Thin-walled composite tubes using fillers subjected to quasistatic axial compression

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Haidar F. AL-Qrimli*[1]
[1]Department of Mechanical Engineering, Curtin University,
CDT 250 98009, Miri, Malaysia

Fadhil A. Mahdi [2]
[2]Department of Electrical Engineering, University of Baghdad,
Jadriyah, Baghdad, Iraq

Firas B. Ismail [3]
[3]Deptment of Mechanical Engineering, Universiti Tenaga Nasional
43000 Kajang, Selangor, Malaysia

Ibrahim S. Alzorqi [4]
[4]Department of Chemical & Environmental Engineering
The University of Nottingham, 43500 Semenyih, Malaysia

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

Abstract. It has been demonstrated that composites are lightweight, fatigue resistant and easily melded, a seemingly attractive alternative to metals. However, there has been no widespread switch from metals to composites in the automotive sector. This is because there are a number of technical issues relating to the use of composite materials that still need to be resolved including accurate material characterization, manufacturing and joining process. The total of 36 specimens have been fabricated using the fibre-glass and resin (epoxy) with a two different geometries (circular and corrugated) each one will be filled with five types of filler (Rice Husk, Wood Chips, Aluminium Chips, Coconut Fibre, Palm Oil Fibre) all these type will be compared with empty Tubes for circular and corrugated in order to comprehend the crashworthiness parameters (initial failure load, average load, maximum crushing load, load ratio, energy absorption, specific energy absorption, volumetric energy absorption, crushing force efficiency and crush strain relation) which are considered very sufficient parameters in the design of automotive industry parts. All the tests have been done using the "INSTRON Universal machine" which is computerized in order to simply give a high precision to the collection of the results, along with the use of quasi-static load to test and observe the behaviour of the fabricated specimens.

[1] Haidar F. AL-Qrimli, Department of Mechanical Engineering, Curtin University Sarawak

1. Introduction

These Today, fibre reinforced composites used in a variety of structures, ranging from space-craft to buildings and bridges. This wide use of composites has been facilitated by the introduction of new materials, improvements in manufacturing processes and developments of new analytical and testing methods. Their unique integration of mechanical properties along with their customized fabrication provides the building blocks of our modern infrastructure. From aerospace to the automotive industry, from household products to optical devices, composite materials with unique characteristics are moving aggressively [1-5]. Although the fibre reinforced materials primarily comprise a reason system plus a fibrous reinforcement, other components are frequently added to produce decorative effects, aid handling, and improve moulding characteristics and cured properties. Fillers are used to modify the properties of resin systems either during processing or in the cured state or perhaps both. Often, the primary reason for adding the filler is to reduce the cost of the system; however, invariably, other properties are modified as well. To maximize the benefits of using filler, the correct type and grade needs to be chosen with care, taking into account the modelling process and end use of the moulding. Almost any powdered material may be used as filler; indeed, such materials as crushed egg shells and ground coconut shells have been used. The most common fillers, however, are those obtained from the natural deposits such as chalk slate, quartz or clay. These may be wet or dry ground to produce suitable powders, or subjected to chemical treatment to purify them. Other fillers used include metal powders, and glass spheres and flakes [6-10]. . Mallik, 2008 [11] give Examples of natural fibres are jute, flax, hemp, remi, sisal, coconut fibre (coir), and banana fibre (abaca). All these fibres are grown as agricultural plants in various parts of the world and are commonly used for making ropes, carpet backing, bags, and so on. The components of natural fibres are cellulose microfibrils dispersed in an amorphous matrix of lignin and hemicelluloses. Depending on the type of the natural fibre, the cellulose content is in the range of 60–80 wt% and the lignin content is in the range of 5–20 wt%. In addition, the moisture content in natural fibres can be up to 20 wt%. Menachem, 2007 [12] said that the initial structure of a cotton fibre is determined by biosynthesis, a series of processes that are subject to substantial influence during fibre growth. After the boll opens, there are many factors that affect the structure, from the weather before the fibre is harvested to the industrial processes such as mercerization. Cotton fibres are composed mostly (e.g., 95%) of the long-chain carbohydrate molecule, cellulose (the sugar of cell walls). A large number of impact tests have been carried out on woven-roving and chopped-strand-mat glass reinforced; hand laid-up polyester laminates of different thicknesses and weights. Deflection, force, absorbed energy and damaged area results for these tests have been presented and compared, and the failure modes described. A simple analysis assuming shear-dominated defection gave good correlations with the experimental data. Prediction of the damaged area proved to be more difficult, although some correlation was seen. Further investigation into the nature of the damage is required (Sutherland et al. 1999) [13]. Collapse behaviour of aluminium thin conical frusta with shallow spherical caps (shells of combined geometry) is studied both experimentally and numerically. These shells were of four different thicknesses and were subjected to axial compression between two rigid platens under both quasi-static and impact loading (Gupta et al. 2008) [14]. The bending fatigue behaviours were investigated in glass fibre-reinforced polyester composite plates, made from woven-roving with four different weights, 800, 500, 300, and 200 g/m2, random distributed glass-mat with two different weights 225, and 450 g/m2 and polyester resin (Raif et al. 2007) [15]. Experimental investigations were carried out in order to study the effects of segmentation on the crushing behaviour of quasi static laterally compressed composite tubes. Load–deformation curves and failure mechanism histories of typical specimens are presented and discussed (Abosbaia et al. 2004) [16]. In this paper specimens made of glass fibre/epoxy have been experimentally fabricated with two different geometries (circular and corrugated). Five types of fillers

