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Biaxially loaded high-strength concrete-filled steel tubular slender beam-columns, part II: Parametric study

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ABSTRACT

Biaxially loaded high strength rectangular concrete-filled steel tubular (CFST) slender beam-columns with large depth-to-thickness ratios, which may undergo local and global interaction buckling, have received very little attention. This paper presents the verification of a multiscale numerical model described in a companion paper and an extensive parametric study on the performance of high strength thin-walled rectangular CFST slender beam-columns under biaxial loads. Comparisons of computer solutions with existing experimental results are made to examine the accuracy of the multiscale numerical model developed. The effects of the concrete compressive strength, loading eccentricity, depth-to-thickness ratio and columns slenderness on the ultimate axial strength, steel contribution ratio, concrete contribution ratio and strength reduction factor of CFST slender beam-columns under biaxial bending are investigated by using the numerical model. Comparative results demonstrate that the multiscale numerical model is capable of accurately predicting the ultimate strength and deflection behavior of CFST slender beam-columns under biaxial loads. Benchmark numerical results presented in this paper provide a better understanding of the local and global interaction buckling behavior of high strength thin-walled CFST slender beam-columns and are useful for the development of composite design codes.

1. Introduction

High strength thin-walled rectangular concrete-filled steel tubular (CFST) slender columns with large depth-to-thickness ratios are increasingly used in lateral load resisting systems in high-rise composite buildings to resist heavy axial loads as well as biaxial bending moments. These composite beam-columns are characterized by high strength, large depth-to-thickness ratio, slenderness and biaxial bending. The failure mode of thin-walled CFST slender beam-columns may involve local and global buckling interaction, which significantly complicates their analysis and design procedures. There has been a lack of experimental and numerical studies on this type of composite columns and that their fundamental behavior has not been adequately understood. Therefore, researches on the structural performance of high strength thin-walled CFST slender beam-columns under biaxial bending are much needed. This paper is concerned with numerical studies on the structural performance of biaxial loaded high strength thin-walled CFST slender beam-columns incorporating the effects of local buckling of the steel tube walls under stress gradients.

The performance of CFST short and slender columns under axial load or combined axial load and uniaxial bending has been investigated experimentally by researchers [1–7]. However, there have been relatively few experimental studies on the behavior of biaxially loaded rectangular CFST slender beam-columns with large depth-to-thickness ratios. Bridge [8] performed experiments on biaxially loaded normal strength square CFST slender beam-columns. The main variables examined in the test program were the loading eccentricity, column slenderness and biaxial bending. Test results showed that the ultimate axial strength of CFST slender beam-columns decreased with increasing the loading eccentricity or the column slenderness. Local buckling was not observed because compact steel sections with a depth-to-thickness ratio of 20 were used. Experimental studies were carried out by Shakir-Khalil and Zeghiche [9] and Shakir-Khalil and Mouli [10] to determine the ultimate axial loads of normal strength rectangular CFST slender beam-columns under axial load and biaxial bending. Tests parameters examined included the section size, steel yield strength, concrete compressive strength, column length and eccentricity of loading. The authors reported that the relative load carrying capacity of the composite to steel columns increased when the size of the steel section or the concrete compressive strength was increased. However, they observed reversed influence for the loading eccentricity and column length. The typical failure mode of these tested specimens was overall column buckling. Recently, Guo et al. [11] undertook tests on normal strength rectangular CFST slender beam-columns with rib

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stiffeners and under biaxial bending. Test results showed that local buckling of the steel tube walls between the rib stiffeners occurred after specimens attained their ultimate strengths.

Numerical analysis techniques have been used to study the nonlinear inelastic behavior of short and slender composite columns under axial load and uniaxial bending [12–19]. Lakshmi and Shanmugam [20] used a semi-analytical model to determine the ultimate axial strengths, load-deflection responses and strength envelopes of CFST columns under axial load and biaxial bending. Their analytical results demonstrated that increasing the loading eccentricity significantly reduced the ultimate axial strength and stiffness of CFST slender columns. The semi-analytical model was used to develop the strength envelopes of CFST cross-sections under uniaxial bending. However, the strength envelopes of thin-walled CFST slender beam-columns under biaxial bending have not been investigated by Lakshmi and Shanmugam [20]. In addition, the effects of local buckling were not taken into account in their model and numerical studies. Liang [21,22] employed a performance-based analysis technique accounting for progressive local buckling of the steel tube walls [23] to investigate the effects of the depth-to-thickness ratio, concrete compressive strength, steel yield strength and axial load level on the ultimate axial strengths, load–strain behavior, moment-curvature responses and strength envelopes of thin-walled CFST short columns under axial load and biaxial bending. However, numerical studies on the behavior of biaxially loaded high strength CFST slender beam-columns with local buckling effects have not been reported in the literature.

The purpose of this paper is to validate the multiscale numerical model presented in a companion paper [24] and to study the structural performance of high strength CFST slender beam-columns made of slender steel sections. Verification studies involve thorough and comprehensive comparisons of the predicted ultimate axial loads, ultimate bending strengths and complete load-deflection responses of CFST slender beam-columns to existing experimental results. The parametric study focuses on the ultimate axial strength, steel contribution ratio, concrete contribution ratio, strength reduction factor and strength envelopes of high strength thin-walled CFST slender beam-columns under biaxial loads. The paper is organized as follows. In Section 2, the verification of the numerical model is presented. This is followed by an extensive parametric study on the fundamental behavior of high strength thin-walled CFST slender beam-columns. Finally, important conclusions are given.

