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Experimental study and theoretical analysis on axial compressive behavior of concrete columns reinforced with GFRP bars and PVA fibers

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HIGHLIGHTS

- Axial compressive behavior of GFRP PVA-FRC columns was investigated.
- A constitutive model for confined concrete was proposed.
- A formula for calculating the peak load was proposed.
- GFRP reinforcements and concrete were more coordinated in bearing axial load together.

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ABSTRACT

There have been some studies on the axial compressive behavior of concrete columns reinforced with fiber-reinforced polymer (FRP) bars. But most studies focused on normal concrete without fibers. In this paper, 10 concrete columns reinforced with glass fiber-reinforced polymer (GFRP) bars and polyvinyl alcohol (PVA) fibers were designed to investigate the influence of reinforcement type, longitudinal reinforcement ratio, spacing and size of GFRP ties on the axial compressive behavior of the specimens. Analytical and numerical studies were explored in this paper. The test results indicated that the concrete column reinforced with GFRP bars and PVA fibers (GFRP PVA-FRC column) and the concrete column reinforced with steel bars and PVA fibers (steel PVA-FRC column) had the similar failure processes and failure modes. The axial bearing capacity and brittleness of the GFRP PVA-FRC columns increased with the increasing longitudinal reinforcement ratio. When the volumetric ratio was constant, the confinement efficiency and ductility of the specimens using GFRP ties with smaller diameter and closer spacing were higher than that using GFRP ties with larger diameter and larger spacing. A new stress-strain constitutive model for PVA fiber reinforced concrete confined by GFRP bars was proposed. The numerical results showed that the concrete in the columns reinforced with GFRP longitudinal bars and GFRP ties could give full play to its strength. The conclusions could be references for the engineering application.

1. Introduction

When the steel reinforced concrete components were used in erosion environments such as bridges, ports or chemical plants, the structural performance deteriorated due to the corrosion of steel reinforcements. And the failure of the critical steel reinforcement concrete components could cause the collapse of the whole structure [1]. FRP bars had many advantages over steel bars, such as no corrosion even in harsh chemical environments, a density of one-fifth to one-quarter of that of steel bars and good electromagnetic insulation property. The use of FRP bars as alternative reinforcements in reinforced concrete was an innovative solution to overcoming the corrosion problem of the steel [2–4].

In recent years, various researchers had investigated the behavior of flexural and shear members of FRP reinforced concrete [5–7]. However, there were relatively little research on the axial compressive behavior of concrete columns reinforced with FRP bars. The ACI 440.1R-06 [8] and the CAN/CSA [9] did not recommend the use of FRP bars as compressive reinforcements. China technical code GB50608-2010 [10] only contained provisions for the design of flexural concrete members reinforced with FRP bars.

FRP bars were linear elastic materials, without yielding stage before failure. The tensile strength of FRP bars was higher than the yield strength of steel bars. The axial compressive behavior of concrete columns reinforced with FRP bars (FRP RC columns) was different from that reinforced with steel bars. The experimental

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results on concrete columns reinforced with steel bars (steel RC columns) could not be directly applied to FRP RC columns. So this paper would investigate the axial compressive behavior of the FRP RC columns.

There were four types of FRP bars containing glass fiber reinforced polymer (GFRP) bar, carbon fiber reinforced polymer (CFRP) bar, basalt fiber reinforced polymer (BFRP) bar and aramid fiber reinforced polymer (AFRP) bar. GFRP bars were widely used in constructions because of their high cost effective performance [11], so in this experiment GFRP bars were chosen as longitudinal and transverse reinforcements.

Some previous studies on concrete columns reinforced with steel bars and fibers under axial compression indicated that the fibers delayed the concrete cover spalling and increased the bearing capacity and ductility of the columns [12,13]. So in this experiment PVA fibers were mixed in the concrete columns reinforced with GFRP bars to overcome the brittleness of GFRP bars and the concrete.

As the reinforcements in the compressive concrete component, GFRP bars had a great influence on the behavior of the whole component. There has been some research on the compressive properties of GFRP bars, but the test results were diversity for the anisotropic and nonhomogeneous nature, different components, diameter, manufacturing process and test method of the FRP bars [14]. Zhou et al. tested 35 GFRP bars with a diameter of 17 mm under compression. The test results indicated that the ultimate compressive strength of the GFRP bars was 55% of the tensile strength of the GFRP bars, the compressive elastic modulus was higher than the tensile elastic modulus, and the failure modes of the specimens were related to their slenderness ratio [15]. Sun and Wan tested 14 GFRP bars under axial compression with a diameter of 14 mm. The test results indicated that the GFRP bars had a high compressive strength, and its compressive strength was slightly lower than its tensile strength [16]. Kobayashi and Fujisaki tested GFRP bars under compression. The test results showed that the compressive strength was 30%–40% of the tensile strength. The failure of the GFRP bars was brittle [17]. Deitz et al. tested 45 GFRP bars under compression. The specimens had a diameter of 15 mm and the unbraced lengths were 50 mm–380 mm. The test results showed that the compressive strength of the GFRP bars was 50% of the tensile strength, and the elastic modulus of compression and tension were nearly the same. The GFRP bars had three failure modes containing crushing, buckling, and combined buckling and crushing [18].