have been used namely; Rice Husk, Wood Chips, Aluminium Chips, Coconut Fibre and Palm Oil Fibre.

2. Fabrication of Tubes

Woven roving glass fibre E-600 has been used mixed with epoxy (EP-A215C1) and hardener (EP-B215) to fabrication the specimens, by mixing the epoxy and resin by weight 100 for the epoxy and 20 for the resin (see Figure 1). All the specimens have been fabricated in the same way by using hand lay-up method with 0/90º fibre orientation angle. Four types of fillers used (Rice husk, Wood Chips, Aluminium Chips and Coconut fibre); Figure 2 shows the type of filler that used in this paper. Wood has been chosen as mandrel. There are two types of mandrels. The first one has a circular cross sectional area with a 10 cm diameter and length 30 cm, while the second mandrel has a corrugated cross sectional area with a 10 cm diameter and 30 cm length as shown in Figure 3. The procedure of Hand lay-up method is shown in Figure 4. After fabricating the specimens, than cut them to the desired dimension. The next step will be the filling process. The cross sectional surfaces (top and bottom) of the specimen flattened to distribute the load on the whole top and bottom surfaces. Firstly, one side of the specimens covered by very light material to reduce the weight of the specimen, sticker tape used to cover the specimen by sticking it from one side to another as shown in Figure 3. For each type three specimens fabricated to insure superior results. By subtracting the weight of the specimen before the filling process and after the filling process, the weight of the filler can be found. The density of the filler calculated by dividing the mass of the filler to the volume of the specimen, Table 1 shows the volume and mass for the tubes.

The crushing test had been performed on all the specimens by using an electrical computer-controlled servo-hydraulic INSTRON machine type 4469. The speed was constant with 15 mm/min and the maximum crushing displacement at 90% from the original length which is 100 mm. The specimens were axially crushed between two steel flat platens; one is static and the other one moving with constant speed. The type of failure modes has been observed such as debonding, delamination, fibre pullout and matrix cracking.

Figure 1. Fibre glass E-600 and Epoxy/ hardener containers.

Figure 2. Different fillers used.

Figure 3. Circular and corrugated wooden mandrels. Preparing specimens to add the fillers.

Figure 4. Hand lay-up method.

Table 1. Mass and Volume for the Tubes

Specimen ID	M(Kg)	V (m^3)	DI	DF	Thickness(m)	Length (m)
CUE	0.127	0.000749	0.001730	0.09	0.00251	0.1
CUR	0.201	0.000749	0.001608	0.07415	0.00251	0.1
CUW	0.197	0.000749	0.001857	0.08338	0.00251	0.1
CUC	0.202	0.000749	0.003220	0.09	0.00251	0.1
CUAL	0.295	0.000749	0.001224	0.07188	0.00251	0.1
CUP	0.213	0.000749	0.003220	0.08804	0.00251	0.1
COE	0.141	0.000785	0.002228	0.09	0.00285	0.1
COR	0.2	0.000785	0.001848	0.09	0.00285	0.1
COW	0.203	0.000785	0.002229	0.08995	0.00285	0.1
COC	0.191	0.000785	0.002256	0.09	0.00285	0.1
COAL	0.313	0.000785	0.001730	0.09	0.00285	0.1
COP	0.227	0.000785	0.001983	0.09	0.00285	0.1

