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Compressive behavior of thin-walled circular steel tubular columns filled with steel stirrup-reinforced compound concrete

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ABSTRACT

The reuse of coarsely crushed demolished concrete lumps (DCLs) with fresh concrete (FC) in compound concrete (i.e. concrete composed of DCLs and FC) provides a viable option to recycled concrete aggregates for recycling concrete waste. Compound concrete-filled steel tubular (CCFST) columns further improve the efficiency with which DCLs are used due to the advantages of concrete-filled steel tubular columns, such as improved strength and ductility. This paper presents an experimental study of the compressive behavior of thin-walled circular steel tubular columns filled with compound concrete with and without internal steel stirrups. Twenty CCFST columns were tested for experimental investigation of the effects of the replacement ratio of DCLs, the strength of the FC, the thickness of the steel tubes, and the distribution of steel stirrups. The test results show that steel stirrups can considerably enhance the load-carrying capacity of CCFST columns and significantly improve their ductility regardless of the strength of the FC, and a non-uniform layout (mainly in the middle height of the column) of steel stirrups can further enhance the performance of the CCFST columns without increasing the amount of steel. Based on the results, a simplified design method proposed for CCFST columns reinforced with internal steel stirrups compared well with the test results.

1. Introduction

The recycling and reuse of construction and demolished (C&D) concrete waste have great significance due to the obvious social and environmental merits: reducing the demand for natural resources for construction materials and saving space in landfills. A typical method of reusing C&D concrete waste is to break it into recycled concrete aggregates (RCAs) and use them in recycled aggregate concrete (RAC) [1–3]. However, because RCAs have weak interfacial transition zones and damage/porosity [4,5], RAC has a number of limitations compared with natural aggregate concrete, such as higher water absorption, greater creep and shrinkage, lower strength and stiffness, and inferior durability [6–10]. In the past few decades, extensive studies worldwide [3,10–12] have been carried out to enhance the performance of RAC [13–16]; nevertheless, its use has been limited to nonstructural applications, mainly due to the limitations mentioned above [17]. Compared with the reuse of C&D concrete waste as RCAs in RAC, the direct use of coarsely-crushed demolished concrete lumps (DCLs) with fresh concrete (FC) in structural members to form compound concrete (i.e. concrete composed of DCLs and FC), as proposed by the first author [18], provides another viable option for recycling of concrete waste. In addition to reducing the cost, energy, and time required to produce RCAs from C&D concrete waste, the use of DCLs also avoids significant further damage to the parent concrete (i.e. the C&D concrete waste) caused by a crusher or other tools during the production of RCAs and minimizes the amount of useless debris/ash it creates. Furthermore, by reusing C&D concrete waste in the form of DCLs that are distinctly larger (e.g. 50–300 mm) than RCAs (e.g. normally < 50 mm) in structural members [19], considerable amounts of cement, water, and energy can be saved, thus reducing the emission of carbon dioxide. As a result, reusing C&D concrete waste in the form of DCLs is greener than reusing RCAs in RAC. Given these advantages, studies on recycling C&D concrete waste as DCLs [19–29] or large RCAs [30] have increased in the past decade, and the authors' research group has carried out systematic studies on compound concrete and/or composite structures that incorporate DCLs [19–27].

Previous studies on compound concrete have shown that the DCLs and the FC bond well regardless of whether the strength of the FC is similar to or significantly higher than that of the DCLs, implying the feasibility and reliability of using DCLs in structural members [21–23]. Although the presence of DCLs may have some detrimental effects, such as a reduced compressive strength, a decreased modulus of elasticity,

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and a slightly stronger size effect in the strength of compound concrete, these unfavorable effects can be controlled by limiting the replacement ratio of the DCLs (the mass ratio of DCLs to compound concrete). For example, it has been shown that when the replacement ratio of DCLs is less than 33.3% by mass and the difference in strength between the DCLs and the FC is small (i.e. less than 15 MPa), the effect of DCLs on the structural behavior of compound concrete members is limited: less than a 10% reduction in strength and nearly no decrease in stiffness [19]. It has also been shown that although the characteristic ratio of DCL, defined as the ratio of the characteristic size of the DCLs to the characteristic dimension of the concrete member (e.g. the diameter of a cylinder specimen), has nearly no effect on the modulus of elasticity and the strain at peak stress, the compressive strengths (cylinder strength and cube strength) of the compound concrete decrease gradually as the characteristic ratio increases, suggesting that the characteristic ratio of DCL should be limited (e.g. $< 1/3$) to ensure the efficiency and reliability of using DCLs [22,23]. Based on the research outcomes of previous studies, DLCs have been successfully used in several real construction projects pioneered by the first author of this paper. Examples of the application of DCLs in real projects have been reported [19,31]. Fig. 1 shows two recent examples of using compound concrete made of DCLs and FC that demonstrate the process of on-site casting of compound concrete for buildings slabs in real engineering projects.

