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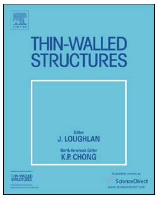

Full length article

Winding orientation optimization design of composite tubes based on quasi-static and dynamic experiments

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ABSTRACT

Compared with traditional metal materials, composite materials can be better designed by changing layup condition or ply orientation to meet performance requirements. In this study, influences of stacking sequence and fiber orientation of glass fiber reinforced polymer (GFRP) circular tube on energy absorption performance were evaluated by axial quasi-static compression, drop weight tests and numerical simulation. Optimal ply angle and layup condition of composite tubes were obtained based on the finite element modeling and regression analysis. The optimization design result was validated by experiments. Drop weight tests results were analyzed and compared with quasi-static experimental results. Experimental and numerical results illustrate that proper increase of axial layups can improve the specific energy absorption of composite tubes.

1. Introduction

Composite materials such as carbon fiber reinforced plastic and glass fiber reinforced plastic (GFRP), have a wide range of applications in automotive and aerospace industries due to their high strength-to-weight ratio and high modulus-to-weight ratio. They also show an advanced energy absorption capability that can absorb the kinetic energy of the impact (such as car collision and aircraft crash) and reduce injuries from impact [1]. Numerous studies about factors that might affect the energy absorption capability of composite materials have been conducted in past two decades including the shape of the structure, such as circular, square, polygon and tapered tubes [2–6]; the structural dimensional parameters, such as wall-thickness and fiber orientation [7–9]; the load condition, such as quasi-static compression tests and dynamic impact tests [10–12].

In view of composite structure design, fiber orientation is considered as one of the most important design parameters because designability is another special characteristic for composite materials providing potential design flexibility over traditional materials. Change of the stacking sequence and fiber orientation have strong impacts on the deformation of the structure after compression and its crashworthiness performance.

Staring from 1980s, researchers began to focus on the layup condition of thin-walled composite tubes. In 1982, Thornton et al. [13] investigated the compressive property of GFRP tubes with $[45/45]_n$ and $[0/90]_n$ layups. The results revealed that tubes with a $[45/45]_n$ lay-up had consistently lower values of specific energy (defined as the energy absorbed/unit weight of collapsed tube) than tubes with $[0/90]_n$ layups in the stable collapse region. In 1983, Farley G L [14] analyzed and compared energy absorption performances of glass/epoxy tubes with $[0/\pm\theta]$ layup , and found that composite tubes showed poor energy-absorption performance when $15^\circ \le \theta \le 45^\circ$. Nevertheless, composite tubes had better performances of impact energy absorption when $60^\circ \le \theta \le 90^\circ$. In 2000, Song et al. [15] conducted quasi-static and impact tests on GFRP wrapped circular metal tubes with different winding angle. They found that the ply pattern $[\pm 15^\circ]$ no longer contributes to the energy absorption during the post-buckling phase, and pattern $[\pm 45^\circ]$ shows a medium energy absorption capability. However, pattern $[\pm 90^\circ]$ is the best. In 2006, El-Hage H et al. [16] obtained a similar conclusion by numerical simulations. In 2012, Pickett L et al. [17] conducted a numerical study to investigate the composite tube with ply orientations of $[0^\circ/\pm\theta^\circ/0^\circ/\pm\theta^\circ]$ $(15^\circ \le \theta \le 90^\circ)$. The SEA (specific energy absorption)-angle θ curve demonstrated that the energy absorption values are fluctuated when θ is less than 45°, and that the SEA increases fairly linearly as θ tends to be 90°.

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Experiments and numerical simulations are two main research methods. With the improvement of commercial finite element software and innovation of simulation methods [18–21], they have been used by many researchers to validate experimental results and conduct optimal design. Boria et al. [22] compared and analyzed CFRP truncated cones with different wall thickness, cone angle and minor internal diameter by quasi-static and dynamic compression tests. The experimental results revealed that SEA values under a dynamic load condition are less than those under a quasi-static load condition. Other researchers [23,24] also obtained similar results. Commercial finite element analysis software are widely used in composite material modeling and structural optimization design. Duan S et al. [25] carried out optimization design on the radius of the semicircular segment and the thickness of a type of corrugated plate in terms of maximum SEA and minimum peak force. Wang et al. [23] optimized the structural dimension of the racing composite nose by response surface methodology.

Up to now, research on stacking sequence and fiber orientation of composite tube are mainly comparative analysis conducted by discrete experiments analysis or pure numerical simulation analysis. The present work compared the energy absorption capability of circular composite tubes with different stacking sequence and optimized the fiber orientation using numerical simulation method combined with axial quasi-static compression tests and drop weight tests. The effect of fiber orientation on energy absorption characteristics of GFRP tubes were investigated and the optimal stacking sequence and fiber orientation were found. The obtained experimental and numerical data and conclusions would provide an effective reference for the layup design.

