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Effects of material and geometry on composite material behavior under compression

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Abstract: The use of light, cheap natural fibres instead of heavy ,expensive materials can reduce noise, increase strength, and reduce fuel consumption in automotive application. This research explores the potential for gradually replacing metallic materials with natural and hybrid fiber . The simplest and common technique hand layup is utilized to study the performance of fiber reinforced epoxy composite tubes under static compression to investigate the effect of using hybrid fibers on the failure mechanism. This study investigates the effects on stress and strain using different types of fibers after determining the tube load-displacement curves. A total of 24 samples are prepared at room temperature and tested at a constant speed of 1.5 mm/s using one resin type (epoxy) and two fiber types (Kevlar, jute). Two circular and square geometries of three heights (200mm, 250mm, 300mm), two circular diameters and two square sides are used to investigate the crashworthiness parameters. Replacing two layers of Kevlar fiber by two layers of natural jute fiber enhanced the crash worthiness parameters particularly, failure type. The hybrid jute / Kevlar accomplished desirable results, especially the circular tube.

الملخص:

يمكن أن يؤدي استخدام الألياف الطبيعية الخفيفة والرخيصة بدلاً من المواد الثقيلة والمكلفة إلى تقليل الضوضاء وزيادة القوة وتقليل استهلاك الوقود في تطبيقات السيارات. يستكشف هذا البحث إمكانية الاستبدال التدريجي للمواد المعدنية بالألياف الطبيعية والهجينة. تم استخدام أبسط تقنية الوضع اليدوي لدراسة أداء أنابيب مركب الإيبوكسي المقوى بالألياف تحت ضغط ثابت للتحقق من تأثير استخدام الألياف الهجينة على آلية الفشل. تبحث هذه الدراسة في الآثار المترتبة على الإجهاد والانفعال باستخدام أنواع مختلفة من الألياف بعد تحديد منحنيات إزاحة - حمل للانابيب. يتم تحضير ما مجموعه 24 عينة في درجة حرارة الغرفة واختبارها بسرعة ثابتة تبلغ 1.5 مم / ثانية باستخدام نوع راتنج واحد (إيبوكسي) ونوعين من الألياف (كيفلر ، جوت). تم استخدام شكلين هندسيين دائريين ومربعين من ثلاثة ارتفاعات (200 مم ، 250 مم ، 300 مم) ، قطرين دائريين وجانبين مربعين لفحص معايير مقاومة الصدمات. أدى استبدال طبقتين من ألياف كيفلر بطبقتين من ألياف الجوت الطبيعية إلى تحسين معايير جدارة الانهيار وخاصة نوع الفشل. حقق الجوت / الكيفلار الهجين نتائج مرغوبة ، بالأخص الأنبوب الدائري .

Keywords –Energy absorption; Hybrid fiber; Kevlar fiber; Jute fiber; Hand layup; Crash worthiness.

الكلمات المفتاحية: امتصاص الطاقة, ألياف هجينة, ألياف كيفلر, ألياف الجوت, تقنية الوضع اليدوي, جدارة الانهيار

Introduction

Thin-walled structures are widely used to absorb kinetic energy due to their high energy absorption performance, low cost and light weight. During collisions, they can dissipate large amounts of kinetic energy through splitting, bending, tension, plastic deformation, and fracture (Sofi, 2015; Ahmed et al., 2017). Improving the energy absorption and failure mode control of thin composite material and using them to replace thin steel columns in vehicle structural components can enhance occupant protection in crashes. Lu (2014) investigated the collapse mechanism of single circular thin-walled metal tube and multi-cell thin-walled tube under axial loads. Researchers tried to reduce the initial peak force and control the collapse behavior by inserting a trigger system into a thin-walled metal tube. The results revealed that the new design is a good energy absorber with low initial peak force and excessive energy absorption efficacy The results showed that the new design is an excellent energy absorber with low initial peak force and excessive energy absorption efficiency.

Thin-walled tube structures for energy-absorbing tubes are now made of a variety of materials, including metals, synthetic fibers, and hybrid composite fibers (Supian et al., 2018). The reinforcement fibers and matrix, as well as fillers, coupling agents, and coatings, are key elements of a fiber-reinforced composite material. Fillers are applied with specific polymeric matrices in order to reduce the cost and enhance the stability of their dimensions. The use of coatings and coupling agents enhances the moisture transfer between fibers and matrix, and promotes cross-bonding across matrix interfaces. Coatings and coupling agents stimulate a superior load transfer between the matrix and the fibers (Albahash and Ansari, 2017, Albahash and Ansari, 2018). Researchers are increasingly interested in finding new or substitute materials such as natural fiber from sustainable sources to construct high-performance hybrid composite energy absorption tubes. The hybridization can enhance the crashworthiness capability and the energy absorbed amount. Selecting compatible fibre types and ensuring that they meet the required properties is a significant challenge when developing hybrid composites (Supian et al., 2018). In order to address this issue, a number of studies have been conducted utilizing a variety of fiber types and geometries.