Some researchers have investigated the behavior of concrete columns reinforced with FRP bars, but the concrete used was focused on normal concrete without fibers. Pantelides tested 10 concrete columns confined by GFRP spirals or steel spirals under axial load. The longitudinal reinforcements were steel bars or GFRP bars. The all steel reinforced and hybrid columns were subjected to accelerated corrosion. The test results indicated that the hybrid specimens had a higher corrosion resistance [19]. The previous studies indicated that the CFRP RC columns and GFRP RC columns had a similar performance to the steel RC columns. The FRP longitudinal reinforcements carried lower load then the steel longitudinal reinforcements. The GFRP and CFRP longitudinal reinforcements contributed 5%–10% and 12% of the column bearing capacity respectively [20–22]. De Luca tested 1 steel and 4 GFRP reinforced square concrete columns under axial load. The test results indicated that the GFRP RC columns and the steel RC column had the similar behavior. The tie spacing had a strong influence on the failure modes of the columns [23]. Tobbi tested square concrete columns reinforced with GFRP bars or CFRP bars under axial compression. The test results indicated that the longitudinal FRP bars provided adequate axial capacity. The FRP RC columns had acceptable strength and ductility behavior [24,25]. Ragab and Eisa tested 7 square GFRP RC columns under axial load. The experimental parameters were reinforcement types, concrete types and steel fiber volume fractions. The results indicated that the behavior of the GFRP RC columns was similar to that of the steel RC columns. The bearing capacity of longitudinal GFRP reinforcements was 20% lower than that of the longitudinal steel reinforcements. The mix of steel fibers improved the ultimate capacity load, cover spalling load and ductility of the columns [26]. Zafar et al. tested 21 circular CFRP RC columns under axial load. The test results indicated that the failure of the CFRP RC columns was attributed to the rupture of the transverse GFRP reinforcements. And reducing the tie spacing increased the axial bearing capacity [27].

A few researchers proposed the confinement models for concrete confined by FRP bars. Afifi et al proposed a confinement model for concrete confined by CFRP bars [28] or GFRP bars [29] in circular columns. Tobbi proposed a confinement model for concrete confined by CFRP bars or GFRP bars [30]. For the confinement models, the calculation of the stress in the transverse reinforcements at concrete peak stress was critical. The existing confinement models considered that the stress in the transverse reinforcements at concrete peak stress was related to the bend strength of the transverse reinforcements. This paper proposed a confinement model for which the stress in the transverse reinforcements at concrete peak stress was related to both bend strength and configuration of the transverse reinforcements.

To date, little research had been done on concrete columns reinforced with fibers and FRP bars and no constitutive models for fiber reinforced concrete confined by GFRP bars had been proposed. This paper investigated the axial compressive behavior of GFRP PVA-FRC columns and proposed a confinement constitutive model. The test results could be references for the theoretical research and engineering application.

1.1. Objectives

This paper reported the test results of GFRP PVA-FRC columns under axial compression. The first objective was to investigate the effect of the reinforcement type, longitudinal reinforcement ratio, spacing and size of GFRP ties on the axial compressive behavior, axial compressive bearing capacity, confinement efficiency and ductility of the GFRP PVA-FRC columns. The second objective was to develop the calculation formula of axial compressive bearing capacity of the GFRP PVA-FRC columns. The third objective was to propose a stress-strain constitutive model for the PVA fiber reinforced concrete confined by GFRP bars.

2. Test program

2.1. Specimen design and fabrication

10 square fiber reinforced concrete columns were constructed and tested to investigate the effect of the reinforcement type, longitudinal reinforcement ratio, spacing and size of GFRP ties on the axial compressive behavior of the columns. Among the 10 columns, a column with no reinforcement and a column with steel reinforcements were introduced as reference specimens, and the other 8 PVA-FRC columns were reinforced with GFRP bars. The width and the height of each specimen were 350 mm and 1200 mm. The concrete cover was 25 mm.

The details of the test specimens were listed in Table 1. Each specimen with reinforcements was identified with letters and numbers. The letters G and S stood for the longitudinal reinforcement type and the transverse reinforcement type respectively. V stood for the longitudinal reinforcement. H stood for the