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Effect of ultra-high strength steel on mitigation of non-ductile yielding of concrete-filled double-skin columns

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HIGHLIGHTS

- Static compression tests were performed on CFDST sections with corner steel tubes.
- It is shown that UHS corner tubes mitigates the non-ductile behaviour of CFDSTs.
- Finite element models were developed and validated utilizing experimental results.
- Analytical formulation was developed to predict the compressive behaviour of CFDSTs.

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ABSTRACT

Concrete-filled tubular (CFT) sections, and the most recent configuration of these sections, concrete-filled double-skin tubular (CFDST) sections, can provide high strength in structural construction. In this study, an innovative fabrication strategy is proposed to prohibit the non-ductile yielding of CFDST sections by applying ultra-high strength steel corner steel tubes. Hence, the static compressive behaviour of CFDST columns containing ultra-high strength steel tubes is experimentally investigated. The results are then compared with those for the same experiment conducted on a CFDST specimen with corner mild steel tubes. In addition, a numerical investigation is conducted to examine the effect of different parameters on promoting the ductility and compressive strength. In order to pave the way for utilizing CFDSTs with corner tubes in engineering practice, a simple analytical formulation is also proposed to predict the load-displacement relationship of these sections based on the experimental and numerical results.

1. Introduction

High strength and ductility are general structural demands in engineering practice. Structural steel sections are renowned for their sufficient ductility, while concrete sections take advantage of their high compressive strength. The employment of composite sections fabricated from both steel and concrete materials in construction is a promising way to take advantage of both the notable compressive strength of concrete and the high ductility of steel. Concrete-filled tubular (CFT) sections and concrete-filled double-skin tubular (CFDST) sections are the most widely used types of steel-concrete composite sections. There is a beneficial interaction between steel and concrete components in these types of composite sections [1–3]. The steel sections used as the skins of a CFT or CFDST section confine the concrete infill and improve its compressive behaviour. At the same time, the concrete infill prevents the steel skins from buckling inward and consequently enhances the stability of their structural behaviour. The structural behaviour of these steel-concrete composite members has been studied by various researchers under different loading scenarios [3–8].

Recently, the compressive behaviour of a new type of CFDST section has comprehensively been investigated experimentally and numerically by the authors [9,10]. Numerous square-shaped CFDSTs consisting of corrugated inner or outer skins were subjected to static compression loading. It has been found that these sections behave almost linearly under axial compressive loading until the ultimate load-bearing capacity is achieved. Subsequently, the compressive strength drops rapidly and plastic deformations grow locally close to one end of these sections [9,10]. Accordingly, insufficient ductility undermines the superior compressive strength of the CFDST sections. Consequently, it remains necessary to improve the behaviour of these sections under compression.

It has been shown that the use of high-strength (HS) and ultra-high strength (UHS) steel in the fabrication of composite sections

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has promising effects on the structural behaviour of these sections [11,12]. Hsiao et al. [13] enumerated these advantages for composite sections consisting of high strength (HS) steel: providing a large elastic deformation capacity, reducing the required cross-sectional size, and reducing the strength contribution of the concrete infill, thereby reducing the strength deterioration of the member. In addition, in order to avoid low ductility due to the smaller rupture strain of high-strength steel, they used a combination of HS outer skin and mild steel inner skin to fabricate CFDST columns [13]. Konstantinos et al. [14] also demonstrated the behaviour of CFTs consisting of HS steel skins under cyclic lateral loading. They showed that HS steel skins postponed the initiation of strength deterioration in the column specimens up to drift angles near to 4%, which can be considered as a sufficient level of storey drift in contemporary seismic design.

Meanwhile, Nassirnia et al. [15] and Javidan et al. [16] took advantage of HS and UHS steel tubes to enhance the compressive behaviour of hollow steel sections. They applied four UHS or HS tubes at the corners of flat and corrugated steel hollow sections. Significant increases have been reported in the axial strength and the energy absorption capacity of hollow steel columns due to the employment of corner UHS tubes [15–17]. In addition, the failure mechanism of the hybrid steel hollow sections with corner UHS steel tubes was different from that of hollow steel sections without corner tubes. It has been shown that corner UHS steel tubes mitigate local buckling along the steel hollow sections, which leads to significant enhancement in both strength and ductility [15,16]. Accordingly, it was intended to implement the same strategy in this study to examine the efficiency of UHS tubes in enhancing the static compressive performance of CFDST sections. It was expected that the dominant axial strength of corner tubes made of HS and UHS steel would help the entire cross-section carry excessive axial loading after the concrete infill and steel skins lose their capacity to tolerate excessive axial loading. CFDST columns with corner tubes can be used as the columns of high-rise buildings and bridges that are subjected to high axial force demand. It is also worth noting that a modular beam-to-column connection has already been devised to connect the typical beams to the columns with corner tubes [18]. Accordingly, the columns with the proposed section can be used in routine structural engineering practice.

