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FLEXURAL BEHAVIOR OF CONCRETE FILLED SEAMLESS STEEL TUBE (CFST) BEAMS

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Summary: *The present paper aims at investigating the flexural strength of concrete filled tubes made of seamless steel and the possibility of replacing the conventional reinforced concrete beam. Since no welding is required, seamless steel tube is stronger and can handle more pressure than welded tube. The experimental program consists of four-point bending tests of six CFSTs and three hollow steel tubes (HST) considering three different Diameter-to-thickness ratios (D/t). The experimental ultimate moments are compared to theoretical nominal moments calculated by four international design codes namely the Architectural Institute of Japan (AIJ), the British Standard (BS), the AISC-LRFD, and the Euro code. Only the AIJ equations predicted unsafe design moment capacities particularly at the higher D/t ratio. The other codes and standards were more conservative since they did not consider the effect of concrete confinement in their design equations. The EuroCode4 equation predicted the most optimum flexural moments for CFST beams among the other conservative codes.*

1 INTRODUCTION

Concrete Filled Steel Tube (CFST) elements have been increasingly considered in tall building and earthquake regions. Several experimental and numerical studies have been conducted to investigate the compression behavior of CFST with different cross-sectional geometries, thicknesses and steel material [1-2]. It was shown that CFST improves the compression behavior since the filled concrete reduces that ability of local buckling of steel. The flexure behavior of CFST has recently got the attention of researchers to study the feasibility of utilizing CFSTs in flexure [3-5]. CFST beams have the potential to overcome some limitations of conventional reinforced concrete and steel structures. For example, one of the unique properties of CFST is that concrete is well confined in the steel tube; thus, the steel tube yields before concrete crushing. Also, concrete in CFST is fully bracing the steel tube; therefore, steel tube local buckling will be delayed. Researchers [3-5] concluded that ductility of CFST is enhanced comparing to traditional reinforced concrete. In addition, because of concrete heat sink effect, the fire resistance of CFST is more than reinforced concrete. Moreover, constructability is enhanced since that CFST does not need formwork, and there is no waiting time for concrete hardening.

Han tested 16 CFST beams with square and rectangular cross-sections to study their flexural behavior [3]. The concrete cube strength for these CFST beams ranged from 27 MPa to 40 MPa, and steel yield strength from 294 MPa to 330 MPa. Han also compared experimental ultimate moments of CFST beams with theoretical results calculated by codes equations such as the Architectural Institute of Japan (AIJ) [4], the AISC-LRFD [5], the British Standard (BS) [6], and the Euro code [7]. It was found that flexural capacities obtained using these codes were conservative; with more than 20% prediction difference using AIJ and AISC, 12% for difference using BS5400 (1979) and around 10% overestimation using EuroCode4. In addition, Han developed two analytical relationships, one for rectangular and the other for circular cross-sections, based on composite mechanics equations and regression analysis to can calculate the flexural capacities of CFST beams. It was mentioned that cooling of the weld produces residual stresses which can be up to 20% of yielding stress in the compression zone and full yielding stress in the tension one. All of the theoretical calculations do not account for these residual stresses which will lead to inaccurate flexural capacities. However, seamless tubes do not have residual stresses since the steel tube is cut directly from the manufactory, without any welding, by extracting the tube from a steel form.

Probst *et al.* tested four 6-meter length CFST specimens with rectangular and circular cross-sections, and also with and without shear connections [8]. The D/t ratio for their circular CFST specimens was 36 and the concrete strength was 22 MPa. It was found that the ratio of experimental ultimate moments for circular CFST beams without shear connection to the EuroCode4 flexural capacity was 0.81, and to the AISC was 0.84. Therefore, they noted that both codes, AISC and EuroCode4, were un-conservative, and they suspect that large diameter of concrete is the reason since the effect of concrete shrinkage will be significant. They suggested further research with various D/t ratios to investigate the applicability of AISC and EuroCode4 for calculating the flexural capacity of circular CFST beams.

Elchalakani *et al.* investigated the flexural behavior of circular CFST beams with a wide range of D/t ratios between 12 and 110 [9]. It was found that local buckling does not occur for CFST specimens that have D/t ratio less than or equal to 40. According to their results, design of CFST using AISC, AIJ, and EC4 was found to be un-conservative for the case of D/t ratios such as 12.8. This could be due to overestimating the CFST flexural capacity when more steel thickness is used.

The aim of this paper is to study the flexural behavior of circular CFST beams using seamless steel tubes and also considering a range of low D/t ratios between 8 and 18. This paper will also investigate the applicability of theoretical results predicted by international design codes such as AIJ, AISC, BS, and EC4, and determine if the conclusions made by the previous studies sill applicable.