Palanivelu et al. (2011) examined how geometry, dimensions, and triggering mechanisms affected the progressive deformations of nine different geometrical shapes in small-scale composite tubes under quasi-static crushing. Ying et al. (2016) investigated the energy absorption ability of the fiber reinforced tapered square metal tube under axial loading, Moreover, they studied the fiber wrapped orientation impact, fiber layer thickness and the angle of tapered square tubes on the axially crushing force and energy absorption capability of the tube. Finite element simulation is used to validate the research method.

Epoxy resins are used widely in aerospace composites market, particularly the epoxy resins family Ge et al. (2018). Comparing to vinyl esters and polyester, epoxy has the maximum values of fracture toughness that could raise the fatigue performance of laminates. Additionally, the shrinkage of epoxies is moderately low around 3-4 %, while the vinyl shrinkage ranges between 5% to10% during cure (Mase et al., 2004). Hand lay epoxy-up, is modest and heavy labor technique for fabricating composites of low-volume. Reinforced material such as Kevlar, mat, glass, woven roving is located by hand in the open mould, and then the resin is sprayed or poured on it (Nagavally, 2017). Vacuum infusion (VI) is a good substitute to more conventional hand lay-up process regardless its high cost, since it is clean and perfect working environment. Additionally, VI achieves resin prepregs level which leads to increase the laminates strength and and decrease their weights (Albahash and Ansari, 2017). Material and structure errors affect the composite structures design. Materials error generally is attributed inexact analyzing of the distinct ply anisotropy nature, inexact damage evaluation in the material, and deficiency in recognizing the environmental sensitivities.

There is a need to a constant strain through the laminate thickness, wherein the level of stress that conveyed by each ply relys on the modulus of the laminate. Consequently, a noteworthy decay in internal shear stresses and stress could occur between the oriented plies at wide angle. Errors of design could occur in composite material with high thermal expansion anisotropic coefficient (Albahash and Ansari, 2017).

The specimen thickness effect, kinetic energy, and impact velocity were investigated by Murat and Rahman (2017) and the results indicated that the damage of impact depends on the thickness of plate and the energy of impact. The polymer matrix brittleness and the interlayer spacing between matrix and fibers may cause an impact damage pervasion to the whole structure. The seriousness of the various modes of damage relys on diversity parameters such as velocity, impactor mass, and the composite structure material orientation. Ismail (2015) investigated the axial crushing behaviour of steel/kenaf hybrid cylindrical tubes under compressive force. The steel tune length was100 mm of diameter 50 mm with different fibre orientations. The results revealed that kenaf yarn fibre around the steel tubes enhanced slightly the crushing perfo rmances. Hu et al. (2016) studied the the energy absorption of composite circular tubes made of woven glass cloth/epoxy under axial quasi static and impact crushing condition with various fiber orientations. the tube diameter is 50 mm with 125 mm height. The results revealed that the capability of energy absorption is improved by using suitable fiber orientation.

Goel (2015) investigated the deformation and the absorption of energy by numerical and simulation of varios thin walled square and circular tubes under axial crushing loading without and with aluminum foam. The square tubes filled with foam are modeled as shell while, the integrated visco-elastic plastic foam model is used to model foam substance in Altairs Radioss. It is observed that the multi-wall tube with foam alters the modes of distortion considerably leading to a substantial increase in energy absorption compared without and with foam. Furthermore, the multi-wall tube filled with foam reveals mixed deformation manners due to a stress wave propagation substantial influence. A total of three

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designs of square tubes and three circular tubes are verified under axial impact loading with various multi-tube structure without and with aluminum foam for both tubes types. The length of each tube is 300 mm with a thickness of 2 mm. Figure.1 displays the simulated deformation of the empty square and circular tubes, while Figure.2 displays the simulation of the square and circular foam filled tube, respectively (Goel, 2015).

