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Seismic behaviour of FRP-concrete-steel double-tube columns with shear studs: Experimental study and numerical modelling

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Highlights

- The seismic behavior of FRP-concrete-steel double-tube columns (DTCCs) was investigated experimentally and numerically.
- DTCCs generally have rounded hysteretic curves with ample energy dissipation capacity.
- The concrete core of DTCCs can effectively suppress the local buckling of the inner steel tube.
- A numerical model was established for DTCCs, which was able to provide predictions with reasonable accuracy.

Abstract

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FRP-concrete-steel double-tube columns (i.e., double-tube concrete columns or DTCCs) are a novel type of structural members composed of two concentrically-placed tubes (i.e., an outer FRP tube and an inner steel tube) with all the space inside the two tubes filled with concrete. Shear studs on the inner steel tube are recommended to increase the composite action when DTCCs are subjected to large bending moments. The optimized section configuration of DTCCs allow the three constituent materials in the columns to deliver their respective advantages and to avoid their respective shortcomings. The limited existing studies on DTCCs have been focused on their compressive behavior. These studies have demonstrated the excellent ductility of DTCCs, an important advantage for their potential applications in regions with seismic risk. However, the seismic behaviour of DTCCs has not been systematically investigated. Against this background, this paper presents a combined experimental and numerical study on the seismic behaviour of DTCCs, where the experimental part included a series of large-scale DTCCs tested under combined cyclic lateral loading and constant vertical compression, while the numerical part included the development of a finite element included the development of a finite element model incorporating beam-column elements and specific stress-strain models to consider the unique behaviour of the two parts of concrete in DTCCs (i.e., the concrete core inside the inner steel tube and the concrete ring between the two tubes). The experimental results revealed that: (1) the increase of FRP thickness had a positive effect on their hysteretic behavior; (2) when the steel ratio was constant, the peak lateral load of DTCCs increased with the steel tube diameter; (3) the concrete core not only enhanced the lateral load capacity and the ductility of DTCCs, but also provided efficient suppression on the buckling of the steel tube. The numerical model, established using the OpenSees platform, is able to provide reasonably accurate predictions of the hysteretic behaviour of all specimens.

Introduction

As an emerging type of high-performance construction material with high strength and remarkable anticorrosion characteristics, fiber-reinforced polymer (FRP) has been extensively used for repairing structures with insufficient strength or significant degradation [1], [2]. Over the past twenty years, FRP has also been used for repairing structures with insufficient strength or significant degradation [1], [2]. Over the past twenty years, FRP has also been explored to be integrated with traditional construction materials (e.g., timber, concrete, steel, masonry) to form new structural members [3], [4], [5], [6], [7], [8]. FRP-concrete-steel double-tube columns (i.e., double-tube concrete columns or DTCCs) are an emerging type of structural members by combining FRP with both steel and concrete [9], [10], [11]. A DTCC (Fig. 1a) consists of two concentrically-placed tubes (i.e., an outer tube made of FRP and an inner tube made of steel), a concrete ring between the two tubes and a concrete core inside the steel tube. Shear studs on the steel tube are recommended for enhanced composite action, and such shear studs are particularly important when DTCCs are subjected to large bending moments. The optimal configuration of DTCCs allow the constituent materials to deliver their respective advantages and to avoid their respective shortcomings: (1) the FPR tube works as an anticorrosion sheath to protect both steel and concrete from external harsh environments, thus prolonging the service life; (2) as confining materials, both tubes of DTCCs provide effective confinement, resulting in enhanced strength and improved ductility; (3) the steel tube works tube are recommended for enhanced composite action, and such shear studs are particularly important when DTCCs are subjected to large bending moments. The optimal configuration of DTCCs allow the constituent materials to deliver their respective advantages and to avoid their respective shortcomings: (1) the FPR tube works as an anticorrosion sheath to protect both steel and concrete from external harsh environments, thus prolonging the service life; (2) as confining materials, both tubes of DTCCs provide effective confinement, resulting in enhanced strength and improved ductility; (3) the steel tube works as the longitudinal reinforcement for DTCCs with its potential local buckling being well suppressed by the surrounding concrete, thus enhancing the compressive, bending and shear capacities of the columns; (4) to facilitate the construction process, the two tubes can be used as formworks for casting the concrete ring and the concrete core.

DTCCs may be regarded as a variant form of hybrid FRP-concrete-steel double-skin tubular columns (i.e., DSTCs) (Fig. 1b) [9], [10], [11]. When DSTCs were initially proposed [12], [13], filling concrete inside the inner steel tube was mentioned to be a possible option. Over the past two decades, DSTCs have been studied extensively which demonstrated their excellent

DTCCs may be regarded as a variant form of hybrid FRP-concrete-steel double-skin tubular columns (i.e., DSTCs) (Fig. 1b) [9], [10], [11]. When DSTCs were initially proposed [12], [13], filling concrete inside the inner steel tube was mentioned to be a possible option. Over the past two decades, DSTCs have been studied extensively which demonstrated their excellent behavior under various loading conditions, such as monotonic axial compression [14], [15], [16], [17], [18], [19], [20], [21], [22], cyclic axial compression [23], [24], [25], eccentric compression [26], [27], combined cyclic lateral loading and constant vertical compression [28], [29], [30], [31], and impact loading [32], [33], [34]. Numerical simulation methods and design models have also been proposed for DSTCs, among which the design method based on Refs. [12], [13] has been included in the Chinese technical code GB 50608-2010 [35]. Furthermore, DSTCs have been successfully applied as bridge piers in China [36].