2 EXPERIMENTS

The experimental program and results are discussed briefly in this section, and more details will be presented in a forthcoming full paper. Six CFST beams and three hollow steel tubes (ST) were prepared with one diameter (114 mm) and three different steel thicknesses. The experimental program matrix that was followed in this paper is shown in Figure 1. The average concrete compressive strength was 43 MPa and the average yield strength for the seamless steel was 245 MPa.

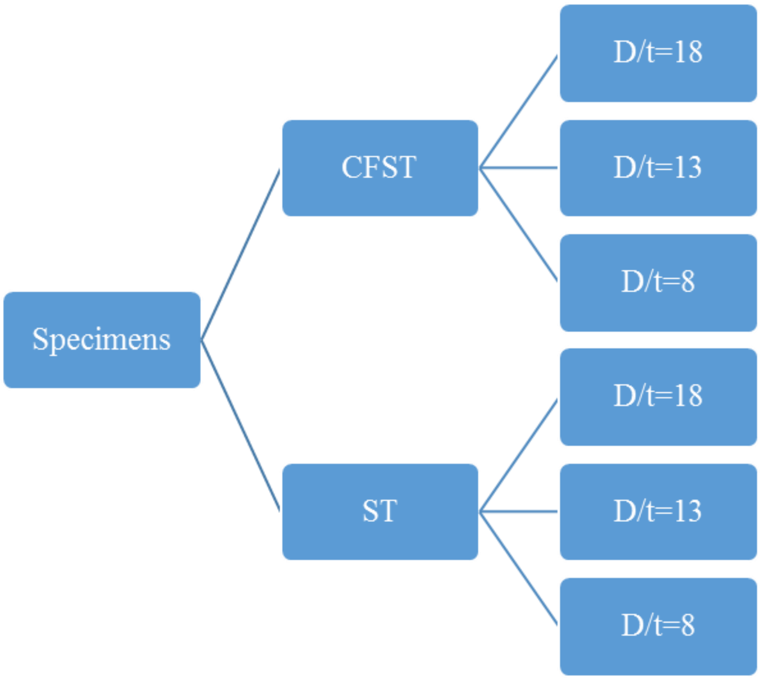

Figure 1: Experimental Program

All beams have the same length of 1100 mm and were tested under four-point test setup as shown in Figure 2 using a Universal Testing Machines (UTM). The span length was fixed to 1000 mm and the shear span was limited to 300 mm for all beams. Strain gauges were attached in both lateral and longitudinal directions at the center of each CFST beam. In order to track the mid-span deflection, a Linear Variable Displacement Transducer (LVDT) was put at the bottom of each CFST beams and tubes as illustrated in Figure 2.

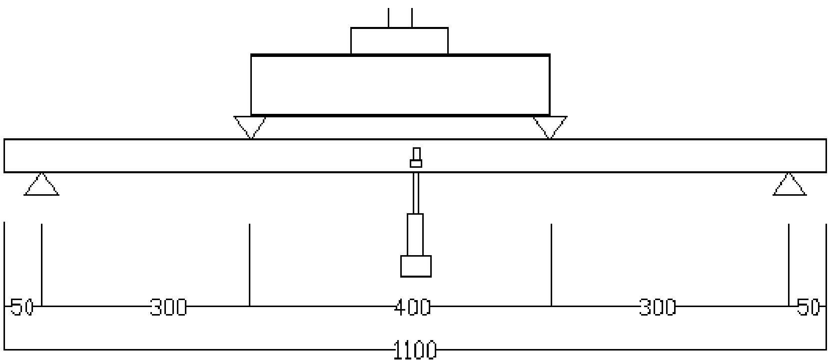

Figure 2: Test setup and dimensions in mm

3 THEORETICAL BACKGROUND

The theoretical moment capacity M_n of each CFST specimen was calculated based on equations provided by AISC, AIJ, BS 5400, and EC4 standards and also using Han equation. Although these standards have studied CFST based on common mechanism, each one has some different assumptions and approaches than others. These common and differences are explained in the following sections. For example, the AISC and AIJ codes use plastic stress distribution method to calculate the flexural capacity of CFST. The AISC also permits the use strain compatibility method to calculate the flexural capacity. The AIJ code considers the concrete confining effect in calculating CFST flexural capacity.

Han proposed an equation to calculate CFST flexural capacity based on regression analysis [3].