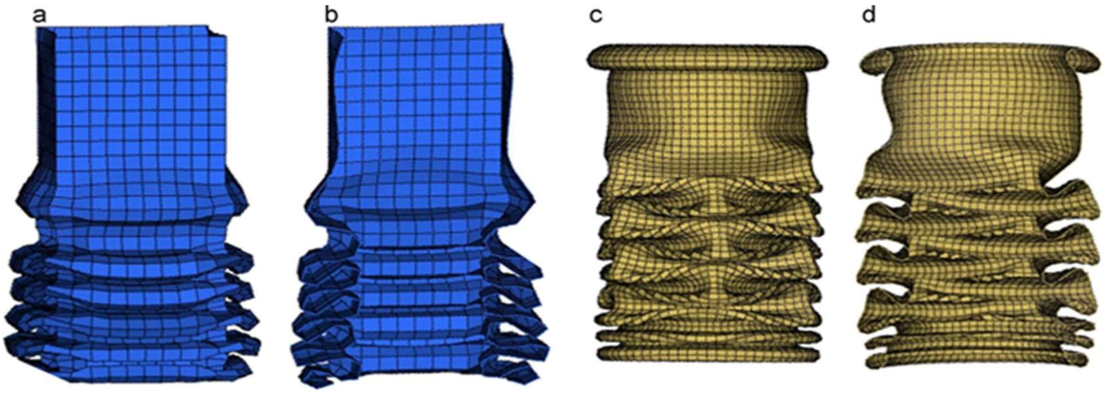

Figure 1: Simulated deformed-cut section single tube (Goel, 2015).

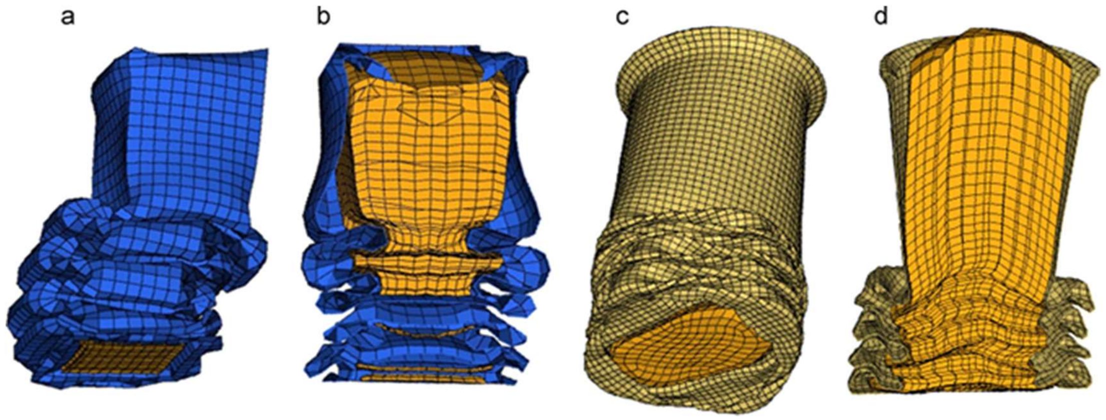

Figure 2: Simulated deformed and deformed-cut section single tube (Goel, 2015).

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In this study, circular and square cross section tubes made of various fiber types (glass, Jute, Kevlar, hybrid Jute fiber and Kevlar, hybrid Jute fiber and Glass) are exposed to axial quasi static crush test with orientations (0/90º). Three diverse heights are used; two sides length of square tube, and two diameters of circular to achieve optimal design. This paper is arranged as follows. Section II explains the research methodology. Section III discusses the results, and section IV introduces conclusions.

At present, the trends are starting towards mixing or replacing traditional support materials such as glass and carbon fiber with innovative composite materials like natural fibre-reinforced polymers (NFRP). Utilizing NFRP especially in most automobile applications is expected to increase due to several properties such as low weight, high strength, and resistance of corrosion (El-Shekeil et al., 2014). Natural fibres such as jute, hemp, bamboo, sisal, and kenaf have been studied and tested owing to their mechanical properties and their possible usage in composite materials.

Patil, Shashidhar S., et al.(2017) Studied the behaviour of hybrid Kevlar/jute fiber with epoxy in order to decrease the thickness and reduce the cost by using the metal.the hybrid samples of this research is fabricated using hand layup technique with three thickness 2,3,4 mm.three tests have been used (TENSILE, COMPRESSION, BENDING), the result shows that 3mm recorded the best results for all tests . The kevlar to jute ratio increases the specimen's bending strength, compression strength, tensile strength, and reduces specimen weight. Kevlar percentages are higher, so epoxy percentages are lower, and the specimens are less expensive

Naik, S., Dandagwhal, R. D et al.(2020).wrote a research about An aramid fibre, Kevlar is widely used in the defense, aerospace, biomedical, and automobile industries. A focus has been placed on characterization and structural features of Kevlar fiber reinforced composites. Kevlar fibre reinforced composites for ballistic applications are an important area of research related to it.

