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Square concrete-filled stainless steel/carbon steel bimetallic tubular stub columns under axial compression

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ABSTRACT

This paper is an attempt to study the mechanical behavior of square concrete-filled bimetallic tubular (CFBT) stub columns subjected to axial compression. The bimetallic tubes in the CFBT columns in this research comprised an outer layer made of stainless steel and an inner layer made of carbon steel. 200-mm square carbon steel tubes (wall thickness $t_{sc} = 3.30$ mm) were manufactured first, then the bimetallic tubes were fabricated by cladding the carbon steel tubes with stainless steel sheets. In the experimental program, fourteen CFBT columns and two conventional concrete-filled steel tubular (CFST) counterparts were tested to failure under axial compressive loading. The test parameters included the stainless steel grade (Grade 316, 304, and 202), wall thickness of the stainless steel tube layer ($t_{ss} = 0.84$, 1.32, and 1.88 mm), and cube compressive strength of concrete ($f_{cu} = 54.5$, 68.4, and 80.5 MPa). A finite element analysis (FEA) model was established and validated against the experimental measurements. The failure mode and mechanical behavior of the square CFBT stub columns were then investigated and compared with those of the conventional CFST columns. Finally, the ultimate loads obtained from the experiments were compared to those predicted by the available design codes.

1. Introduction

Concrete-filled steel tubular (CFST) members have been extensively investigated and widely applied in the practical engineering [1], especially in high-rise even super high-rise buildings and long-span bridges. Besides the conventional CFST members using single-layer tubes made of carbon steel, there have been some other improved types of steel-concrete composite tubed sections proposed by researchers around the world, like concrete-filled stainless steel tubular (CFSST) members [2–6], and concrete-filled dual steel tubular (CFDST) members with outer stainless steel tubes [7–11]. One major purpose of the derived members is to increase the rust and corrosion resistance, which could be the controlling factor in structural design under some special circumstances.

Stainless steel is well known for its extreme durability, high resistance to rusting and corrosion, and easy maintenance. Recently, there has been a fast increasing interest in the use of stainless steel in construction all over the world [12]. However, this type of advanced material is much more expensive than the carbon steel, and could only be widely applied in structures when the relatively cheap lean duplex material is used [13–15] or smarter utilization method adopted at this stage.

With the purpose of fully utilizing the behavior of stainless steel and compensating the high cost, a new type of CFST member, i.e., concrete-filled bimetallic tubular (CFBT) member, was proposed in [16,17]. The CFBT members are bimetallic tubes, which contain two layers made from different materials, infilled with core concrete. To meet the specific requirements in practical applications, the bimetallic tubes could be combinations of various different metals, such as stainless steel (external)-carbon steel (internal) bimetallic tubes. The cost of CFBT members is expected to be between those of the conventional CFST members and CFSST members.

Ten circular CFBT stub column specimens and two CFST counterparts were tested under axial compression by Ye et al. [16] to preliminarily investigate the mechanical behavior of CFBT members. The experimental results confirmed the composite actions between different components of the CFBT column, which led to good load-carrying capacity and ductile structural behavior of the composite member. Square is another common cross-sectional shape besides of circle, and the square CFST members exhibit obviously different behavior compared to the circular ones, primarily due to the different confinement effects provided by the outer steel tube. It can be expected that, square CFBT columns would show different performance from circular ones. Thus, this paper is devoted to study the axial compressive behavior of CFBT stub columns with a square cross section. The main purpose of the research conducted herein is threefold: (1) to experimentally investigate

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Nomenclature

A_c	cross-sectional area of concrete core
A_{sc}	cross-sectional area of carbon steel tube layer
A_{ss}	cross-sectional area of stainless steel tube layer
A_t	total cross-sectional area
B	width of square cross section
E	elastic modulus
f_{ck}	characteristic compressive strength of concrete
f_{cu}	cube compressive strength of concrete
f_{sc}	characteristic compressive strength of CFST section
f_{yc}	yield stress of carbon steel
$f_{y,c}$	yield stress of corner material
$f_{y,v}$	yield stress of virgin material
f_c'	cylinder compressive strength of concrete
L	length of column specimen
n	strain-hardening exponent of stainless steel
N	axial load
N_u	axial compressive strength
$N_{u,c}$	ultimate strength calculated by design codes
$N_{u,e}$	experimental ultimate strength
$N_{u,FEA}$	ultimate strength predicted by FEA modelling
$p_{c\text{-}s}$	interaction stress for the interface between the steel tube and concrete core
$p_{s\text{-}s}$	interaction stress for the interface between the two layers of a bimetallic tube
r_i	internal corner radius of cold-formed carbon steel section
SI	strength index
t	wall thickness
t_t	total wall thickness
t_{sc}	wall thickness of carbon steel tube layer
t_{ss}	wall thickness of stainless steel tube layer
Δ	axial deformation
Δ_u	axial deformation corresponding to ultimate strength
ε	strain
ε_s	steel strain
ε_{yc}	yield strain of carbon steel
$\overline{\varepsilon}$	average axial strain
σ	stress
$\sigma_{0.2}$	0.2% proof stress of stainless steel
$\sigma_{0.2,c}$	0.2% proof stress of corner material
$\sigma_{0.2,v}$	0.2% proof stress of virgin material
ξ	confinement factor, $\xi = (A_{sc} \cdot f_{yc} + A_{ss} \cdot \sigma_{0.2})/(A_c \cdot f_{ck})$ for CFBT members; or $\xi = (A_s \cdot f_y)/(A_c \cdot f_{ck})$ for conventional carbon steel CFST members

