior of carbon / glass fibre/epoxy circular cylindrical shells. Journal of Materials Processing Technology. 2003;132:49-57.

14. Mertens KO, Bank LC, Plesha ME. Experimental studies of the progressive tearing failure of pultruded FRP composite tubes in flexure. American Society of 160 Composites, Proceedings of the 16th Annual Technical Conference, Virginia Tech, VA, September 9-12 CD-ROM; 2001.

15. Elgalai E, Mahdi AMS. Hamoudo BS. Sahari, crushing response of composite corrugated tubes to quasi-static axial loading. Composite Structure. 2004;66:665-671.

16. Lee KS, Kim SK, Yang IY. The energy absorption control characteristics of Al thin-walled tube under quasi-static axial compression. Journal of Materials Processing Technology. 2001;445–449.

17. Jose´ Daniel D. Melo, Andre´ Luiz S. Silva, John Edward N. Villena. The effect of processing conditions on the energy absorption capability of composite tubes. (Department of Materials Engineering, Universidade Federal do Rio Grande do Norte, Campus Universita´ rio, S/N, Natal – RN, 59072-970, Brazil). Composite Structures. 2008;82(4):622-628.

18. Giovanni Belingardi, Maria Pia Cavatorta *, Davide Salvatore Paolino. A new damage index to monitor the range of the penetration process in thick laminates. (Mechanical Engineering Department, Politecnico di Torino, Corso Duca degli Abruzzi, 24 – 10129 Torino, Italy), Composite Science and Technology. 2008; 68(13):2646-2652.

19. Hakim S. Sultan Aljibori, Rahezar Ramle, Haidar Al-qrimli, Chong WP. Quasi-static axial crushing of a ±45° fiber orientation angle with a different number of layers: Part 1. Experimental Study American Journal of Scientific Research ISSN 1450-223X. Euro Journals Publishing. 2009;4:72-84.

20. Maria V. Fernández, Marcelo F. S. F. de Moura, Lucas F. M. da Silva, António T. Marques. Characterization of composite bonded joints under pure mode II fatigue loading. Composite Structures. 2013;95: 222-226.

APPENDIX

A. 1. Crushing stages of the specimens

A. 2. Crashing stages of the specimen