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Buckling behavior of CFRP-aluminum alloy hybrid tubes in axial compression

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Novel hybrid members, namely, CFRP-Al hybrid tubes, which are composed of Al (aluminum alloy) and CFRP (carbon-fiber-reinforced polymer) jackets, represent promising axial load members in civil engineering. Long CFRP-Al hybrid tubes with circular and square hollow sections are investigated in this study using bending and axial compressive buckling tests. Compression buckling analysis is performed using finite element analysis (FEA) and section analysis, which allow one to better understand the unique "partial elastic buckling" behavior of long hybrid members. In addition, a good agreement between FEA and bucking test results is achieved. Finally, based on FEA and the traditional Perry-Robertson formula, the column curves for long CFRP-Al hybrid tubes are given for design.

1. Introduction

Efficiently combining FRP (fiber-reinforced polymer) and traditional materials, such as concrete and metals, to create hybrid structural members can provide favorable properties, including higher bearing capacities [1], greater buckling resistances [2–7], longer fatigue lives [8–12], and greater energy absorption [13]. When used for structures, Al and FRPs have the common advantages of low weight, corrosion resistance, no ferromagnetic properties and flexible manufacturing procedures [14–17]. Additionally, each material makes up for the defects of the other, namely, FRPs increase the stiffness and strength of pure Al members, and Al provides ductility, which is not an attribute of FRP members. The stiffness and compressive capacity of Al are relatively low and thus require improvement. The application of hybrid Al-CFRP tubes may help to solve this problem because hybrid Al-CFRP tubes can exhibit improved behaviors, including higher bearing capacities, higher stiffness and lighter weight. In addition, from the perspective of performance, the combination of the elastic material CFRP and the elastic-plastic material Al can achieve a bilinear behavior. Due to these merits, CFRP-Al hybrid members can be applied in reticulated shells; space grid structures; long bridges; the domes of long-span spatial structures, such as stadiums, greenhouses and indoor swimming pools; overhead sign structures [11]; offshore structures and marine structures. Thus, they are promising concepts in the field of civil engineering.

The compressive bearing capacity of stub CFRP-Al hybrid tubes was investigated via testing and FEA [18]. However, to apply CFRP-Al hybrid tubes in engineering practice, the buckling behavior of long tubes also requires study. In contrast to pure metal tubes, such hybrid tubes are composed of Al and CFRP jackets; thus, a part of the elastic material in the section will never yield during testing. Moreover, the buckling behavior of hybrid tubes is completely different from that of pure metal tubes, an area that requires further theoretical and design study.

The buckling of metal columns is a complex phenomenon involving various failure types, including global and local buckling and elastic and elastic-plastic buckling, and has been widely studied. For example, the dynamic elastic-plastic buckling of thin-walled square tubes was analyzed by Karagiozova et al. [19], who found that the initiation of buckling was influenced significantly by elastic and plastic stress waves. Wang et al. [20] studied the lateral-torsional stability of Al extruded I-section beams under pure bending and provided a design method. Adeoti et al. [21] studied the flexural buckling behavior of 6082-T6 Al columns with an H-section and rectangular hollow sections under axial compression and presented a column curve formula. Kucukler et al. [22] gave a flexural-torsional buckling assessment of steel beam-columns based on a stiffness reduction method by reducing

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the Young's and shear moduli. In addition, both the global and local buckling behaviors of Al columns were analyzed by Liu et al. [23]. Cheng et al. [24] also studied the load-strain model for steel-concrete-FRP-concrete columns in axial compression. Wang et al. [25] investigated the structural performance of compressed high strength steel square and rectangular hollow sections, and analyzed the compressive local buckling response. However, a limited number of studies have been conducted on the buckling behavior of hybrid compressed specimens composed of an elastic jacket and an inner elastic-plastic metal [26,27], especially CFRP-Al hybrid tubes.

This paper focuses on the buckling behavior and design of long hybrid CFRP-Al tubes. First, bending and axial compression tests of long hybrid CFRP-Al hybrid tubes are conducted. Their equivalent bending stiffness and buckling loads are obtained, and their special force-lateral displacement curves are described and analyzed. Second, FE modeling is conducted to simulate the partial elastic buckling behavior and is verified to be accurate based on the test results. Third, the mechanism underlying the hybrid tubes is discussed, and the Perry-Robertson formula is taken as a basic form for design. Finally, the column curves for design are determined based on FEA.