3. Results and Discussion

3.1. Load Displacement Relations

Load-displacement curve can be classified into two main zones the first zone represent the elastic behaviour stage which is called the pre-crushing stage of the specimen then the initial failure will observed (Pi), after the initial failure the plastic zone starts and it's the second zone of the load displacement curve and it's called the post-crushing stage. The load displacement curve shows the maximum load (P_{max}), average load (P_{av}) and the displacement of the failure. From here, the other crashworthiness parameters can be also calculated. Table 2 shows a comparison between the specimens. The empty corrugated tube fluctuated in the same range of the crushing load. And for the corrugated tubes which are filled with filler material can recognize that the load displacement curve increase gradually to the end (See Figure 5 and 6).
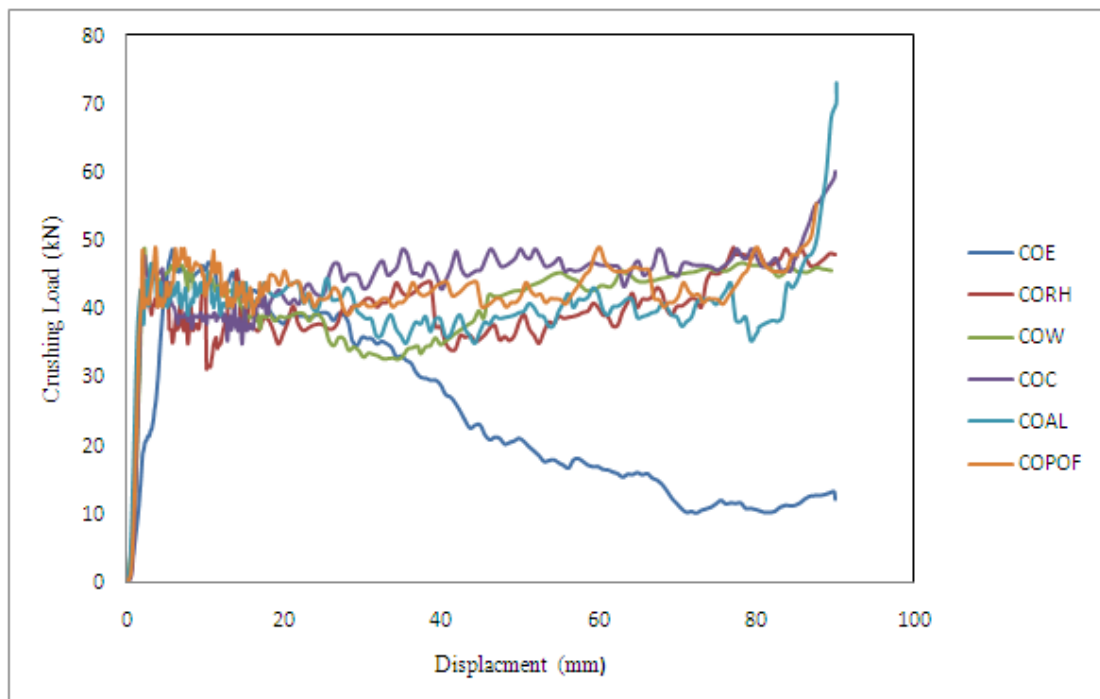

