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Retrofitting scheme and experimental research of severally damaged carbon fiber reinforced lattice-core sandwich cylinder

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ABSTRACT

To improve the reutilization of advanced carbon fiber reinforced composite (CFRC) lattice-core sandwich cylinder (LSC), a severely damaged LSC was retrofitted by CFRC laminate through wrapping and riveting schemes. Free vibration and uniaxial compression experiments were carried out to reveal its mechanical performances. Natural frequencies and vibration modes of the repaired cylinder are close to the intact cylinder. Compared with the stiffness of the intact cylinder, 98.7 kN/mm, stiffness of the repaired cylinder is 138.83 kN/mm, even a little stiffer. Failure of the repaired cylinder locates at the lower end. Initially, the inner skin delaminated from the core and finally fracture of the outer skin made the cylinder out of work. The repaired segment is not damaged. Ultimate load of the repaired cylinder is 377.38 kN, only a little smaller than of the intact cylinder. The retrofitting scheme is effective to re-utilize the severally damaged CFRC LSC.

1. Introduction

CFRC lattice structures are light but strong and stiff [1–9]. Vasiliev et al. [1] reviewed the development and application of GSC. In a range of load indices that are representative of most astronautic applications, sandwich structures appear to be the most efficient. Fan et al. [10–12] have made CFRC LSCs. Load capacity and stiffness of LSC reach 524.6 kN and 161.8 kN/mm [10], several times stiffer and stronger than the referenced GSC [2]. Zhang et al. [13] revealed its free-vibration behaviors. LSC of the same weight and dimensions with GSC is stiffer, indicating that LSC has higher fundamental frequency and can be lighter in most astronautic applications to satisfy the requirement for the lowest frequency [13]. This structure can be applied to the satellite payload adapter, the rocket fairing, the rocket interstage segment, the missile body structure and even the aircraft barrel structure. Zhang et al. [13] also reported its failure mode. Skin fracture and delamination appear at the central cylinder. Usually making a CFRC LSC is expensive and time-consuming. If the damaged skin of the cylinder is repaired, the cylinder can be re-utilized. Kara et al. [14] pointed out that repairs made with composite patches on damaged fiber reinforced composite pipes offer distinct advantages over traditional repairs in addition to reduced cost. Usually, hybrid (riveted/bolted) method is applied to retrofit lap joints [15]. To reveal the mechanics of composite shells, refined plate theory [16, 17], nonlinear analysis method [18], experimental and numerical analyses were developed. These methods can also be applied to analyze behaviors of the CFRC LSC.

In this study, the crushed CFRC LSC was retrofitted by CFRC laminates. End-free free vibration and uniaxial compression behaviors of the retrofitted cylinder were tested to check the contribution of the retrofitting scheme.

2. Damaged cylinder and retrofitting scheme

2.1. Damage mode

Zhang et al. [13] adopted rubber mold, filament winding and twice co-curing method to make a LSC reinforced by T300 carbon fibers, as shown in Fig. 1, whose diameter is 300 mm and height is 500 mm. The facesheet thickness is 2.5 mm and the lattice core thickness is 8 mm. The inner skin consists plies of [+90°, −30°, +30°] orientations and the outer consists plies of [0°, −60°, +60°] orientations. They are all quasi-isotropic. There are 18 Kagome lattice cells circumferentially and 11 cells longitudinally. The cell dimension is 26.1 mm and the rib thickness is 2.0 mm. The cylinder is 5.6 kg.

In compression, the cylinder rendered excellent linearity with a compression stiffness of 98.7 kN/mm. Compression failures of

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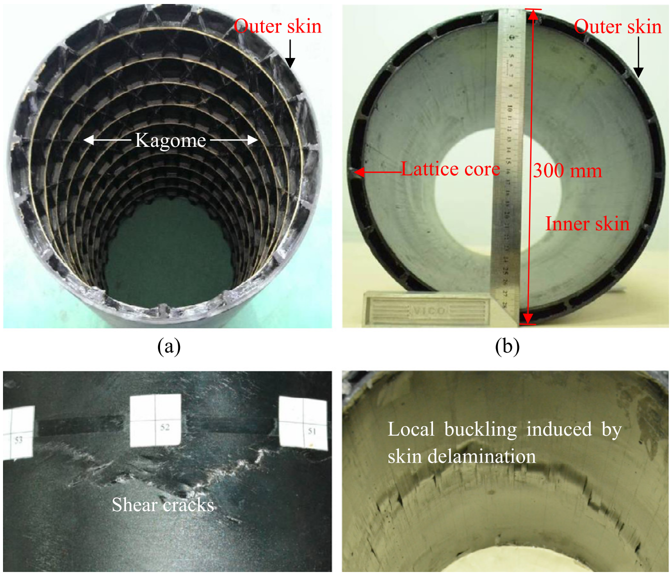


(a) (b)

