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Lateral crushing of empty and polyurethane-foam filled natural flax fabric reinforced epoxy composite tubes

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ABSTRACT

In this research, empty and polyurethane-foam filled natural flax fabric reinforced epoxy composite tubes were fabricated using a hand lay-up process. These circular flax/epoxy tubes were laterally crushed under quasi-static compression. The effects of tube thickness (2, 4 and 6 plies), tube inner diameter (64 and 86 mm) and the foam filler on the crushing characteristics and energy absorption capacity of these tubes were investigated. The progressive crushing of these tubes were analysed from photography. In addition, the energy absorption capacities of these empty and foam filled tubes were compared with the existing circular empty and/or foam filled tubes made of metallic materials (i.e. aluminium, brass, and titanium) and synthetic fibre reinforced composites (i.e. glass and carbon). The test results indicate that under lateral compression, the foam filled flax/epoxy tubes deformed showing a capability of spreading the deformation. The use of polyurethane-foam suppressed the fibre fracturing and eventually enhanced the energy absorption of the tubes during flattening process. The foam filled tubes with more fabric plies exhibited better crashworthiness compared to the empty tubes. The comparison with the existing tubes shows that the specific energy of natural flax/epoxy tube can be designed comparable to that of conventional aluminium tube and the glass/carbon composite tube as energy absorbers. It also was found that the specific energy of the empty and foam filled flax/epoxy tubes in lateral crushing were significantly lower than those in axial crushing.

1. Introduction

With an increase in fuel price in recent years and the concern of better fuel economics in cost and fuel reserves, there has been an increased interest in the development of lightweight vehicles. Mass is an important criterion in addition to crashworthiness in automotive engineering sector. Indeed, lower mass corresponds to less fuel consumption and fewer environmental hazards [1]. The crashworthiness of transportation structures is a key parameter which can be used to evaluate the safety of the structure in vehicle design. 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 [2]. It 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 [3].

Nowadays, fibre reinforced polymer composites have been widely considered in aerospace, civil engineering, automotive and marine industries [4–9]. In automotive industry, fibre reinforced polymer composites are used to reduce mass and dioxide emission so as to meet the legislative demands because of their high energy absorption capacity, high specific strength and stiffness [10]. The crashworthiness of synthetic fibre reinforced composites (i.e. glass and carbon) has been documented well e.g. [11–13]. A properly designed composite structure has been demonstrated to be safer than conventional metallic structures, such as steel and aluminium. This enables the composite structures to be considered as excellent substitutes for conventional metals for energy absorption application [14,15].

Most recently, attempts have been made to reduce the use of expensive glass, aramid or carbon fibres by using some natural fibres which could lighten car's body due to their lower density [16]. Natural fibres are cost-effective with low density and embodied energy. They are biodegradable and non-abrasive [17]. In addition, they are readily available and their specific mechanical properties (e.g. flax fibres) are comparable to glass fibres as reinforcement [18]. Composites reinforced with natural fibres have promising

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potential to provide benefits to companies, natural environment and end-customers due to dwindling petroleum resources [18]. The use of sustainable materials is also a demand of European regulations, i.e. according to the European Guideline 2000/53/EG issued by the European Commission, 85% of the weight of a vehicle had to be recyclable by 2005. This recyclable percentage will be increased to 95% by 2015 [19]. Therefore, bio-composites have potential being widely used in the future as the next generation of structural members due to the favourable mechanical performance of natural fibres.

With regard to the investigation of bio-composites as energy absorbers for vehicle design, only very few studies are available in literature. Meredith et al. [20] compared energy absorption capacity of several natural fibre (i.e. unwoven hemp, woven flax and woven jute) reinforced epoxy composite cones with carbon/epoxy composite cones in dynamic axial crushing. The study showed that natural fibre composite cones fabricated using vacuum assisted resin transfer moulding exhibited high values of specific energy which are comparable to carbon fibres: with carbon fibre of 55.7 J/g, unwoven hemp of 54.3 J/g, woven flax of 48.5 J/g and woven jute of 32.6 J/g. Ataollahi et al. [21] and Eshkoor et al. [22] considered woven silk fibre/epoxy tubes under quasi-static axial compression. Their studies indicated that generally buckling (either local buckling or mid-length buckling) and hinge formation are the two main characteristics of woven silk/epoxy tubes, displaying a catastrophic failure. The specific absorbed energy and crush force efficiency of their silk/epoxy composite tubes is around 5.4 J/g and 0.26, respectively [21]. Yan and Chouw [23] tested woven flax/epoxy composite tubes with different tube inner diameters (36, 54 and 82 mm), cell wall thickness (1, 2 and 3 plies of laminate) and length-to-diameter ratios (1, 1.5 and 2) under quasi-static axial crushing. The study showed that most of the empty flax/epoxy tubes crushed in a brittle manner with a progressive crushing pattern with favourable specific energy absorption capability. The optimal empty flax/epoxy tube has a specific energy of 41 J/g and its crush force efficiency is 0.78. Therefore, these preliminary studies (e.g. [20–23]) indicate that natural fibre reinforced polymer composites have potential to be energy absorbers in axial crushing.