II. Experimental Setup

The hand layup technique is used to fabricate the samples. The reinforced material like woven roving or mat, is positioned by hand in the open mould and then poured and sprayed by the resin. Once the first face is comple, the fiber rolling is sustained round the mandrel. To guarantee the mold dryness, it was left 24 hours. Lastly, the fabricating tube is ready for he following process. Similar procedure is utilized for fabricating hybrid tubes. Then, the tubes are cut into diverse heights (200mm, 250mm, 300mm) by a cutting machine. The samples are weighed and labeled before and after crushing to identify the difference after the crash. L1, L2, and L3 characterize specimens lengths (200mm, 250mm, 300mm) respectivily, J denotes jute fiber, K refers to the Kevlar fiber and H1 signifies hybrid fibers of (1 Kevlar +2 Jute) . The diameters of circle are represented by C1 (50mm) and C2 (100mm). The square side lengths are represented by S1 (50mm) and S2 (100mm). Since one epoxy type was utilized, the matrix (epoxy) was not represented.Then a quasi static load is placed on the specimens using a computer-controlled servo-hydraulic INSTRON machine, system ID (4469 H2005) with scale load 100 kN to perform crushing test at 15 mm/minute speed.

III. Results and Discussion

A. Load Displacement and Failure Modes

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when the specimen cannot resist the applied load, a structure failure occurs. Tube crushing has been investigated in several failure modes. The photos that taken through the crushing test assisted to study the failures, which happen in each specimen. The observed failure modes are:

1) Kevlar fiber

a. Circular Tube

The variation in the curve of load-displacement of the circular Kevlar fiber /epoxy with 50mm diameter and 300mm length (C1KL3) is displayed in Figure 3. The loads is increased suddenly from 0kN until it reached 10.662kN at 0.9922mm, this load denotes the primary failure load where the pre-crushing zone terminated. Then the load is diminished suddenly due to buckling failure. After that the load starts to rise and fluctuate due to splaying failure and decreases significantly due to splitting and buckling failure at the tube upper end until the crushing test end.

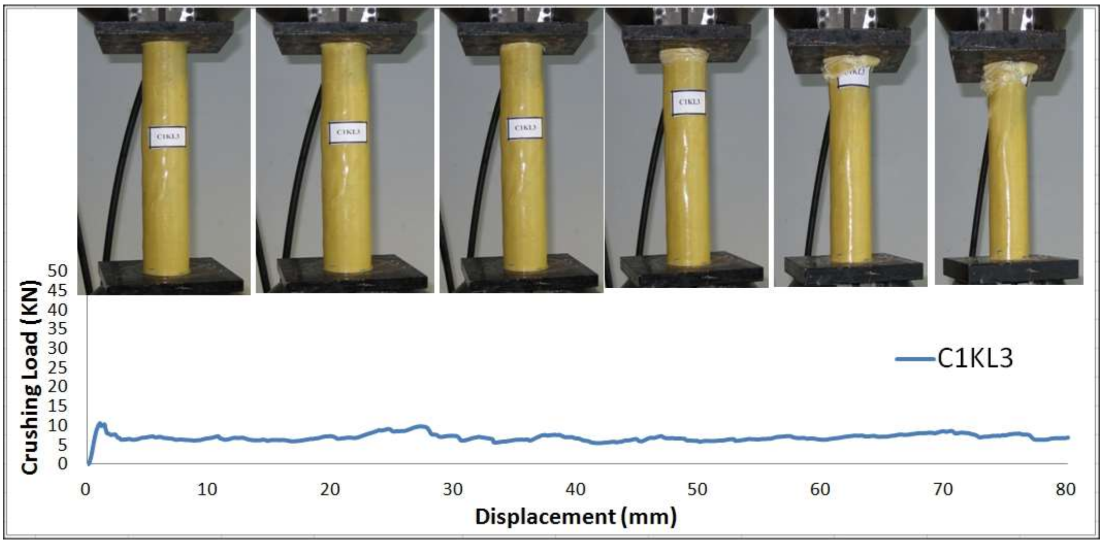

Figure 3: The load-displacement curve of the circular Kevlar fiber /epoxy with 50mm diameter and 300mm length (C1KL3)

The curve of load displacement for circular Kevlar fiber/epoxy of 100mm diameter and 300mm height (C2KL3) is displayed in Figure 4. It can be noted that the pre–crushing zone starts with increasing the load suddenly from 0kN until it reaches 8.853kN at 1.364mm, this value signifies the initial failure and maximum crushing load at which pre-crushing ended. The decline is acute due to the buckling at the tube upper end. Then the structure is recovered from the failure due to splaying, and the load is raised until it reaches 6.024kN at 54.2mm displacement. Therafter, the load diminishes due to the buckling failure at upper end until reaching around 65mm, then fluctuates and decreases due to buckling and splitting at the tube upper end.

