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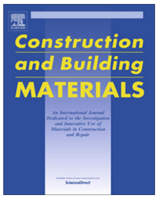

Mechanical properties of pultruded basalt fiber-reinforced polymer tube under axial tension and compression

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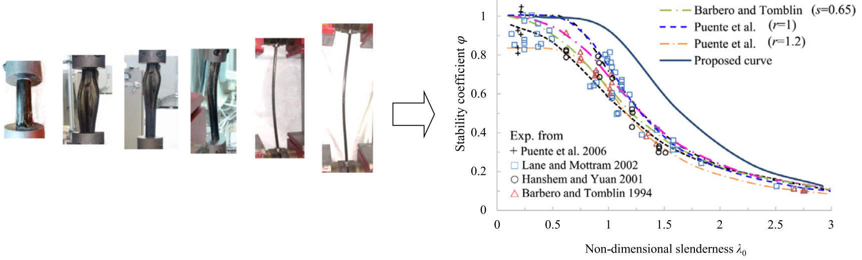
HIGHLIGHTS

- High tensile and compressive strength of short BFRP tube of 1011 MPa and 405 MPa.
- Three failure modes of micro-buckling, local buckling and overall buckling.
- Positive effect of fiber sheets on BFRP tubes with large slenderness ratios.
- Stability equation with high accuracy for compressive strength BFRP tubes.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper explores mechanical properties of pultruded basalt fiber-reinforced polymer (BFRP) tubes for truss structures subjected to tensile and compressive axial loading. The tensile and compressive strength of BFRP tubes were first tested. For the stability under compression, the slenderness ratios varying from 6 to 90 were adopted while the failure modes were recorded. The effects of confinement on the buckling by an additional layer of fiber sheets were investigated. Based on the experimental results, stability equation for predicting compressive strength of slender BFRP tubes were derived and validated. The results show that the tensile strength of short BFRP tube could reach 1011 MPa, while the compressive strength has been around 40% of tensile strength with relatively larger variation. Compared with the single tensile failure mode of BFRP tubes, three types of compressive failure modes, including micro-buckling, local buckling and overall buckling were observed. It can be concluded that a layer of fiber sheet slightly decreases the compressive strength. However, with the increase of slenderness ratios, the positive effect on the compressive strength by fiber sheets becomes significant. The accuracy of the proposed equation was validated by additional five groups of BFRP tubes with different slenderness ratios. It is also shown that the existing prediction equation of GFRP in literature is not suitable for predicting the stability of BFRP.

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1. Introduction

Fiber reinforced polymer (FRP) composites are widely accepted as structural reinforcing materials in civil, environmental, energy and aerospace engineering fields owing to their superior physical, mechanical and chemical properties compared with conventional steel reinforcement [1,2]. In the field of civil infrastructure, aside from the typical applications of internal or external FRP reinforcement in reinforced concrete (RC) structures, to avoid corrosion, and in cable-supported bridges, to enhance spanning ability [3,4], another promising application is to apply the FRP profiles, such as tube or H shapes, in truss structures to realize lightweight and durable structures. Compared with conventional structural

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materials, FRP elements are advantageous in bridge construction due to their high specific strength (strength-to-weight ratio) and resistance to corrosion, temperature and chemicals [7,8]. Furthermore, FRP bridge elements are easy to produce, transport and install and require only minimal maintenance [9–11].

Previous studies on a conventional FRP truss bridge [12,13] revealed that the tensile and compressive behavior of FRP tubes are major concerns when determining structural behavior such as strength and stiffness in typical tube applications. As indicated, the tensile strength of GFRP tubes ranges between 240 MPa and 300 MPa while the compressive strength varies from 200 MPa to 300 MPa, and the elastic modulus is approximately 30 GPa [14–16]. Meanwhile, the compressive behavior with buckling should also be evaluated to avoid overall instability and fateful consequences. For this purpose, a distinguishing criterion between short and long FRP composite compressive behaviors [17] need to be established. It was apparently clear that manufacturing initial curvatures, material imperfections and possible slight eccentricity in the application of axial loads may lead to lower load-carrying capacity for FRP composites, meanwhile, the stiffness of FRP composite materials is the critical design criteria for compression elements instead of the strength.

However, typical FRP profiles for truss structures made from glass FRP (GFRP) exhibit high strength-to-weight ratio, their long-term deficiency, such as creep, may generate large deformation under service load. Although carbon FRP (CFRP) can eliminate the structural deficiency induced by GFRP, the high cost of carbon fibers always limits wide application of CFRP in civil structures [18,19]. During the last decade, possible applications of basalt FRP have been the subject of intensive research. Basalt is a mineral of volcanic origin, the fiber is produced from volcanic rock using a single raw material and drawing fibers from molten rock at a temperature of 1400–1500 °C. The fiber has a number of excellent properties of good mechanical strength, excellent sound and thermal insulator and so on. On the basis of the previous study, it can be concluded that basalt FRP (BFRP) may be a good alternative to GFRP in terms of the application as structural members in truss structures [20] (30% higher strength and modulus, comparable cost, greater chemical stability than GFRP, a wider range of working temperatures and better resistance to corrosion). Moreover, it may be a suitable replacement form of CFRP (the price of BFRP is one sixth that of CFRP) Aside from high performance to cost ratio, basalt fiber is also an environmental friendly material as it is pulled over a roller with neither precursor nor additives in the manufacturing process [21,22]. Thus, the application of BFRP can also benefit sustainable development of construction.