3.1 AIJ [4]:

AIJ discussed composite sections in general and specify a whole chapter to design and analysis CFST as beam-column member. The flexural capacity of CFST M_u can be calculated by adding the concrete flexural capacity M_u^c to the steel flexural capacity M_u^c as given in Eq. (1). To use this equation, the AIJ code states that the length of CFST specimen should be less than 12 times the diameter of steel tube. All of the specimens of this study qualify for this condition (1100mm < 12×114=1368mm).

$$M_u = M_u^c + M_u^s \tag{1}$$

The parameters that affect the concrete flexural capacity, M_u^c, include the angular location of the neutral axis, θ_n, concrete diameter, D_c, and the confined strength of concrete, σ_{cB}^c as follows:

$$M_u^c = \sin^3\theta_n \frac{D_c^3\ \sigma_{cB}^c}{12} \tag{2}$$

The confined strength of concrete depends on the concrete strength, f_c', steel tube thickness, t_s, steel yield strength σ_y^s and diameter of the CFST as given in Eq.(3). A reduction factor of r_u^c = 0.85 is also used by the AIJ code.

$$\sigma_{cB}^c = r_u^c \times f_c' \times \frac{1.56\, t_s\ \sigma_y^s}{D - 2t_s} \tag{3}$$

The flexural capacity of steel tube, M_u^s, is calculated using Eq. 4. AIJ code distinguishes between steel tube part in compression and in tension zones. For compression, AIJ reduces the steel yield strength by the reduction factor β_1=0.89, and increases the steel yield strength in tension by the modification factor β_2 =1.08.

$$M_u^s = (\beta_1 + \beta_2)\sin\theta_n \frac{(1-\frac{t_s}{D})^2}{2} D^2\ t_s\ \sigma_y^s \tag{4}$$

Theoretical CFST flexural capacities of AIJ were the most accurate comparing to the other codes for all specimens in this study. The Mean value of theoretical to experimental moment M_n / M_u was 1.009. It seems that accounting the concrete confining effect into calculations helps predicting accurate CFST flexural capacities.

3.2 AISC [5]:

The AISC allows using stress distribution or strain compatibility approaches to calculate flexural capacity of composite section. It considers load-moment interaction diagrams for CFST and provides equation for each unique point in the interaction diagram. The point of pure bending (i.e., zero axial load) is the one that is used to calculate the flexural capacity of CFST, M_B, as follows:

$$M_B = F_y\ Z_{sB} + \frac{1}{2}\ 0.95 f_c^{'}\ Z_{cB} \tag{5}$$

where Z_{sB} and Z_{cB} are the plastic modulus of steel and concrete, respectively. AISC does not account for confided concrete since it assumes that CFST behave as other composite sections. In fact, it reduces f_c' by 5%.

3.3 BS [6]

The BS approach considers the steel plastic section modulus, *S*, in calculating the CFST flexural capacity, M_u as follows:

$$M_u = 0.91\, S\, f_y \left(1 + 0.01m\right) \tag{6}$$

where the factor (m) is determined using a chart in BS depending on the ratio of concrete cubic strength to steel yield strength for a given D/t ratio. It is clear that BS does not rely on concrete strength and accordingly does not account for confined concrete effect.

3.4 EuroCode4 [7]

Similar to the other codes, EuroCode4 treat CFST as a composite section to determine its flexural capacity. The flexural capacity of CFST, $M_{pl.Rd}$, is calculated by subtracting the neutral moment of CFST, $M_{n.Rd}$, from the maximum moment of CFST, $M_{\max.Rd}$, as per the following set of equations:

$$M_{pl.Rd} = M_{\max.Rd} - M_{n.Rd} \tag{7}$$

$$M_{\max.Rd} = w_{pa} f_{yd} + 0.5 w_{pc} f_{cd} \tag{8}$$

$$M_{n.Rd} = w_{pan} f_{yd} + 0.5 w_{pcn} f_{cd} \tag{9}$$

$$w_{pc} = \frac{(D-2t)^3}{6}; \quad w_{pa} = \frac{D^3 - (D-2t)^3}{6}; \quad w_{pan} = D h_n^{\,2} - w_{pcn}; \quad w_{pcn} = (D-2t) h_n^{\,2} \tag{10}$$

Where w_{pa} and w_{pc} are plastic moduli of steel tube and concrete, respectively, w_{pan} and w_{pc} are the plastic moduli of steel tube and concrete at $2h_n$, f_{yd} is the yield strength of steel tube, and f_{yd} is the compressive strength of concrete.