Figure 5. Load displacement curves of the circular specimens with different fillers.
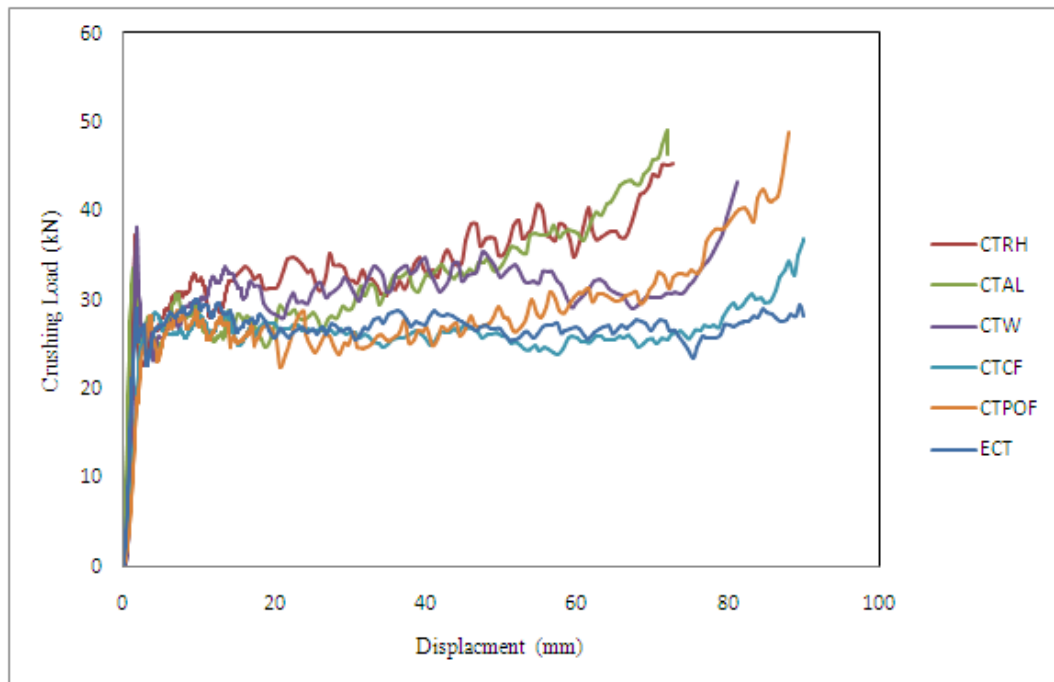
Figure 6. Load displacement curves of the corrugated specimens with different fillers.

3.2. Crashworthiness parameters
The crush worthiness parameters indicate how well the specimen absorbs the energy.

3.2.1 Initial Failure Load (P_i)
Initial failure load is the first peak in the curve which represents a first crush failure. This point lies between the pre-crushing load (elastic) zone and post-crushing load (plastic) zone. In the elastic zone, the structure has the ability to return to its original length without any deformation, but after this point (P_i) the specimen enters the plastic zone and the specimen will be deformed permanently. The corrugated tubes which are filled with Rice Husk (RH) and aluminium chips (AL) have the same range of P_i which is about 48 kN. The corrugated tube with wood chips has the maximum value. There are very slight differences between corrugated tube with rice husk, the circular tubes with palm oil fibre, coconut fibre and the empty circular tube which in turn has the minimum value of initial failure as shown in Table 2.

3.2.2 Maximum Crushing Load (P_{max})
The maximum crushing load is the maximum load that the specimen can endure during the crushing process. The maximum crushing load should be obtained for all specimens, it is very important in the design because it's the maximum amount of the load that can be carried by the composite tube. Figure 7 shows the maximum load for the corrugated tubes which are filled with five different fillers and the empty corrugated tube, totally 6 different types. slight difference in P_{max} can be recognized clearly especially the difference between the corrugated tubes which are filled with rice husk (RH), wood chips (W), aluminium chips (AL) and the corrugated tube without filler. The corrugated tube which is filled with coconut fibre produced the maximum value of P_{max} as shown in Table 2. Figure 8 shows the difference in the maximum load for the circular tubes which are filled with five different types of fillers and the tube without filler. The circular tube which is filled with coconut and the empty circular tube have the lowest maximum load endured. It is clear that the circular tubes which are filled with rice husk, aluminium chips and palm-oil fibre have the maximum value for maximum load, and the