Using DCLs together with FC in steel tubes in the form of compound concrete-filled tubular columns (CCFST) columns was initially proposed by the first author [18]. The previous studies demonstrated that as with concrete-filled steel tubular (CFST) columns, the performance of CCFST columns is significantly better (e.g. enhanced strength, increased deformation capacity, and improved ductility) than that of compound concrete columns. For CCFST stub columns with a steel tube with a diameter-to-thickness ratio (D/t) of 54.8 (i.e. $D/t = 54.8$), it was shown that if the replacement ratio of DCLs was under a certain value (32–35%) [27], the initial stiffness, load-carrying capacity, and ductility of the CCFST stub columns were comparable to those of conventional CFST stub columns. For thin-walled CCFST stub columns with $D/t = 200$, the use of DCLs has only a slightly detrimental effect on the load carrying capacity: the reduction in load carrying capacity is less than 10% compared with the corresponding thin-walled CFST stub column when the replacement ratio of DCLs is not large (e.g. 25–35%). Research was also carried out on slender column [20] and seismic behavior (e.g. deformation capacity and energy dissipation capacity) of both circular [24] and square [25] thin-walled CCFST columns, and it was found that the CCFST columns can achieve behavior similar to that of CFST columns if the replacement ratio is controlled within a certain value (e.g. 0–40%). It was also observed in these studies that the strength and behavior of the CCFST columns were usually governed by premature local buckling of the steel tubes, which was characterized by local bulging of the steel tubes and associated with dilation of the compound concrete, especially in the thin-walled CCFST columns. Teng et al. [29] experimentally explored the efficiency of fiber-reinforced polymer (FRP) confinement on the compound concrete and found that the stress-strain behavior of the confined compound concrete was similar to that of the confined FC if the confinement provided by the FRP was significant. In real engineering application, the steel tube has an additional advantage: it can work as the formwork for casting of the compound concrete, which thus enhances the constructability of the CCFST column. Concept and example applications of composite members that incorporate DCLs on-site in real engineering projects were recently shown by Zhao et al. [20].

This paper presents an experimental study of the compressive behavior of thin-walled circular steel tubular columns filled with compound concrete reinforced with steel stirrups. As existing studies have shown that internal steel stirrups are effective in improving the performance of CFST columns [32–34], one of the aims of our study was to investigate the effects of internal steel stirrups and their distributions on the performance of CCFST columns subjected to concentric loading. In particular, the function of the internal steel stirrups in reducing/eliminating the detrimental effects arising from the local buckling of steel tube will be explored by examining the strain distributions in steel tubes and the steel stirrups, as the local buckling of steel tube is a typical failure mode compromising the good performance of the thin-walled CCFST columns, as mentioned above. It should be noted that the use of internal steel stirrups has additional merits, such as improving the CCFST column's fire-resistance performance (see Zhang [35] for more details), but the research on this issue is beyond the scope of this study.

In the remainder of this paper, measures to enhance the performance of thin-walled CFST columns are briefly reviewed first to provide the necessary background for this study. The test program and set-up are then introduced, followed by a presentation and discussion of the test results. A simplified design method for the design of CCFST columns is then proposed and substantiated with the test results, and our conclusions are summarized toward the end of the paper.

2. Measures for enhancing the performance of thin-walled CFST columns

The internal circular steel stirrup adopted in this study is one of the effective measures capable of enhancing the performance of thin-walled CFST columns. Although a thorough review of the effective measures for enhancement of the performance of thin-walled CFST columns is beyond the scope of this study, this brief review of the most relevant studies on the issue provides the necessary background.

CFST columns have many well-established advantages, such as high ductility, good deformation capacity (well-suited for seismic-resistance), and ease of construction [36–40]. These advantages arise from the favorable interaction between the concrete and the steel tube. The tube confines the core concrete, which in turn restraints the tube's inward buckling When subjected to compression, the steel tubes in CFST columns may suffer from local outward bucking failure, especially for thin-walled steel tubes with a D/t greater than a certain value (e.g. $D/t > 90\left(\frac{235}{f_y}\right)$ according to EC4:2004 [41]), partially due to incompatibility in the modulus of elasticity, the difference in circumferential deformation (due to different Poisson ratios) between concrete and steel in the early stage of loading, and the severe dilation of the core concrete in the later stage of loading [40]. The occurrence of local buckling compromises some of the advantages (e.g. the high ductility and good deformation capacity) of CFST columns. Numerous measures have been shown to alleviate and/or delay the local buckling of steel tubes to achieve better performance of CFST columns (e.g. ductility, deformation capacity, and load-carrying capacity) in one way or another. These measures can be grouped into three categories according to their functions: (1) additional stiffening measures for steel tubes, such as different stiffeners [42–47]; (2) additional confinement/restraint measures for steel tubes, such as binding bars [48], tie bars [49], external steel rings [50–52], and FRP [53–57]; and (3) additional confining/reinforcing steel reinforcements [32–34] or confining FRP [58] for the core concrete. For example, Dong et al. [59] found that external FRP confinement can significantly enhance the load-carrying capacity and deformation capacity of RAC-filled steel tubes and postpone and/or prevent the occurrence of local buckling of the steel tube.

3. Test program

3.1. Test specimens

Twenty circular CCFST stub columns with or without internal steel stirrups were prepared and tested in this study. To increase the reliability of the test results, two nominally identical (i.e. geometric dimensions and material properties) specimens were cast and tested for