Based on the best knowledge of authors, in literature only few studies investigated the axial crushing characteristics of natural fibre reinforced composite structure. To date, no study on lateral crushing of natural fibre reinforced composite structures can be found in literature. Hence, the crashworthiness and energy absorption capacity of natural woven flax/epoxy composite tubes under lateral crushing are considered in this study. To have a better crashworthiness of flax/epoxy tubes under crushing, cellular material such as polyurethane-foam is applied, making the composites like sandwich structures. Therefore, the empty and polyurethane-foam filled flax fabric reinforced epoxy composite tubes were fabricated and crushed under quasi-static lateral compression. The considered parameters include three tube wall thicknesses (2, 4 and 6 plies of laminate) and two tube inner diameters (64 and 86 mm).

2. Experiments

2.1. Materials

Commercial bidirectional woven flax fabrics (550 g/m^2) were used for this study because of they ready availability. The fabric has a plain woven structure with a count of 7.4 threads/cm in warp and 7.4 threads/cm in the weft direction [24]. The epoxy used was SP High Modulus Prime 20 resin and its hardener. The viscosity of the resin system at 20 °C was 1010 mPa/s. The resin had tensile strength of 78 MPa, tensile modulus of 3.5 GPa, elongation at break of 3.5%, flexural strength of 82 MPa and flexural modulus of 2.8 GPa. For flax/epoxy tubes with filler, the polyurethane-foam used had a density of 160 kg/m^3. The approximate modulus of elasticity was 0.022 MPa and the compressive strength at 10% deformation was 0.20 MPa, respectively. The data was measured at room temperature, which was about 21 °C. Two diameters of cylindrical polyurethane-foam were used, i.e. 64 and 86 mm. The diameter of the inner hollow cylinder of the foam was 20 mm. The measured density of the empty flax/epoxy tube was 1.18 g/cm^3.

Flax/epoxy composite tubes were fabricated using a hand lay-up process. The fabrication details of the empty tubes were described elsewhere [25]. Regarding to the foam-filled tubes, the polyurethane-foam was directly considered as the cylindrical mandrels, a coat of epoxy primer (SP High Modulus Prime 20 resin and hardener) was applied to the outer surface of the foam. Then, the flax fabric was wrapped following the same process to that of the manufacturing of empty tubes. The use of a coat of epoxy primer ensured a good interfacial bond between the polyurethane-foam and the flax/epoxy tube. The weft direction of the fabric was aligned parallel to the axis of the tube. The ends of the tubes were grinded to ensure the tubes were free from uneven ends in order to avoid eccentricity loading during the compression.

In this study, the considered tube configurations were: (1) empty flax/epoxy circular tube, termed as FFRP and (2) filled flax/epoxy circular tube, termed as PU-FFRP. Fig. 1 gives the photographs of an empty and a polyurethane-foam filled tube. For each tube configuration, two tube inner diameters (D) were used, i.e. 64 and 86 mm and the length-to-diameter ratio (L/D) of 1.5 was utilized, corresponding the tube length of 96 mm and 129 mm, respectively. The wall of the tube comprised of 2, or 4, or 6 plies flax/epoxy composites, with the thickness of one ply laminate approximately 1.0 mm. Therefore, a total of 12 different types of tubes were considered. For each type of tube, three identical specimens were constructed and tested. In the following text, a geometrical code is used for tubes with different geometry, e.g. *D64-N2*, which indicates that the tube has an inner diameter (D) of 64 mm; the number of layers of laminate (N) is 2. Table 1 gives the nomenclature and the geometrical properties of the specimens.

2.2. Experimental procedure

2.2.1. Yarn testing

To reflect the tensile properties of the flax fabric used, in this study the tensile properties of single-strand flax yarn extracted from the fabric were tested and presented here. Flax fibre single-strand yarns were extracted from the fabric and the maximum tensile strength, elongation at break and the tensile modulus were measured on an Instron 5567 universal test machine according to ASTM D2256. The yarns were 150 mm in length and were handled in a manner to avoid any change in twist or any stretching of the specimens. The test was repeated 20 times with these samples extracted from the same flax yarn. The specimens were tested at room temperature, which was about 21 °C. The relative humidity was about 45%. The cross-sectional area of single-strand flax yarn was assumed to be circular; the diameter of the yarn was measured with the help of a scanning electron microscopy (Fig. 2).

2.2.2. Quasi-static lateral compression

Crushing of the tubes was performed by applying lateral quasi-static compressive forces using the Instron 5567 machine with the loading capacity of 100 kN. The specimens were tested at room temperature, which was about 21 °C. The relative humidity was about 45%. A linear variable displacement transducer (LVDT) was used to record the deformation of the specimens. The crosshead speed used was 10 mm/min. Fig. 3 gives the load–displacement