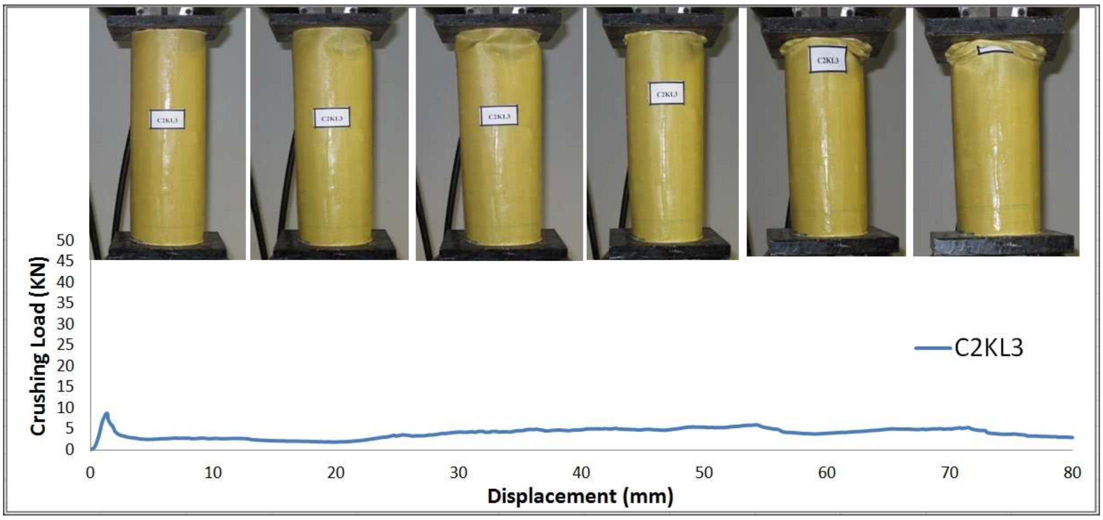

Figure 4: The load displacement curve for circular Kevlar fiber/epoxy of 100mm diameter and 300mm height (C2KL3)

b. Square Tube

Figure 5. illustrates the curve of load displacement of square Kevlar fiber/epoxy of 100mm and 50mm sides length and 300mm height (S1KL3). It can be observed that the load is raised sharply until reaching the primary failure and maximum load of 11.43kN at 1.864 mm. Then the load declines significantly due to multiple failure buckling and micro cracking failure. With gradual buckling action, longitudinal cracking occurrs at the side, and the load continues to decrease til the test end.

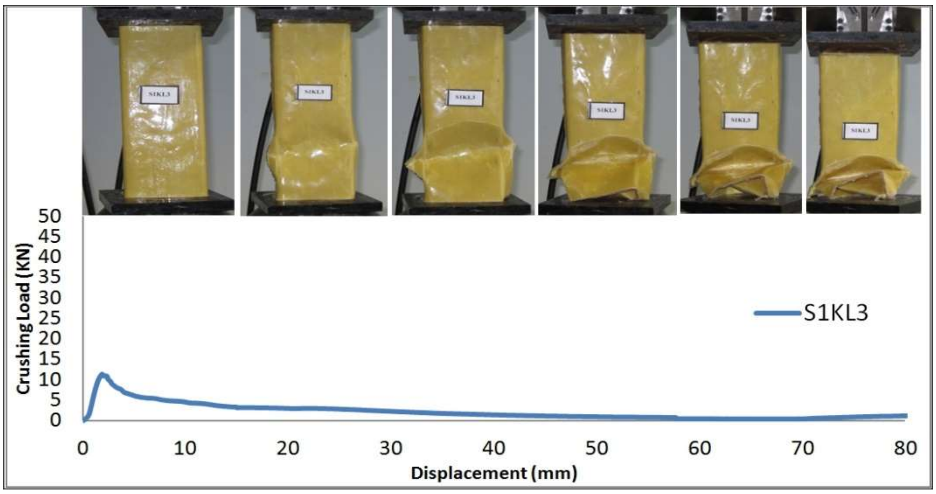

Figure 5. The load displacement curve for square Kevlar fiber/epoxy of 100mm and 50mm sides length and 300mm height (S1KL3).

The curve of load displacement for square Kevlar fiber/epoxy of 100mm and 100mm sides length and 300mm height (S2KL3) is illustrated in Figure 6. It reveals that the load is increased steadily from

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0kN until reaching the initial failure and maximum load of 4.334kN at 5.435mm. Then the load is decreased significantly until reaching 25mm displacement due to the buckling failure at the upper of the tube, then continued to decrease until the test end.