As a variant form of DSTCs, DTCCs were less investigated but have received increasing attention recently. In the early studies on DTCCs, they were often used as companion specimens of DSTCs. Ozbakkaloglu's group [37], [38] tested a series of DSTCs under monotonic axial compression with companion DTCCs, and investigated but have received increasing attention recently. In the early studies on DTCCs, they were often used as companion specimens of DSTCs. Ozbakkaloglu's group [37], [38] tested a series of DSTCs under monotonic axial compression with companion DTCCs, and concluded that DTCCs had higher averaged stress for the confined concrete but less ductile performance than DSTCs. Teng et al. [9] tested circular DTCCs with a high-strength steel tube subjected to monotonic axial compression, and demonstrated the high strength of steel could be fully utilized as the steel tube buckling was effective suppressed by the concrete. Zeng et al. [39] tested square DTCCs with a circular high-strength steel tube under monotonic axial compression. Wang [10] proposed an analysis model for DTCCs under monotonic axial compression by considering the compressive behavior for the concrete core and the concrete ring differently. Zhang et al. [11] systematically investigated DTCCs under monotonic axial compression and examined the effects of fiber winding angles. Zhang et al. [11] found that, with the increase of fiber angles, the FRP confining effect increased while the overall ductility of DTCCs decrease. Due to the remarkable composite action, DTCCs had an axial load capacity much larger than the sum of the axial compressive capacities of three constituent materials individually under winding angles. Zhang et al. [11] found that, with the increase of fiber angles, the FRP confining effect increased while the overall ductility of DTCCs decrease. Due to the remarkable composite action, DTCCs had an axial load capacity much larger than the sum of the axial compressive capacities of three constituent materials individually under compression. Wang [10] also conducted experiments on DTCCs under cyclic axial compression and eccentric compression, and proposed design models for DTCCs under these loading conditions.

It is evident from the above review that existing studies on DTCCs have been generally focused on their compressive behaviour, while their seismic behaviour has not been systematically investigated. To the best of the authors' knowledge, the only experimental study related to the seismic behaviour of DTCCs was reported by Zhang et al.'s [28], in which the beneficial effects of filling the inner steel tube in DSTCs with concrete were demonstrated using one single specimen. It should be noted that even this single specimen was technically not a DTCC specimen as the concrete was filled in the steel tube for only the bottom 300-mm-high of the specimen. Against this background, this paper presents a combined experimental and investigated. To the best of the authors' knowledge, the only experimental study related to the seismic behaviour of DTCCs was reported by Zhang et al.'s [28], in which the beneficial effects of filling the inner steel tube in DSTCs with concrete were demonstrated using one single specimen. It should be noted that even this single specimen was technically not a DTCC specimen as the concrete was filled in the steel tube for only the bottom 300-mm-high of the specimen. Against this background, this paper presents a combined experimental and numerical study on the seismic behaviour of DTCCs, where the experimental part included a series of large-scale DTCCs tested under combined cyclic lateral loading and constant vertical compression, while the numerical model was established on the OpenSees platform [40].

Section snippets

Details of specimens

Six large-scale specimens were fabricated and investigated in this study, with the key testing parameters being the FRP thickness, the steel tube type, and the presence / absence of the concrete core (Table 1). It is well known that

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Section snippets

Details of specimens

Six large-scale specimens were fabricated and investigated in this study, with the key testing parameters being the FRP thickness, the steel tube type, and the presence / absence of the concrete core (Table 1). It is well known that, the FRP tube thickness is a crucial parameter affecting both the strength and the ductility of concrete confined by FRP. For DTCCs, the steel tube type (i.e., different diameter and thickness for the steel tube) affects the sectional configuration and the steel…

General

For ease of subsequent discussions, the directions of cyclic lateral load were defined in Fig. 6 based on the moving direction of the servo actuator. When the servo actuator was in the push direction, Side-E of the column was subjected to compressive stresses, while Side-A of the column was in tension. In the following discussions, tensile strains/stresses are defined as negative, and compressive stresses/strains are taken as positive; the term "lateral

Constitutive models of constituent materials

A numerical model was built for both DTCCs and DSTCs with OpenSees platform [40] to simulate their hysteretic behaviours. The constitutive model for each constituent material was considered properly to realize accurate and efficient simulations, as elaborated below.

Following Refs. [29], [30], [31], the "ReinforcingSteel" uniaxial stress-strain model in OpenSees [40], which had been widely used for simulating steel reinforcements using the fiber-based discretization, was used for the steel tube. ...

Conclusions

This paper has presented a combined experimental and numerical study involving large-scale tests on DTCC specimens and companion DSTC specimens under combined cyclic lateral loading and vertical constant compression, as well as the development of numerical models for simulating their seismic behavior. The results and discussions presented above allow the following conclusions to be drawn:

drawn:

(1) DTCCs generally have rounded hysteretic curves with limited pinching, indicating their excellent seismic ...

CRediT authorship contribution statement

Bing Zhang: Conceptualization, Funding acquisition, Supervision, Investigation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Shuhong Lin:** Investigation, Formal analysis, Writing – original draft, Writing – review & editing. **Sumei Zhang:** Supervision, Writing – review & editing. **Xingbao Lu:** Data curation, Investigation. **Tao Yu:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing....

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper....

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