Based on the research focus of FRP truss structures and potential limitations of FRP, this paper will present a comprehensive study of the mechanical properties of BFRP tubes in terms of both tensile and compressive loads and investigate the parameters affecting stability prediction. A comprehensive understanding of BFRP's tensile and compressive behaviors and the prediction of its stability strength under compression are necessary for its safe and reliable application as a structural member in engineering applications.

2. Experimental program

2.1. Parameters and specimen preparation

BFRP tube adopted in the experiment had an external diameter of 16 mm and a thickness of 2 mm. For producing the BFRP tube, basalt fibers with the diameter of 13 μm and strength of 2400 MPa were provided by Jiangsu GMV New Material T&D Co., Ltd, China [23]. The matrix was vinyl-ester resin with the tensile strength of 90 MPa provided by the Reichhold Polymers (Tianjin) Ltd. The BFRP tube was produced by pultrusion with the fiber volume ratio of 60%. Two types of fiber arrangement were designed for the BFRP tubes including Type I, with all fiber roving of 1200 tex, and Type II, with basalt fiber roving of 1200 tex and a layer of two-directional (0/90°) basalt fiber sheets of 400 g/m^2. The fiber volume fraction in 0° direction of BT and BTS is 60% and 56.5%, respectively. For BTS, the volume fraction in 90° direction is 3.5%, the total fraction volume keeps a constant value of 60%. The layer of two-directional basalt fiber sheet was distributed between the inner and the outer basalt fiber roving. The specimens of BFRP tubes are shown in Fig. 1. The Type I BFRP tubes (BT) were addressed to investigate tensile and compressive strength, while Type II BFRP tubes with sheets (BTS) were adopted to verify the effect of basalt fiber sheet on the buckling of BFRP tube.

The specimens of BFRP tubes for tensile test were prepared according to ASTM D2105-01[24]. Each specimen had a total length of 1000 mm, which included a free length of 600 mm and two anchor lengths of 200 mm. In order to assure the failure occurs in the free length of BFRP tube, the anchor portion of the tube was specially treated. First, hollow tube was filled by a BFRP tendon with the length of 200 mm and the diameter of 12 mm to resist the clamping force at the anchor portion. Afterwards, the outer surface of BFRP tube was wound by impregnated fiber roving and subsequently was hardened by compression molding. Finally, the anchor portion of BFRP tube exhibited an outer diameter of 20 mm with solid cross section as shown in Fig. 2.

For the compression test, the specimens were prepared according to ASTM D695-10 [25]. The lengths of the specimens were determined by the slenderness ratio, which is defined by the ratio of free length of BFRP tube to the radius of gyration. GB/T1448-2005 specifies that the slenderness ratio of common specimens should equal to or be less than 10, and it should be set to 6 when there is instability for the specimen [26]. In order to facilitate the distinction, a BFRP tube with a slenderness ratio less than or equal to 6 is named as a short BFRP tube in this paper, while the slender BFRP tube has a slenderness ratio lager than or equal to 10. Thus, a 60 mm-long BFRP tube with a slenderness ratio of 6 was adopted to obtain the axial compression capacity and material properties of the short BFRP tube. Meanwhile, to comprehensively study the compressive strength with respect to the slenderness ratios, five types of slenderness ratios were adopted from 10 to 90 for slender BT, and four types of slenderness ratios from 10 to 70 were adopted for the study of slender BTS as stated earlier. A total of 11 specimens were prepared. The details of the experimental parameters of BFRP tubes are listed in Table 1.

Where, slenderness ratios is calculated by kL/i, where k is the coefficient for the length related to the end bearding conditions, respectively, k = 0.5 for fixed support at both ends and k = 1.0 for both pinned ends. L is the length and i is the radius of gyration, $i = \sqrt{\frac{\pi(D^4-d^4)}{64 \cdot A}} = 5$, D is the outer diameter of the tube, d is the inner diameter of the tube, A is the area of the cross section.

2.2. Test setup and loading procedure

The test procedure for BFRP tubes were according to BS EN 13706-2 [27], which were conducted on a servo hydraulic testing machine with a capacity of 1000 kN, provided by walter + bai Testing Machines Co. Ltd. The stroke-controlled mode was chosen and the loading rate for the BFRP tube was set as 2 mm/min. The load and deformation along the vertical direction were automatically recorded by the load cell and extensometer in the testing machine. The data collection frequency of the test system was set as 1.

2.2.1. Axial tension and compression without buckling

Fig. 3 illustrates the setup for the tensile test, the anchor treated specimen was directly installed in the machine by a hydraulic

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