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Crashworthiness characteristics of flax fibre reinforced epoxy tubes for energy absorption application

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ABSTRACT

The study reported here entailed an experimental investigation of the crashworthiness characteristics of natural flax fibre reinforced epoxy composite circular tubes from the point of view of energy absorption. The specimens tested under uniaxial compression include three inner diameters (36, 54 and 82 mm), three numbers of plies (1, 2 and 3) and three length-to-diameter ratios (1, 1.5 and 2). A total of 81 hollow tubes were tested (three specimens for each type) and the energy absorption capabilities of the specimens were evaluated. The parameters measured were the maximum crushing load, maximum stress, total absorbed energy, specific absorbed energy and crush force efficiency. The failure modes of the specimens were analysed from photography. Test results indicate that flax fibre reinforced epoxy composite tube has the potential to be used as energy absorber.

1. Introduction

The use of thin-walled fibre reinforced polymer (FRP) columns is continually growing in civil engineering [1–3], automotive engineering [4–6] and other industries due to their high strength-to-weight ratio, corrosion resistant and energy absorption capability. Crashworthiness studies have attracted much attention, particularly to evaluate the deformation behaviour and to determine the energy absorbing efficiency of various thin walled components of different composites. In automotive engineering, crashworthiness is defined as the capability of a vehicle to protect its occupants from serious injury or death in case of accidents of a given proportion [6]. Crashworthiness is concerned with the energy absorption through controlled failure modes that enable the maintenance of a gradual decay in the load profile during energy absorption.

To reduce the overall weight and improve the fuel economy of vehicles, an increasing number of component parts made of FRP composites are used to replace the conventional metal components. The crushing modes of FRP composite materials are significantly different from those of metallic materials. In compression, the metal structures collapse under impact in the form of buckling and/or folding in an accordion (concertina) pattern involving extensive plastic deformation. For structural vehicle crashworthiness, glass/carbon FRP composites are able to collapse in a progressive, controlled manner thereby exhibiting high specific energy absorption when crushing [7]. Unlike metals, the progressive energy absorption of composite structures is dominated by extensive micro-fracture.

As energy absorbers, crashworthy components have been designed in various geometrical shapes i.e. cylindrical tubes, square tubes, cones, conical frusta, square frusta and grooved or un-grooved pyramids [8,9]. A thin walled tube is the most common shape utilized. The failure of tubular composites in crushing is a sequence of fracture mechanisms involving micro-cracking development, fibre breakage and buckling, matrix cracking and crushing, fibre–matrix de-bonding, delamination, inter-laminar fracture and fracture of lamina bundles. It has been generally recognized that the highest energy absorption of composite tubes occurs in two progressive crushing mechanisms which are brittle fracture and lamina bending [10]. These two crushing mechanisms absorb energy mainly as a consequence of inter-laminar fracture, intra-laminar crack growth and fracturing of lamina bundles.

The presence of each failure mechanism is highly dependent on the geometry of the component, the various reinforcement types and matrix materials used, lamina orientation, layer-up sequences, and type of trigger and crush speed, all of which can be suitably designed to develop high energy absorbing mechanisms [4]. Composite materials can be tailored to exhibit specific energy absorption capabilities superior to those of conventional metals. Therefore, composite materials are being proposed for application to aircraft and automotive industries to meet strength, weight and cost constraints. Large scale studies have shown that composite materials can be an efficient energy absorbing material in crashworthiness design.

Most recently, natural fibres as reinforcement materials for polymer composites to replace synthetic glass fibres has gained

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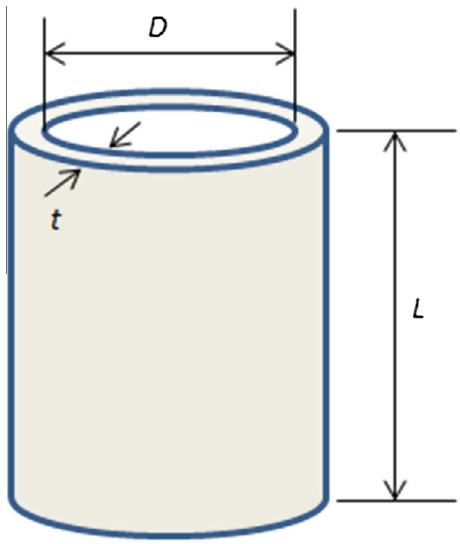

Fig. 1. Flax FRP hollow tube.

popularity in engineering applications due to increasing environmental concern [11]. Natural fibres are cost-effective, have low density with high specific strength and stiffness, and are readily available. Very few studies have been conducted to investigate the crashworthiness characteristics of natural fibre reinforced polymer composite materials as an energy absorber. Therefore, the present work focuses on using flax fibre due to the good mechanical properties and widely commercially availability of this material. The effects of inner diameter, length-to-diameter ratio and tube thickness on the crashworthiness characteristics of flax fibre reinforced epoxy circular tubes have been evaluated. The crashworthiness characteristics considered include load–displacement history, total absorbed energy, specific absorbed energy, crush force efficiency and the failure mechanisms.