2. Experiments

2.1. Specimen processing

All specimens were fabricated by E-glass/PET 199 (E-glass fiber and unsaturated polyester resin 199) using filament winding process. Firstly, a metal mandrel was made and the surface of it was galvanized to reduce the surface friction so as to make the tube easier to demould. And then the continuous glass fiber bundle was wrapped on the mandrel with a specific angle. After the winding process, a long composite tube was cured at room temperature nearly for two days. In next step, the cured tube was demolded from the mandrel (shown in Fig. 1a) and waited for post-processing including cutting into a required length and chamfering. Restricted by the design parameter of the winding machine, the winding angle has a range from 10°to 90°. So 10°is the limiting angle that is close to the axial direction.

All specimens are 100 mm long with an inner diameter of 80 mm and a wall thickness of 2.4 mm with a 45 °chamfer on one end of the tube (shown in Fig. 1b). Each of them was winded by using 20 plies E-glass/PET 199 with a stacking sequence of $[\pm 75]_{10}$. The material parameters of the composite are given in Table 1.

Table 1
E-glass/PET199 material properties (filament winding fabrication) [26].

Property	Description	Value
ρ	Density	2.0×10^3 kg/m^3
E_a	Modulus in longitudinal (fiber) direction	37.9 GPa
$E_b = E_c$	Modulus in transverse direction	11.5 GPa
G_{12}	Shear modulus	4.5 GPa
ν_{12}	Major Poisson's ratio	0.29
ν_{21}	Minor Poisson's ratio	0.0811
X_t	Longitudinal tensile strength	936 MPa
X_c	Longitudinal compressive strength	484 MPa
Y_t	Transverse tensile strength	25.7 MPa
Y_c	Transverse compressive strength	143 MPa
S_c	Shear strength	16.1 MPa
S_b	Inter-laminar shear strength	62.6 MPa
V_f	Fiber volume fraction	70%

2.2. Quasi-static compression tests

Quasi-static axial compression tests were performed on specimens at room temperature using electronic universal material testing machine CMT-6105 (loading capacity 100 kN) with a constant speed of 2 mm/min. The maximum vertical displacement of tests was 60 mm (3/5 of the overall specimen's length).

The specimen shows a progressive and stable compression process shown in Fig. 2, corresponding to the axial load versus displacement curve. At the initial crushing stage of the test, the compression force rises to the peak and then drops promptly to an average value. After that the axial load remains relatively constant and fluctuates within a small range. It is also can be from the Fig. 2 that the peak load of the tube with chamfer is much lower than the tube without chamfer.

3. Numerical simulations and optimization design

3.1. Numerical model of circular composite tube

The numerical model was built using a commercial nonlinear dynamic finite element analysis software LS-DYNA, with the Altair HyperMath pre-post processing. MAT54 which is based on the Chang-Chang [27] failure criterion (material card *MAT_ENHANCED_COMPOSITE_DAMAGE) in LS-DYNA was chosen to predict the energy absorption characteristics of GFRP [28,29]. There are 21 parameters in MAT54 that need to be determined, and 11 parameters are8 independent material constants showed in Table 1 and seven numerical parameters shown in Table 2 cannot be measured experimentally but need to be calibrated by trial and error [30]. The geometry is meshed using shell element of 2.5 mm × 2.5 mm which was based on convergence tests in terms of mesh density and analysis time and there are twenty integration points corresponding to 20 plies represented by shell element.

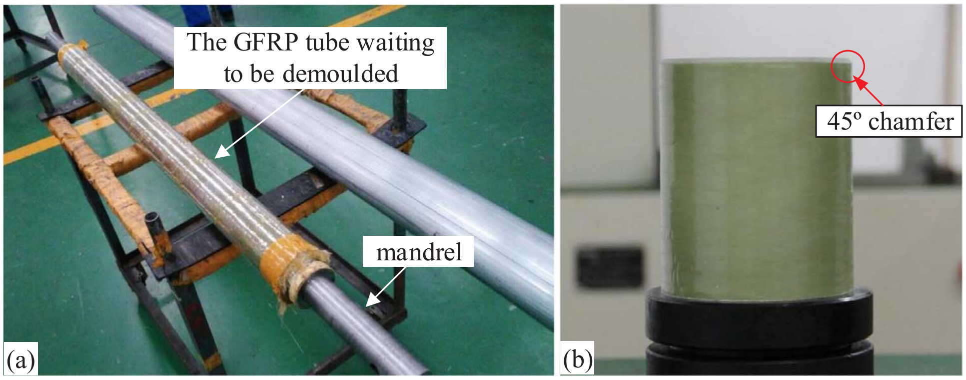

Fig. 1. (a) GFRP tube after winding process and waiting to be cured (b) GFRP tube (with 45 °chamfer).