And the location of the neutral axis (h_n) is calculated as follows:

$$h_n = \frac{A_c f_{cd}}{2Df_{cd} + 4t(2f_{yd} - f_{cd})} \tag{11}$$

3.5 Han [3]

Han proposed two equations for CFST beams; one for square and rectangular cross-sections and the other is for circular cross-section. Han's equations were derived based on mechanics of composite and regression analysis as follows:

$$M_u = \gamma_m W_{scm} f_{scy} \tag{12}$$

Where $W_{scm} = \pi D^3 / 32$ is the section modulus for circular CFST and f_{scy} is the yield strength of the composite section. Han Used regression analysis to determine the flexural strength index (γ_m) and f_{scy} as given by Eq.(13) and Eq.(14), respectively.

$$f_{scy} = (1.14 + 1.02\xi) f_{ck} \tag{13}$$

$$\gamma_m = 1.1 + 0.48 \ln(\xi + 0.1) \tag{14}$$

Where the confinement factor ξ is defined in terms of the steel cross-sectional area, A_s, and its yield strength f_{sy} and the concrete cross-sectional area, A_c, and its compressive strength, f_{ck}, as follows:

$$\xi = \frac{A_s f_{sy}}{A_c f_{ck}} \tag{14}$$

4 RESULTS AND CONCLUSIONS

The flexural capacity of CFST beams calculated using the above-mentioned equations have been compared with the experimental results as shown by the bar chart shown in Figure 3. The comparisons are presented in terms of the ratio of the experimental results to the theoretical values for the three D/t ratios considered. A ratio of more than one indicates a non-conservative design moment using that code due to overestimating the CFST flexural capacity.

The flexural capacities predicted using AIJ equations were almost the same as the ultimate moments for D/t ratios of 8 and 13, but un-conservative for the case of D/t = 18. This observation is in agreement with Elchalakani results [3]. The AISC and BS, on the other hand, predicted more conservative results for all D/t ratios. This may be attributed to the fact that the concrete confining effect was ignored by both standards. The EuroCode4 predicted less conservative and more accurate CFST flexural capacities than AISC and BS for all D/t ratios. The equation proposed by Han [3] predicted conservative flexural capacities for D/t ratios of 13 and 18, but highly overestimated the experimental results for the lower D/t ratio of 8. This is because Han's equation was developed based on regression analysis for CFST specimens with relatively higher D/t ratios.

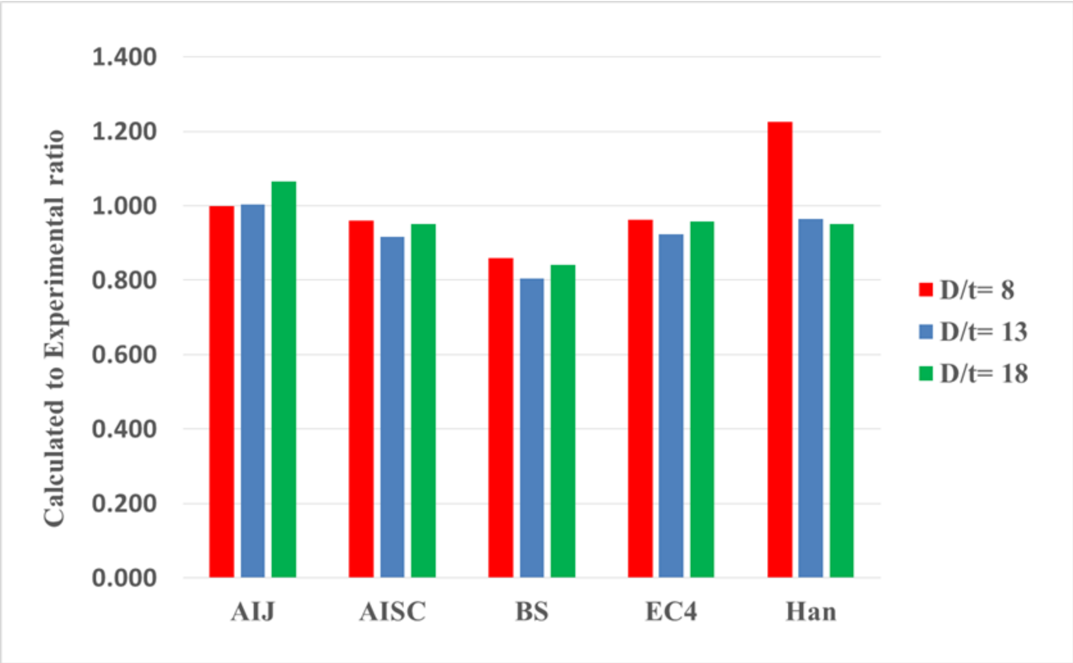

Figure3: Comparisons of flexural capacity of CFST with international codes.

In summary, AIJ and Han equations were found to be unsafe for design of CFST beams with high D/t ratios for the former and with low D/t ratios for the latter. EuroCode4 equation was the best among the other conservative codes to predict the flexural capacity for CFST beams.

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