the full-range behavior of square CFBT columns subjected to axial compression, the failure mode, load versus deformation response, and ultimate strength will be studied; (2) to establish a three dimensional finite element analysis (FEA) model for square CFBT stub columns under axial compression, the FEA model is validated against experimental results and used to study the composite actions within the CFBT member; and (3) to validate the current design codes for CFST members in predicting the ultimate strength of square CFBT columns.

2. Experimental program

2.1. General description

Fourteen CFBT and two CFST column specimens with a square cross section were fabricated and tested to failure under axial compression. The bimetallic tube in the CFBT column comprised an outer layer made of stainless steel and an inner layer made of carbon steel. The cross sections of the CFBT columns and CFST counterparts are illustrated in Fig. 1, where B is the width of the square cross section, t_{ss} and t_{sc} are wall thicknesses of the stainless steel tube layer and carbon steel tube layer, respectively. The value of t_{sc} for all the specimens was 3.30 mm. The outer width of the CFST section was 200 mm, and the internal corner radius (r_i) was 15 mm. The bimetallic tubes were obtained by capping stainless steel sheets to the flank surfaces of carbon steel tubes, so the outer width of the CFBT section was $(200 + 2t_{ss})$ mm. The length (L) for all the column specimens was set to be 600 mm, approximately three times the cross-sectional width (B). The main experimental variables included:

(1) Wall thickness of the stainless steel tube layer (t_{ss}), t_{ss} varied from 0.84 mm to 1.88 mm;
(2) Cube compressive strength of concrete (f_{cu}), f_{cu} varied from 54.5 MPa to 80.5 MPa; and
(3) Grade of stainless steel, Grade 316, 304, and 202.

A summary of the test information is listed in Table 1, where t_t is the total wall thickness of the tube, $t_t = t_{sc}$ for the CFST specimens, and $t_t = t_{sc} + t_{ss}$ for the CFBT specimens. The specimen labels in Table 1 are designed based on the following rules: (1) "CFST-_" and "t_c_-_-_" represent the CFST and CFBT specimens respectively; (2) for CFBT specimens, the letter "t" stands for the wall thickness of the stainless steel tube layer, and the number after "t" varies from 1 to 3, representing a wall thickness varying from 0.84 to 1.88 mm; the letter "c" stands for the compressive strength of the core concrete, and the number after "c" varies from 1 to 3, representing a compressive strength varying from 54.5 MPa to 80.5 MPa; (3) the number after the first hyphen stands for the different stainless steel grades; and (4) the last number after the second hyphen stands for the different specimen in the same test group. In each test group, two identical samples were fabricated and tested to confirm the reliability of the experimental results.

2.2. Specimen preparation

Up to now, there have been various techniques to manufacture the bimetallic tubes, and the techniques can generally be classified into two categories, i.e., mechanical combination and metallurgic combination [18], in the latter one the two different metallic tube layers are bonded together. To meet the dimensional requirements in the current research, the square bimetallic tube used to fabricate the CFBT column was manufactured by mechanically cladding stainless steel sheets onto the flank surfaces of the square carbon steel tube. All the carbon steel tubes, both for the CFST and CFBT specimens, were manufactured by welding two U-shaped semi-tubes together at room temperature. The bimetallic tube was obtained by cladding the carbon steel tube with two welded U-shaped stainless steel semi-tubes, which were compatible in shape and size with the carbon steel tube. Full-penetration weld was adopted in the above welding, and the weld seams in the outer stainless steel tube layer were staggered from those in the inner carbon steel tube layer, as shown in Fig. 1. Prior to cladding, the to-be contacted surfaces of the two tube layers were properly treated and the possible rust and oil were removed. Besides the longitudinal welding, the two tube layers were fully welded at both tube ends, to prevent additional air or moisture from getting inside the possible layer-layer gap and causing rusting in the carbon steel.

It should be mentioned that, the carbon steel without proper treatment would rust if contacted to the stainless steel, due to the electrochemical reaction between different metals. However, the rusting procedure of carbon steel takes water and oxygen to carry on, and the process can be terminated if the carbon steel is isolated from the atmosphere. Therefore, the sealing effect of the carbon steel tube layer in a bimetallic tube is of essential importance to the rust/corrosion resistance of CFBT members. In the practical application of CFBT members, seamless stainless steel tube could be used as the stainless steel tube layer in a