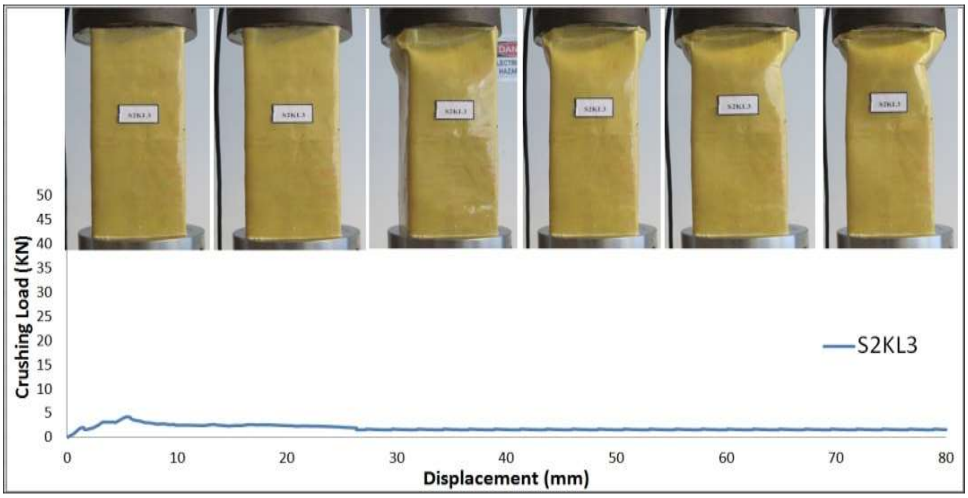

Figure 6. The load displacement curve for square Kevlar fiber/epoxy of 100mm and 100mm sides length and 300mm height (S2KL3)

3) Hybrid Fiber

Hybridization of fiber (one layer of Kevlar + 2 jute layers) affectes the failure modes and the behavior of load displacement curve. Micro cracking, buckling, delaminating, splaying and splitting failures modes are common behaviours of hybrid fiber tubes.

Circular Tube

Figure 7. illustrates the curve of load displacement of circular hybrid (jute-Kevlar) fiber/epoxy of 50mm diameter and 300mm height (C1H1L3). The load increases dramatically from 0 kN until it reached 28.86 kN at 6.535 mm displacement, Post-crushing zone started with dropping the load sharply from the maximum to 9.79 kN at 7.714 mm due to buckling failure on upper end tube. The structure resisted the crushing load causing an increase in the load until it reached 28 mm, then the load dropped slightly due to the continuation of buckling and splitting. The load was increased due to splaying failure and dropped dramatically due to splitting and delamination failure.

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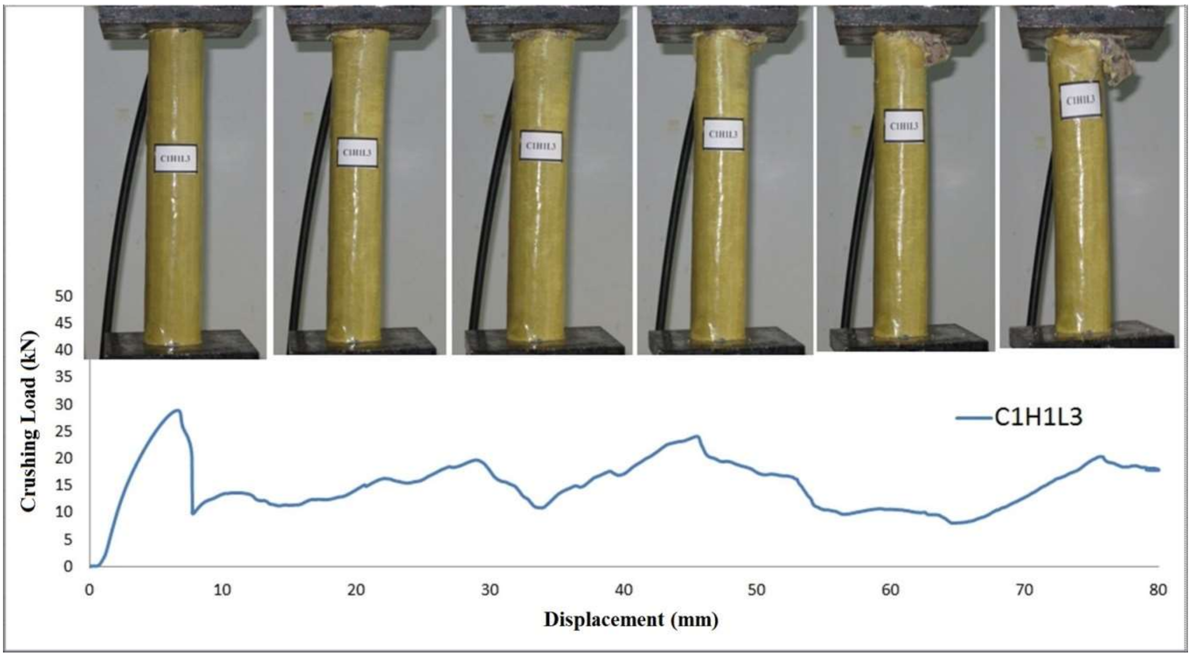