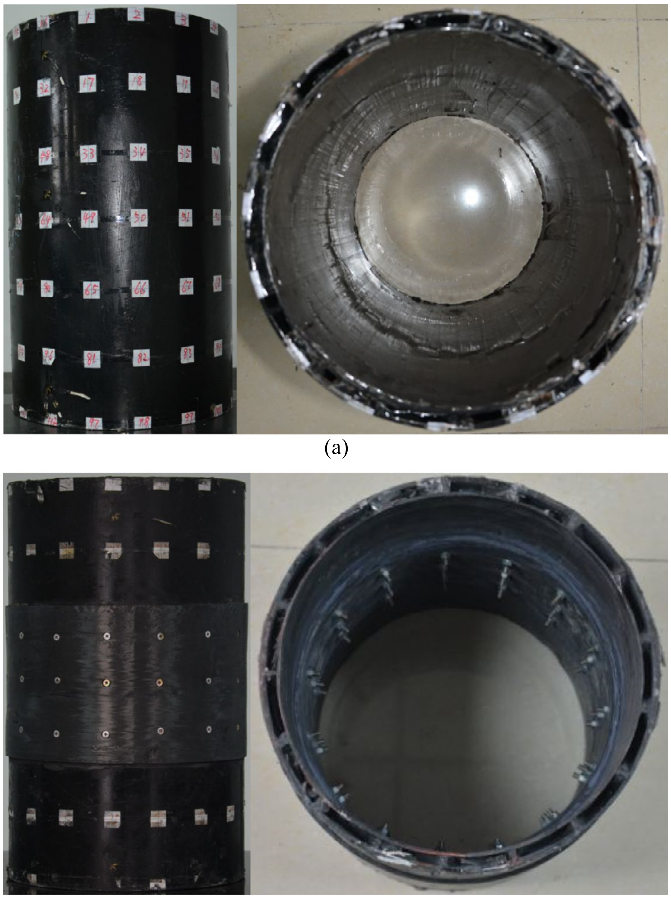
(c) (d)

Fig. 1. CFRC sandwich cylinder: (a) initially cured GSC before inserting the inner skin; (b) transverse cross section of finished LSC after the second curing; (c) cracks on the outer surface of the cylinder and (d) skin delamination on the inner surface of the cylinder [13].

the skins control the collapse of LSC1 with a maximum measured strain of 2500×10^{-6} at the lower end. Cracks appearing at the central of the outer skin and local delamination at the central of the inner skin, as shown in Fig. 1, let the load drop abruptly when the measured displacement reaches 5.39 mm. Peak load of the cylinder is 499.51 kN.

2.2. Retrofitting scheme

Making a CFRC LSC is time-consuming, laborious and costly. For multi-launching aerospace structures, structural damages in the pre-launching should be effectively restored. Till now, few schemes have been proposed to re-utilize launched or damaged CFRC LSC. A retrofitting scheme was suggested in this research, as shown in Fig. 2. The cylinder failed at skin rupture and delamination at the central cylinder. Firstly, the delaminated skin was re-dipped by epoxy resins. Then CFRC laminate was adhered to the inner surface and wound to the outer skin layer by layer. The retrofitted skin thickness, t, is decided by $t \geq t_r + \rho^* c/2$, where t_r is the initial skin thickness. c and ρ^* denote the thickness and the relative density of the lattice core. Equation (1) could guarantee the retrofitting skins have comparable load capacity to the intact sandwich wall. Here, it requires that $t \geq 3.1$ mm. The inner retrofitted skin lay-up consists of plies of $[+90^\circ, -30^\circ, +30^\circ]$ orientations and the thickness is 3.8 mm. CFRC laminate was placed and wounded onto the outer surface of the cylinder alternately. The outer retrofitted skin lay-up consists of plies of $[0^\circ, -60^\circ, +60^\circ]$ orientations and the thickness is 3.8 mm. According to the experiment of the intact cylinder, $P_s = 499.51$ kN. To achieve this load, length of the retrofitted segment is 190 mm. After the resins were completely solidified, the added laminates and the cylinder were riveted together by three rows and 15 columns of bolts, as shown in Fig. 2. Diameter of the bolts is 4 mm. The weight of the retrofitted cylinder is 7.2 kg, 1.4 kg heavier than before. In designing, the retrofitting contribution of the riveting to the strength was not included, which would enhance the designing redundancy.



(a)

(b)

Fig. 2. CFRC LSC: (a) crushed and (b) retrofitted.

3. Mechanical behaviors of retrofitted cylinder

3.1. Free-vibration behaviors

To reveal the free vibration behavior, the retrofitted LSC was suspended through light elastic rubber bands to separate the rigid-body mode to build a free configuration, as shown in Fig. 3. Single-input single-output test method was adopted in the test to measure the system's frequency response function (FRF), $H(\omega)$, where ω is the angular frequency (in rad/s). The structure, modeled as an n-DOF (degree-of-freedom) system, was excited at one point impacted with a hammer and its response was measured by means of the accelerometer at the same or another point. Little hardware is required in this circumstance and we can acquire a row or a column of the system's FRF matrix by moving the excitation point and keeping the response point fixed. A matrix consisting of 7 rows along the height and 16 columns circumferentially was set to measure the vibration responses. DASP-MAS-IMPACT measurement system of China Orient Institute of Noise & Vibration (COINV) was applied to collect the data and analyze the natural frequencies and vibration modes. Complex Modal and Single Degree of Freedom Analysis Method (CMSDFAM), a frequency domain method (FDM) in the system can automatically simulate the natural vibration modes.

The first six natural frequencies and vibration modes were revealed by experiments, as listed in Table 1 and shown in Figs. 3 and 4. Primary frequencies were determined by measured magnitudes of frequency response functions (FRFs), as shown in Fig. 4. The first mode shape reveals that the vibration is in the plane of