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Behavior of prestressed concrete-filled steel tube (CFST) beam

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ABSTRACT

Concrete-filled steel tube (CFST) member is widely used for building, bridge and foundation structures because of its excellent performance. When a CFST member is subjected to axial loads, the filling concrete is confined by the steel tube, resulting in a tri-axial state of compression that improves its strength, stiffness and ductility. However, the cracking of concrete in tension zone would decrease this enhancement when the CFST member is subjected to flexure, especially when it is used as a major flexural member with large-scale section in bridges. To overcome this weakness, the prestressed CFST concept is investigated in this paper. Eight prestressed CFST beams with large-scale section (300 × 450 mm) were tested under bending. Two concrete strengths (C50 and C60) and two different degrees of prestressing (0.26 and 0.40) were studied in the experimental program. The full vibration and grouting method was introduced to gain a good performance of specimens. The perfobond rib shear connector was adopted to achieve the composite action. The flexural behaviors were verified by comparing with predictions from a proposed model considering the confinement effects. A simplified method is proposed to determine the ultimate moment capacity based on the plastic stress block hypothesis. Both experimental and analytical results show that the prestressed strands could significantly enhance the confinement effect of the core concrete under bending, which, in turn, improves the prestressed CFST beam performance in strength, stiffness and ductility.

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1. Introduction

Concrete-filled steel tube (CFST) members are composite structures which evolved on the basis of the hollow steel tube (HST). For the hollow steel tube, local buckling of the flange may occur when the width-to-thickness ratio (B/t) is larger than a certain value [27,54,23]. Thus, the plastic bending moment of an HST beam may not be achieved or maintained. Filling concrete is an efficient way to prevent local buckling and to enhance performance of HST beams. Although the filling concrete would increase the dead weight to a certain level, it is still considered an efficient way to enhance strength, stiffness and ductility of HST members. Zhao and Grzebieta [55] proved that the increase in rotation angles of CFST members at ultimate moment can be three times larger than that of HST beams. CFST members can provide an excellent seismic resistance in two orthogonal directions as well as show good damping characteristics. They also show an excellent hysteresis behavior under cyclic loading when compared with HST tubes [21]. CFST members have been used in tall structures and in retrofitting damage bridge piers in USA and Japan [15]. The use of CFST members in moment resisting frames eliminates the need for additional stiffness elements in panel zones and zones of high strain demand [14]. Bridges with CFST members are expected to reduce noise and vibration levels when compared to ones with pure steel members [35]. Moreover, CFST members have been proven to be cost effective in building structures [50]. The example of Aurora pedestrian arch bridge does demonstrate that the CFST is an appealing modular system and is easy to fabricate and erect [44].

Many research efforts on the compressive behavior of CFST have been carried out in the past decades, however, the flexural performance of CFST is still very limited. Earlier studies on CFST beams were published by Furlong [16] and Bridge [5]. Furlong [16] found that the flexural capacity of CFSTs was increased by 49% compared to the bare steel tube beam. Bridge [5] also observed that the core concrete can provide approximately 7.5% more bending capacity than the hollow steel section. After these earlier studies, investigations were mainly focused on the depth-to-width ratio [33], shear span-to-depth ratio [37], and width-to-thickness ratio [46]. Uy [47] demonstrated that the CFST member had a significant yielding

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Nomenclature

B, H	the outer width and height of the section, respectively
λ	the degree of prestress
M_0	the decompression moment that produces zero concrete stress at the extreme fiber of the section nearest to the centroid of prestressing force when added to the action of effective prestress
M_u	the ultimate moment
σ_h	the effective compressive prestressing at tensile edge
W_0	the flexural modulus
E_s	the Young's modulus of steel
f_y	the yield strength of steel
f_u	the ultimate tensile strength of steel
e_u	the percentage elongation at fracture of steel
f'_c	the compression strength of concrete
f_t	the tensile strength of concrete
E_c	the Young's modulus of concrete
σ_{ps}, ε_{ps}	stress and strain of prestressed strand, respectively
E_p	the Young's modulus of prestressed strand
E'	the slop at the original point of Ramberg–Osgood curve
m	the coefficient for Ramberg–Osgood curve shape
μ_ϕ	the curvature ductility
ϕ_u	the curvature at ultimate when the steel fiber reaches a specified limiting value
ϕ_y	the curvature when the tension fiber first reaches the yield strength.
A_p	the area of prestressed strand
N_{s1}	the force of upper compressive flange zone for steel tube
N_{s2}	the force of compressive web zone for steel tube
N_{s3}	the force of tension web zone for steel tube
N_{s4}	the force of underside tension flange zone for steel tube
C	*the force of compressive flange zone for filled concrete*
X	the height of compression concrete
t	the thickness of steel tube
b, h	the inner width and height of the steel tube
f_p	the ultimate strength of prestressed strand
a_p	the distance from the center of prestressed strands to the outside edge of steel tube
M_{lb}	the buckling moment