Figure 7: Circular hybrid (jute-kevlar) fiber/epoxy crushing process.

Square Tube

The curve of load-displacement of the square (jute-Kevlar) fiber/epoxy of (100mm , 50mm) width and 300mm height (S1H1L3) is shown in Figure 8. The load increased sharply until it reached the initial failure and maximum load of 50.1 kN at 3.39 mm. The load was decreased in three stages. In the first stage, it decreased due to the buckling failure from maximum load until it reached 35.902 kN at 5.499 mm. In the second stage, the load decreased due to continuous buckling with cracking failure at lower half of the tube until it reached a 7.052 mm displacement. The third stage involved a decrease in the load with a slight fluctuation until it reached 54.603 mm displacement due to delamination and breakage, which occurred at the middle of the of the specimen. The test was continued until the end of the test at 800 mm.

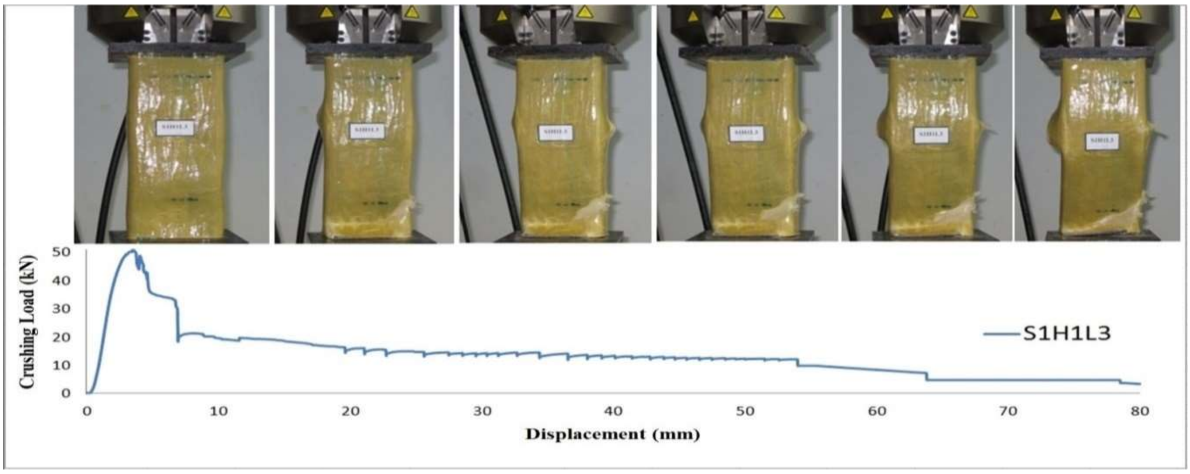

Figure 8: Square hybrid (jute-Kevlar) fiber/epoxy crushing process

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B. Absorption Parameters of Crushing Energy

The area beneath the curve of load displacement shows the elastic and plastic zone that denotes the total energy absorption (TEA) of a tube through crushing which can be gained by load displacement curve integration. The absorption of crushing energy can be computed based on several parameters such as EA (kJ),SEA (kJ/kg) that introduced in the following:

Specific Energy Absorption

Specific energy absorption (SEA) is a significant parameter. It can be determined by the following equation (Aljibori et al., 2008) :

$$SEA= \frac{EA}{CM} \tag{4}$$

Where EA is the energy absorption in kJ and CM is the crushing mass (kg). The SEA can be improved by utilizing materials with highest energy absorption and lowest mass. Figure 9 demonstrates the square (S) and circular (C) tubes SEA.