2. Experiments

2.1. Material, fabrication and geometry

Commercial bidirectional woven flax fabric (550 g/m^2) was used for this study. The fabric has a plain woven structure with a

Table 1
Test results of flax FRP tubes with a diameter of 36 mm.

Specimen	Layers (N)	D (mm)	L (mm)	R L/D	m (g)	A (mm^2)	P_{max} (kN)	σ_{max} (MPa)	P_{avg} (kN)	CFE	AE (J)	SAE (J/g)
D36-N1-R1-S1	1	36	36	1	9.5	193	10.0	51.90	4.37	0.44	114.3	12.03
D36-N1-R1-S2					9.1		11.4	58.64	6.21	0.54	150.5	16.54
D36-N1-R1-S3					9.4		10.9	56.07	5.78	0.53	138.4	14.72
Average							10.7	55.54	5.45	0.50	134.4	14.43
S.D.							0.76	3.40	0.79	0.05	15.05	1.85
C.o.V (%)							7.10	6.12	14.50	10.0	11.19	12.82
D36-N2-R1-S1	2	36	36	1	18.5	402	24.7	63.83	16.44	0.67	406.0	21.95
D36-N2-R1-S2					18.0		23.0	57.20	18.63	0.81	446.6	24.81
D36-N2-R1-S3					18.7		24.9	64.35	18.25	0.73	432.7	23.14
Average							24.2	61.79	18.11	0.74	428.4	23.30
S.D.							0.85	3.25	0.96	0.05	16.85	1.17
C.o.V (%)							3.51	5.26	5.30	6.76	3.93	5.02
D36-N3-R1-S1	3	36	36	1	30.1	628	45.9	73.07	29.93	0.65	1049.2	34.86
D36-N3-R1-S2					31.6		39.7	63.21	26.17	0.66	1206.6	38.18
D36-N3-R1-S3					30.3		44.3	70.53	28.45	0.64	1169.4	38.59
Average							42.8	68.14	28.05	0.65	1141.7	33.88
S.D.							2.63	4.18	1.55	0.01	67.2	1.67
C.o.V							6.14	6.13	5.52	1.54	5.88	4.93
D36-N1-R1.5-S1	1	36	54	1.5	12.1	193	8.2	42.55	5.32	0.65	188.1	15.55
D36-N1-R1.5-S2					12.9		7.0	36.33	4.86	0.70	216.9	16.81
D36-N1-R1.5-S3					13.0		8.0	41.51	5.24	0.66	210.4	16.19
Average							7.7	40.13	5.14	0.67	205.1	16.18
S.D.							0.52	2.72	0.20	0.02	12.3	0.51
C.o.V (%)							6.75	6.78	3.67	2.98	6.00	3.15
D36-N2-R1.5-S1	2	36	54	1.5	25.7	402	22.6	56.21	17.36	0.77	661.0	25.72
D36-N2-R1.5-S2					27.6		22.0	54.71	17.86	0.81	687.0	24.89
D36-N2-R1.5-S3					27.8		23.1	57.20	17.84	0.77	695.3	25.01
Average							22.3	55.46	17.61	0.78	681.4	25.21
S.D.							0.45	1.02	0.23	0.02	14.6	0.37
C.o.V (%)							2.01	1.84	1.31	2.56	2.14	1.47
D36-N3-R1.5-S1	3	35	54	1.5	42.1	628	45.7	72.75	26.75	0.59	1650	39.19
D36-N3-R1.5-S2					42.7		44.1	70.20	24.39	0.54	1484.7	34.77
D36-N3-R1.5-S3					43.0		44.6	71.00	26.34	0.59	1613.2	37.52
Average							44.8	71.32	25.83	0.57	1582.6	37.16
S.D.							0.67	1.06	1.03	0.02	70.86	1.82
C.o.V (%)							1.50	1.48	3.99	3.51	4.48	4.90
D36-N1-R2-S1	1	36	72	2	20.2	193	11.1	57.60	4.34	0.39	156.8	7.76
D36-N1-R2-S2					19.0		12.5	64.87	4.66	0.26	205.8	10.83
D36-N1-R2-S3					19.0		11.8	61.24	4.61	0.39	198.7	10.45
Average							11.8	61.24	4.50	0.35	187.1	9.68
S.D.							0.57	2.97	0.14	0.06	21.62	1.37
C.o.V (%)							4.83	4.85	3.11	17.14	11.55	14.15
D36-N2-R2-S1	2	36	72	2	34.4	402	32.1	79.80	14.36	0.45	574	16.69
D36-N2-R2-S2					37.2		23.7	59.23	13.27	0.56	572.4	15.39
D36-N2-R2-S3					36.4		30.2	75.07	14.26	0.47	587.3	16.14
Average							28.7	71.36	13.96	0.49	577.9	16.07