2. Experimental study

2.1. Specimens

The specimens for the bending and axial compression tests were of the same material, Al wall thickness and manufacturing process. The nominal yield strength $f_{0.2}$ of the square Al tube and circular Al tube was 227 MPa and 291 MPa, respectively; the wall thickness t_A of the square Al tube and circular Al tube was 3.0 mm and 3.1 mm, respectively; the elastic modulus E_A of the square Al tube and circular Al tube was 68.6 GPa and 70.3 GPa, respectively; and the Poisson's ratio of the square Al tube and circular Al tube was 0.351 and 0.360, respectively. For the CFRP samples, the material properties were as follows: the average value of the elastic modulus in the longitudinal direction was 71.5×10^3 MPa, the average value of the elastic modulus in the transverse direction was 3.37×10^3 MPa, the shear modulus was 1.53×10^3 MPa, the Poisson's ratio of the longitudinal and transverse directions was 0.36, and the average thickness of one CFRP layer in the CFRP samples was 0.65 mm. Stress-strain curves of the Al tubes and CFRP samples are shown in Fig. 1. The Al specimens that were tested in this study were fabricated in the same manner as in the previous study [18]. As shown in Fig. 2, edge of the Al tube refers to the farthest face or point of the Al tube from the axis. For square tubes, it is the outer face of the Al tube. For circular tubes, it is the inner remote point of the Al tube. In addition, orthogonal CFRP layers were applied to the Al tubes; this process is denoted as $[0/90]_n$. Each specimen was named based on the configuration of the metal section (i.e., square or circular), the nominal diameter (circular tubes) or the cross-sectional width (square tubes), and the number of pairs of CFRP layers. The terms used to describe different CFRPs are defined in the same manner as in a previous study [18]. The elastic modulus of the adhesive is 2.995 GPa.

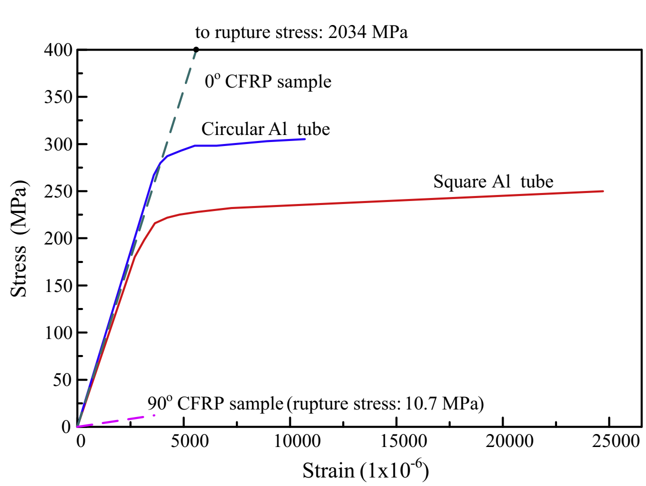

Fig. 1. Stress-strain curves of the Al tubes and CFRP samples.

2.2. Bending test

To verify the calculation method for the equivalent bending stiffness *EI* of the hybrid specimens, two groups of six square tubes were investigated using four-point bending tests. Moreover, the bonding of CFRP jackets and Al tubes can be checked using the bending test. The experimental device is shown in Fig. 3. Strain gauges with a length of 20 mm were placed at the top and bottom surfaces of the mid span. The details of the specimens and the test results are shown in Table 1.

From Fig. 4, it is seen that obvious plastic deformation with local buckling occurred in every specimen. The bonding of CFRP jackets and Al tubes is good in most parts of the specimen except for inward or outward local buckling, CFRP rupture, and local delamination or debonding occurring in very limited areas. The best bonding is obtained from the vacuum bag compression process used in the preparation of the specimens and for sufficient numbers of transverse layers wrapped around the Al tubes. Therefore, the bonding of CFRP and Al tubes was verified to be reliable. Moreover, Fig. 5 shows the force-midspan deflection curves of the bending specimens.

The contribution of the CFRP layers in the transverse direction is typically neglected in composite materials because the elastic modulus and strength of the transverse FRP layer are much lower than those of the longitudinal FRP layer. For the CFRP in this test, the elastic modulus in the transverse direction is 6.7% of that in the longitudinal direction; the strength in the transverse direction is 3.7% of that in the longitudinal direction. Therefore, the equivalent section area A can be obtained from the Al area coefficient κ_A, as shown in Eq. (1):

$$A = \frac{\sum_{i=1}^{n} E_{Li}A_i + E_A A_A}{E_A} = \frac{A_A}{\kappa_A} \tag{1}$$

where A_A is the section area of the Al, E_A is the elastic modulus of Al, A_i is the section area of the ith CFRP layer in the longitudinal direction, and E_{Li} is the equivalent elastic modulus of the ith CFRP layer in the longitudinal direction. n is the total number of longitudinal CFRP layers. Similarly, the Al bending stiffness coefficient κ_I is often used to describe the ratio of the bending stiffness that is provided by the Al material to that of the entire specimen; thus, the equivalent bending stiffness *EI* of the specimens can be determined using Eq. (2), which is based on the plane section assumption and laminated plate theory:

$$EI = \sum_{i=1}^{n} E_{Li}I_i + E_A I_A = \frac{E_A I_A}{\kappa_I} \tag{2}$$

where I_i is the inertia moment of the ith CFRP layer in the longitudinal direction and I_A is the inertia moment of the Al. Thus, the regularized slenderness ratio $\bar{\lambda}$ of the hybrid specimens is calculated using the following equations:

$$\lambda = \frac{L}{r} = \frac{L}{\sqrt{EI/(E_A A)}} = \frac{L}{\sqrt{\frac{E_A I_A}{\kappa_I} \Big/ \left(\frac{E_A A_A}{\kappa_A}\right)}} = \frac{L}{\sqrt{\frac{I_A}{\kappa_I} \Big/ \left(\frac{A_A}{\kappa_A}\right)}} \tag{3}$$