In the current study, the static compressive behaviour of two short CFDST columns consisting of corner steel tubes is experimentally investigated. One specimen takes advantage of corner mild steel (MS) tubes, and the other one has UHS steel tubes at its corners. The validity of the aforementioned hypothesis on the effect of employing corner UHS steel tubes on the axial compressive behaviour of CFDSTs has been examined, based on the experimental findings. In addition, a finite element (FE) modelling framework is validated against the experimental results. Several numerical simulations are then conducted to reveal more details about the compressive behaviour of CFDST sections with corner tubes fabricated from different steel materials ranging from mild to UHS steel. Finally, a simple analytical formulation is proposed in order to predict the entire load-displacement curve of CFDST short columns with corner tubes.

2. Static compressive experiments

In order to investigate the effect of employing corner tubes on the compressive behaviour of CFDST short columns, two experiments were conducted. The corner tubes used to fortify the CFDSTs were made from different types of steel material, ranging from Grade 350 mild steel (MS) to Grade 1200 ultra-high strength (UHS) steel. Although the experimental tests were conducted only on CFDST columns with corner MS or UHS steel tubes, the results of the experiments were then implemented to validate a FE modelling framework. Consequently, the compressive behaviour of different CFDST sections fortified with different grades of corner steel tubes has been simulated numerically.

The schematic cross-section of both experimental specimens is depicted in Fig. 1, and the material properties of these specimens are summarized in Table 1. The height of both specimens was chosen equal to one meter. The specimens with UHS and mild steel corner tubes were named “ICT-UHS” and “ICT-MS”, respectively. Term “IC” in the name of these specimens indicates that corrugated plates were utilized to fabricate the inner skins of these specimens. The geometry of the corrugated plates used in fabrication of the inner skins of the specimens is shown in Fig. 1.

2.1. Fabrication of the experimental specimens

The outer steel skins of both ICT-UHS and ICT-MS specimens were fabricated from the same plates and with the same dimensions. 3 mm thick Grade 250 mild-steel plates were used for the outer skin. Four flat plates and four corner tubes were then assembled together using longitudinal fillet welds. The plates and tubes were welded along their one-meter length utilizing 2.4 mm welding wires of type AWS A5.9 ER2209. In this study, it has been tried to keep the strength of corner tubes as the only variable among different experimental specimen and numerical archetypes. This helped the authors to attribute reasonably the difference in the failure mechanism and the ultimate compressive capacity observed for the different samples to the different strength of the applied corner tubes. Hence, the same welds were used to assemble both specimens. Both mild-steel and UHS tubes used in this study had the same nominal outer diameter of 76.1 mm and the same nominal wall thickness of 3.2 mm. The UHS tubes were fabricated from UHS structural steel with an average yield strength of 1247 MPa [16]. UHS tubes manufactured by SSAB Corporation (branded as Raex 400) were utilized in this research. The UHS tubes were manufactured using homogenous longitudinal welds. On the other hand, the mild steel tubes used in specimen ICT-MS were fabricated from mild steel with an average yield strength of 305 MPa [16]. Fig. 2 shows the stress-strain curves for mild and UHS steel obtained from the standard tensile experiments conducted by Javidan et al. [16]. Although the strength of mild steel tubes is less than that of UHS tubes, the mild-steel tubes are more ductile than UHS tubes [16].

The inner steel skins of both specimens were the same and fabricated by welding four corrugated plates with the dimensions shown in Fig. 1. The corrugated plates were cold-formed from Grade 250 flat mild-steel plates, which were 247.5 mm wide, 1000 mm long, and 3 mm thick, using the press-braking method. The type of welding implemented to assemble the corrugated inner steel skins was butt (groove) welding, in which ER2209 wires were utilized to carry out the gas tungsten arc welding (GTAW).

The fabrication procedure explained above resulted in some geometric imperfections in the final steel sections. These imperfections might have affected the stability of the compressive behaviour of the final CFDST section. Hence, an attempt was made to measure the imperfections in the fabricated steel sections before the concrete pouring, since imposing the measured imperfections on the intact geometry in the numerical modelling would improve the accuracy of the simulation results. The imperfections were measured along and across each face of the fabricated hollow sections relative to a datum point. Out-of-plane imperfections were measured at two points across and 4 points along each face of the hollow sections with a digital touch-probe coordinate measuring gauge. The maximum longitudinal and transverse imperfections