2. Verification of the multiscale numerical model

To verify the accuracy of the multiscale numerical model developed, the predicted ultimate strengths and axial load-deflection responses of biaxially loaded CFST slender beam-columns are compared with existing experimental results in this section.

2.1. Ultimate axial strengths of CFST slender beam-columns

The geometry and material properties of biaxially loaded CFST slender beam-columns tested by independent researchers are given in Table 1. Experiments on specimens SCH-3, SCH-4, SCH-5 and SCH-6 were conducted by Bridge [8]. These column sections with a depth-to-thickness ratio (D/t) of 20 were considered to be compact. The ultimate tensile strength (f_{su}) of steel tubes was assumed to be 430 MPa. Experimental results on specimen R6 in Table 1 were given by Shakir-Khalil and Zeghiche [9]. The axial load was applied at eccentricities of 16 mm and 24 mm about the major and minor axes respectively. Specimens M2–M9 shown in Table 1 were tested by Shakir-Khalil and Mouli [10]. The concrete cylinder compressive strength ($f_c{'}$) shown in Table 1 was taken as 0.85 times the concrete cube strength. Initial geometric imperfections (u_o) at the mid-height of specimens R6 and M2–M9 were not measured. To consider this effect, the initial geometric imperfection of $L/600$ at the mid-height of the columns as suggested by Portolés et al. [17] was taken into account in the present numerical analysis.

Ultimate axial strengths obtained from experiments ($P_{n.\ \mathrm{exp}}$) and numerical analyses ($P_{n.\ \mathrm{num}}$) are compared in Table 1. It can be seen from Table 1 that there is a good agreement between computational solutions and experimental results. The mean value of $P_{n.\ \mathrm{num}}/P_{n.\ \mathrm{exp}}$ ratio is 1.01 with a standard deviation (SD) of 0.05 and a coefficient of variation (COV) of 0.05. This comparative study demonstrates that the macroscale model for simulating the load-deflection responses can accurately predict the ultimate axial strengths of CFST slender beam-columns under biaxial loads. It should be noted that the numerical model for high strength CFST slender beam-columns under axial load and uniaxial bending has been validated by Liang [21,22] and Patel et al. [18].

2.2. Ultimate bending strengths of CFST slender beam-columns

The ultimate bending strengths of CFST slender beam-columns were determined using the macroscale model for simulating strength envelopes and compared with experimental results presented by Bridge [8], Shakir-Khalil and Zeghiche [9] and Shakir-Khalil and Mouli [10]. The initial geometric imperfection of $L/600$ at the mid-height of the columns was taken into account in the numerical analysis if it was not measured in the tests. The experimental ultimate axial loads were used in numerical analyses to determine the corresponding ultimate bending strengths. Computational and experimental ultimate bending strengths obtained are given in Table 2, where the experimental ultimate bending strength $M_{n.\ \mathrm{exp}}$ was calculated as $M_{n.\ \mathrm{exp}} = P_{u.\ \mathrm{exp}} \times e$. It can be seen from Table 2 that numerical predictions are in good agreement with experimental results. The ratio of the mean ultimate bending strength computed by the numerical model to the experimental value is 1.0. The standard deviation (SD) of the ratio is 0.08 while the coefficient of variation (COV) is 0.07. This comparison shows that the macroscale

Table 1
Ultimate axial strengths of biaxially loaded CFST slender beam-columns.

Specimens	$B \times D \times t$ (mm)	D/t	L (mm)	e_x (mm)	e_y (mm)	e (mm)	α (°)	u_o (mm)	$f_c{'}$ (MPa)	f_{sy} (MPa)	f_{su} (MPa)	E_s (GPa)	$P_{n.\mathrm{exp}}$ (kN)	$P_{n.num}$ (kN)	$\frac{P_{n.num}}{P_{n.\mathrm{exp}}}$	Ref.
SCH-3	200 × 200 × 10.03	20	2130			38	60	0.79	37.2	313	430	205	2180	2201.1	1.01	[8]
SCH-4	200 × 200 × 9.88	20	2130			38	45	0.56	39.2	317	430	205	2162	2259.2	1.04	
SCH-5	200 × 200 × 10.01	20	3050			38	60	0.28	44.3	319	430	205	2037	2135.2	1.05	
SCH-6	200 × 200 × 9.78	20	3050			64	45	1.12	36.1	317	430	205	1623	1601.2	0.99	
R6	80 × 120 × 5	24	3210	16	24	28.84	33.69		38.25	343.3	430	205	268	271.5	1.01	[9]
M2	80 × 120 × 5	24	3210	8	12	14.42	33.69		36.21	341	430	205	348	331.5	0.95	[10]
M3	80 × 120 × 5	24	3210	28	42	50.48	33.69		39.27	341	430	205	198.5	212.9	1.07	
M4	80 × 120 × 5	24	3210	40	24	46.65	59.03		36.04	362.5	430	205	206.8	197.1	0.95	
M5	80 × 120 × 5	24	3210	16	60	62.10	14.93		34.68	362.5	430	205	209.8	228.6	1.09	
M7	100 × 150 × 5	30	3210	10	15	18.03	33.69		39.27	346.7	430	209.6	596.2	569.9	0.96	
M9	100 × 150 × 5	30	3210	50	75	90.14	33.69		40.12	340	430	208.6	254.6	270.9	1.06	
Mean															1.01	
Standard deviation (SD)															0.05	
Coefficient of variation (COV)															0.05	