plateau because of the high strength steel. Similarly, a favorable post-yield behavior of CFST member was reported by Gho and Liu [18]. The distinguishing feature of ductile collapse and smooth loading process was further studied based on the unified theory by Han [22] and Han et al. [24]. Finite element method [32], simplified analytical method [26] and cross-sectional fiber analysis [41] were proposed to predict the stiffness and bending strength. Eichalakani and Zhao [12,13] found that the static strength of CFST member was significantly influenced by cyclic loading.

Although previous studies have proved that the CFSTs had outstanding strength capacity, ductility, and seismic performance, Nakamura et al. [35] noted that the composite bending stiffness of CFST was similar to the theoretical stiffness of the bare steel tube due to the concrete cracking. Wheeler and Bridge [51] also found that the concrete cracking in tension zone in the early loading stage would significantly decrease the ultimate capacity to a value extremely close to the stiffness of bare steel section. The cracking moment was around 5% of ultimate moment. Chitawadagi and Narasimhan [8] reported that the increase of concrete strength relative to a given thickness tube did not increase the moment capacity to a great extent. It is hypothesized that cracking may cause the confinement degradation, which, in turn, results in the reduction of strength, stiffness and ductility in CFST beams. Therefore, a modified CFST named as prestressed CFST, is proposed here in order to reduce these deficiencies. The main idea is that the triaxial state of core concrete will be further strengthened by the combined effect of steel tube and prestressed strands. Chen et al. [7] and Xu et al. [53] have discussed this proposed concept in theory. Tuan [44,45] also studied the prestressed CFST as an axial tension member and successfully applied it as the bottom chords in a pedestrian arch bridge in Aurora, NE (Fig. 1).

This paper focuses on the flexural performance of prestressed CFST beams under bending. All specimens have the same compact section (300 × 450 mm). Two concrete strength (C50 and C60) and two different degrees of prestressing (0.26 and 0.40) were investigated in the experimental program. The full vibration and grouting method was introduced to gain a good performance of the specimens. Additionally, both three-point and four-point loading setups were applied for the loading program in order to study the influence by loading pattern. A theoretical model was introduced to study the moment–curvature relationship. A simplified method was proposed to predict the ultimate moment capacity based on the plastic stress block hypothesis. Experimental and theoretical results demonstrate that the prestressed strand could increase the confinement effect of the core concrete under flexure, and the prestressed CFST beam performs well in terms of its strength, stiffness and ductility.

2. Experimental program

2.1. Parameters of specimens

A total of eight specimens were designed and prepared to investigate the flexural behavior. The specimens were fabricated from cold-weld steel hollow sections, and two different strength concretes were filled. The dimensions of the specimens are showed in Fig. 2. All specimens have the same outer width of 300 mm and the same height of 450 mm. CFST members are usually classified as a compact section, non-compact section or slender element section according to the local buckling potentials of the steel tube. And the width-to-thickness ratio (B/t) is used to measure the local buckling potential for rectangular CFST members. Currently, there exist differences on B/t limit value specified in different codes [1,4,10]. Most codes define the B/t limit with the elastic modulus and the yield strength of steel. For a rectangular hollow steel tube, flange plane is slenderer than web plane, thus the section type mainly depends on the width-to-thickness (B/t) of flange. Although there are a few differences in the definition of B in existing codes, a unified expression of B is defined as the outer width of the section in this paper. The comparison among different codes is illustrated in Table 1. Table 1 shows that all specimens with nominal B/t ratios of 50 and 37.5 satisfy the limits. In order to investigate the prestressing effect, the degree of prestress, λ, is defined as follows [34]:

$$\lambda = \frac{M_0}{M_u} \tag{1}$$

$$M_0 = \sigma_h W_0 \tag{2}$$

where λ = the degree of prestress; M_0 = the decompression moment that produces zero concrete stress at the extreme fiber of the section nearest to the centroid of prestressing force when added to