circular tubes which are filled with rice husk have the maximum load between the bigger one and smaller one.
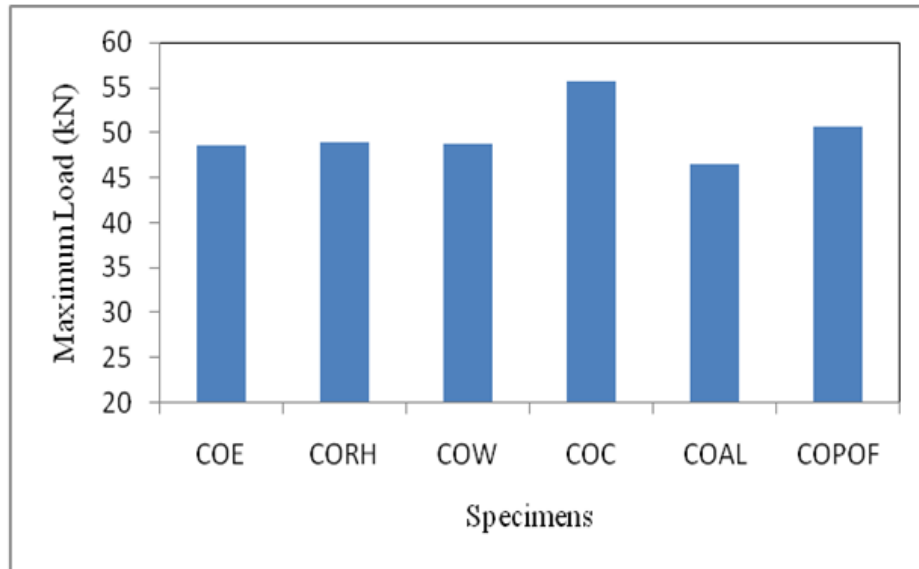
Figure 7. Maximum Loads for Corrugated Tubes
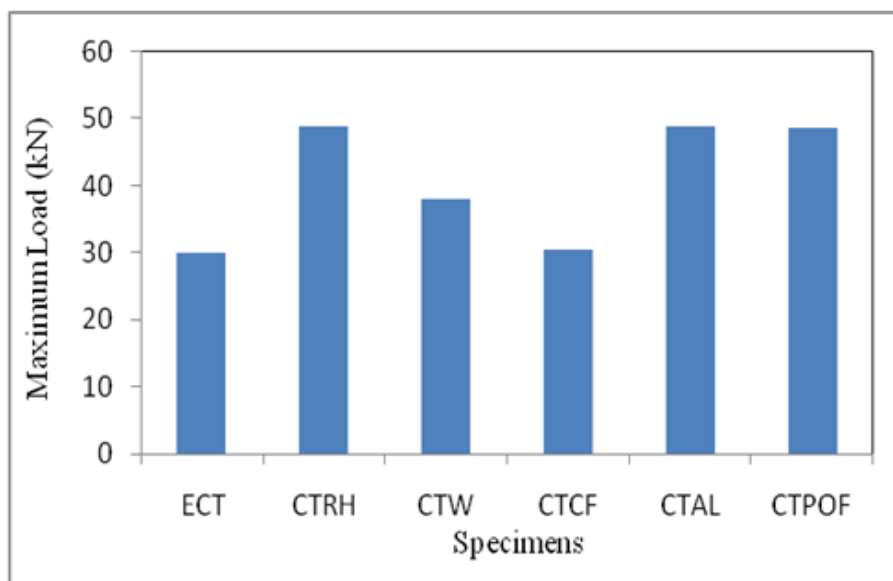
Figure 8. Maximum Loads for Circular Tubes

3.2.3 Average Crushing Load (P_{av})
The average crushing load is the mean of all crushing loads during the crushing process in the plastic zone. The empty tube has the lowest value of average crushing load P_{av}. A very large difference of P_{av} is found between the corrugated tubes which are filled with filler and the empty corrugated tube. The corrugated tube which is filled with rice husk has the lowest value of P_{av} of the corrugated tubes with fillers, the maximum P_{av} for the corrugated tubes which are

filled with coconut fibre and palm-oil fibre. The circular tube which is filled with coconut fibre has the lowest value of P_{av}, the corrugated tubes which are filled with palm oil fibre and the empty tube have smaller values of P_{av} but they are greater than the circular tube which is filled with coconut fibre. The circular tubes which are filled with aluminium chips and wood chips have large values of P_{av}. The maximum value of P_{av} is circular tube filled with rice husk.

3.2.3 Load Ratio (LR)

Load ratio (LR) can be defined as the ratio between the initial crushing and the maximum crushing during the process. This parameter is very important to study the failure modes during the crushing process. If the load ratio is less than 1 it means the structure is initially crushed by a matrix failure, if the load ratio equals 1, it means that the structure is initially crushed in ultimate failure mode. The results show that the empty corrugated tube has the lowest LR. This value is increased for the corrugated tube with coconut filling.

3.2.3 Total Energy Absorbed (TEA)

Total energy absorbed is the energy that can be absorbed from the structure and this value can be obtained from the area under the load displacement curve. The empty corrugated tube has the lowest energy absorption; very large differences can be recognized between the empty corrugated tube and the corrugated tubes which are filled by filler material. The corrugated tube which is filled with wood chips has the maximum energy absorption, and there are very slight differences between the filled corrugated tubes as shown in Table 2.