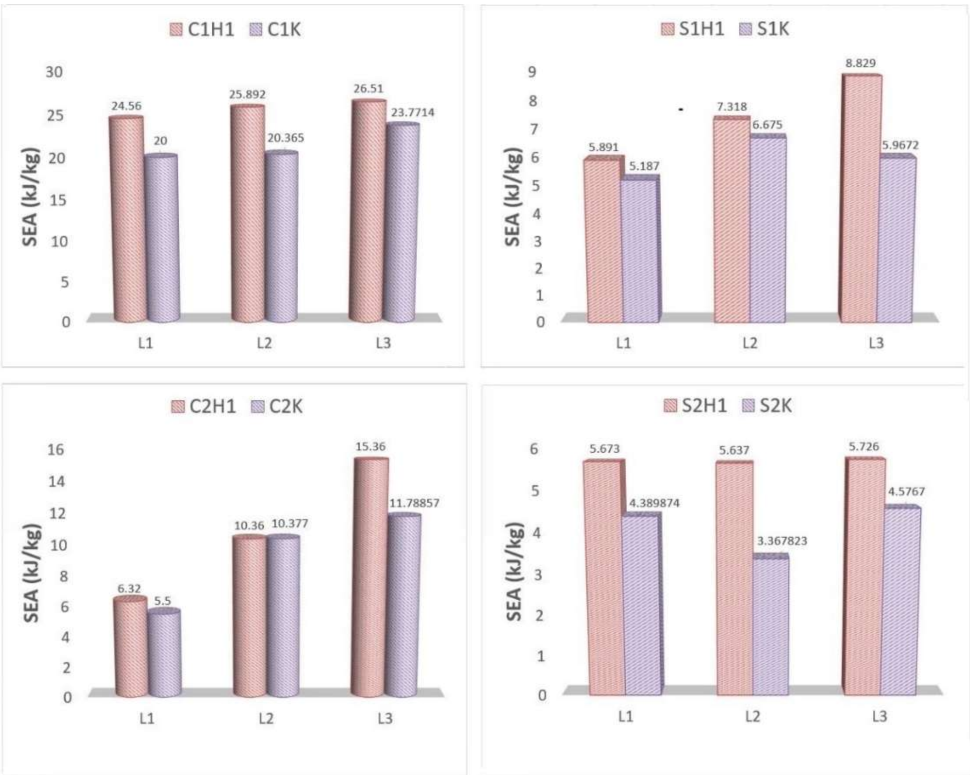

Figure 9: SEA for circular and square tubes

Figure 9 demonstrates that best and maximum stability outcomes are attained by the hybrid H1 (Kevlar + Jute) fibre. The larger circular tube (C2H1L3) attained 15.36 kJ/kg and the smaller circular tube (C1H1L3) attained 26.51 kJ/kg,. The square hybrid H1reveals similar results where the small square tube (S1H1L3) maximum SEA is 8.829 kJ/kg, and (S2H1L3) attained 5.726 kJ/kg. The hybrid H1

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attained finest results due to splaying failure that increases the SEA and the EA. The breaking failure happened in all square tubes particularly Jute fiber tubes.

2) crush force efficiency : The crush force efficiency (CFE) represents the ratio between the average failure load Favr and the max failure load Fmax. Crush force efficiency can be calculated using the equation. (Aljibori et al., 2008) :

$$SEA= \frac{F_{avr}}{F_{max}} \tag{5}$$

Specimen ID kevlar	CFE	Specimen ID hybrid	CFE
C1KL1	0.5207	C1H1L1	0.5136
C1KL2	0.5027	C1H1L2	0.5075
C1KL3	0.5598	C1H1L3	0.5273
C2KL1	0.2906	C2H1L1	0.1837
C2KL2	0.4929	C2H1L2	0.293
C2KL3	0.4514	C2H1L3	0.5005
S1KL1	0.3294	S1H1L1	0.2503
S1KL2	0.4373	S1H1L2	0.168
S1KL3	0.1846	S1H1L3	0.1596
S2KL1	0.4889	S2H1L1	0.4169
S2KL2	0.3787	S2H1L2	0.3659
S2KL3	0.4603	S2H1L3	0.2561

Table 7: Crash force efficiency

The table 1 shows that sligt difference between the kevler and the hybrid for the 300mm hight but the enhancement in energy absorption as shown in figure where C1KL3 recorded CFE of 0.5598 and C1H1L3 recorded CFE of 0.5273 while C1H1L3 recorded SEA 26.51 kJ/kg which is higher than all samples.

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IV. Conclusions

Twenty four specimens made of Kevlar and jute fiber , circular and square geometries have been crushed statically to study the response of SEA and CFE on crashworthiness parameters. According to the results, we concluded that:

1) The circular geometry attained better results than the square geometry in both load displacement curve and failure modes.

2) Fiber Hybridization enhanced all crash worthiness parameters considerably,which is performed by replacing two layers of natural jute fiber .

3) The results indicated that the 30cm height (L3) with (C1,S1) recorded better results than the 20cm and 25cm heights when comparing to hybrid fibre.

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