3.2.3 Specific Energy Absorption (SEA)

Specific energy absorption (SEA) means the energy absorption divided by the weight. It is one of the most important parameters because weight is an important factor in reducing the load and this leads to reduced fuel consumption for cars, motorcycles and airplanes. The corrugated tube which is filled with aluminium chips has the lowest value of specific energy absorption (SEA) because it has a relatively heavy weight. When it is compared with the other fillers, for corrugated tube with coconut fibre has the maximum specific energy when compared with other filler materials.

3.2.3 Volumetric Energy Absorption (VEA)

Volumetric energy absorption (VEA) is the ratio between the energy absorption and the volume of the structure. The corrugated tube filled with palm-oil fibre has the largest value due to high efficiency in absorbing the energy, while the empty corrugated tube had the lowest value of (VEA) because it is the least efficient type in absorbing energy. The other filled corrugated tubes had varied values but close to one another. The values of the (VEA) for all types of circular tubes varied slightly, but also it shows that the circular tube filled with wood chips had the largest value of (VEA), while the circular tube filled with aluminium chips had the smallest value of (VEA). The other filled circular tubes along with the empty tube had similar values of (VEA) between one another.

3.2.3 Crush Force Efficiency (CFE)

Crushing Force Efficiency is the ratio between the average load and the maximum load (P_{av}), (p_{max}) respectively. The circular tube with palm oil-fibre filler has lowest crushing force efficiency, of the tubes which are filled with filler materials, the corrugated tube with coconut

fibre has the maximum crushing force efficiency but the empty corrugated tube has the maximum value of crushing force efficiency as shown in Table 3.

Table 2. Load Parameters.

Specimen	P_i	P_{max}	P_{av}	LR
		kN		kN / kN
ECT	28.90	30.02	27.31	0.962692
CTRH	37.20	48.89	32.5	0.760892
CTW	38.01	38.01	30.94	1
CTCF	27.28	30.56	26.76	0.89267
CTAL	33.39	48.99	30.47	0.681568
CTPOF	27.75	48.69	28.36	0.569932
COE	22.87	48.52	31.94	0.471352
CORH	42.50	48.89	39.9	0.869298
COW	48.77	48.765	42.08	1
COC	46.65	55.64	43.06	0.83848
COAL	42.71	46.56	41.5	0.917354
COPOF	48.44	50.65	43.81	0.956328

Table 3. Crashworthiness Parameters

Specimen	EA(kJ)	SEA(kJ/kg)	EV (kg/m3)	CSR	CFE
ECT	2.411	18.982	3218.496	0.883	0.910
CTRH	2.358	11.729	3147.684	0.725	0.665
CTW	2.522	13.275	3367.586	0.815	0.814
CTCF	2.322	13.046	3100.444	0.868	0.876
CTAL	2.153	7.176	2874.371	0.707	0.622
CTPOF	2.405	11.034	3211.609	0.848	0.582
COE	2.803	19.883	3571.258	0.878	0.658
CORH	3.517	16.284	4480.592	0.882	0.816
COW	3.691	18.184	4702.293	0.877	0.863
COC	3.778	20.646	4813.066	0.877	0.774
COAL	3.663	11.704	4666.503	0.883	0.891
COPOF	3.856	16.270	4912.133	0.880	0.865

3.3. Conclusions

The 36 specimens were fabricated using woven roving fibre glass E-600 with epoxy. Two different geometries have been used in this study circular and corrugated with different types of fillers wood chips, rice husk (RH), coconut fibre (C), aluminium chips (AL) and palm-oil fibre (P) by comparing these fillers with a void tube(E). These specimens where subjected to a quasi-static compression load. The results show that the corrugated tubes are better than the circular tubes for the crashworthiness parameters, initial load, maximum load, average load, energy absorption, crush force efficiency and crush strain relation. All these parameters are better in corrugated tubes when compare with circular tubes as shown in Tables 1, 2. The corrugated tube which is filled with coconut fibre has a higher value of specific energy absorption. The effect of the filler is to increase the area under the curve in

load-displacement curves. The corrugated tube which is filled with coconut-fibre filler (COC) has the highest energy absorption of all the fillers.

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