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Advanced design for trusses of steel and concrete-filled tubular sections

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ABSTRACT

This paper presents an experimental and analytical investigation of buckling behavior of bare steel and concrete-filled steel (CFS) tubes used as columns and as members of trusses. The member resistances of the columns and trusses consisting of steel and CFS tubular members are compared to demonstrate the beneficial effects of the in-filled concrete, with their resistances predicted using the conventional effective length and second-order analysis methods of design in various international standards such as Eurocode 3 (EC3), Eurocode 4 (EC4), CoPHK, AISC-LRFD and AS5100. Test results are further used to validate the proposed second-order analysis, which skips the assumption of effective length, for accurate and reliable design of composite members. The present holistic approach of considering composite members as constituting elements in a truss represents a piece of original work on testing and design of structures as a system, rather than designing members in isolation in the traditional member-based design.

1. Introduction

Extensive experiments have been conducted and reported on composite columns to investigate their structural resistances under various loading conditions. Furlong [1] tested concrete-filled steel tubular columns and indicated the local buckling of the steel tube was delayed by concrete infill. Circular and square concrete-filled steel tubes with different slenderness ratios were tested by Knowles and Park [2] to investigate the confinement effect on concrete under various slenderness ratios. The results indicated the benefits on ultimate capacity from the confinement effect of short circular columns. Tomii et al. [3] carried out tests on circular, octagonal and square concrete-filled steel tubular columns, and noted that the concrete core provided confinement effects only on circular and octagonal sections. Shakir-Khalil and Mouli [4] performed tests on concrete-filled steel tubular columns and concluded that higher concrete strengths or larger steel sections provided a greater structural efficiency for composite columns. The shape effect of steel tubes on strength and behavior of concrete-filled steel tubes were studied by Schneider [5]. Fourteen circular, square and rectangular tubes were tested and the results indicated that the circular tubes provided greater ductility than the other two section shapes and the confinement effect on the concrete core was observed only on circular tubes when the yield strength was approached. Kilpatrick and Rangan [6] reported test results on concrete-filled steel tubular columns, and indicated the effects on the behavior and strength of composite columns due to the slenderness and load eccentricity. Li et al. [7] carried out tests on six high-strength concrete-filled square steel tubular columns under bi-axial eccentric load and indicated that both the steel area ratio and slenderness ratio influenced the capacity of the columns significantly. Chan and Fong [8] tested steel and composite trusses with high-strength in-filled concrete to compare the beneficial effect of the in-filled concrete.

From the review on the subject, most previous experiments focused on the behavior of isolated columns under pinned or fixed end conditions, and tests on steel and concrete-filled steel (CFS) tubes acting as members of a frame or truss structures are limited. In this paper, tests on trusses composed of the bare steel and CFS tubes as chords and webs in the truss are reported and compared with the second-order analysis and design method. In order to compare the behavior of the members in an isolated column and in the truss system, the columns with same properties of the members in the truss under pinned and fixed ends are tested. The reported work in this paper is believed to be novel in providing the response of the members in the configuration of a structural system as a truss, which should be a good reference for the future research and design of composite trusses and frames.

Various international design codes provide different methods of design for steel and composite members under different loading conditions such as EC3 [9], EC4 [10], AISC LRFD [11], AS5100 [12] and CoPHK [13]. The accuracy of these design methods have been verified by many researchers such as Wang [14], Al-Rodan [15], Zeghiche and Chaoui [16]. Most comparisons of experimental and predicted results from these codes were focused on isolated

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Table 1
Material properties of steel tube.

Item	Steel section	*B* (mm)	*D* (mm)	*t* (mm)	Yield stress (f_y) (N/mm^2)	Ultimate tensile stress (f_u) (N/mm^2)	Young's modulus (E_s) (kN/mm^2)	f_u/f_y
Columns	60 × 60 × 3	60.40	60.30	3.10	407.98	480.22	206.36	1.18
Truss members	60 × 60 × 3	60.20	60.20	3.10	404.11	473.55	205.72	1.17

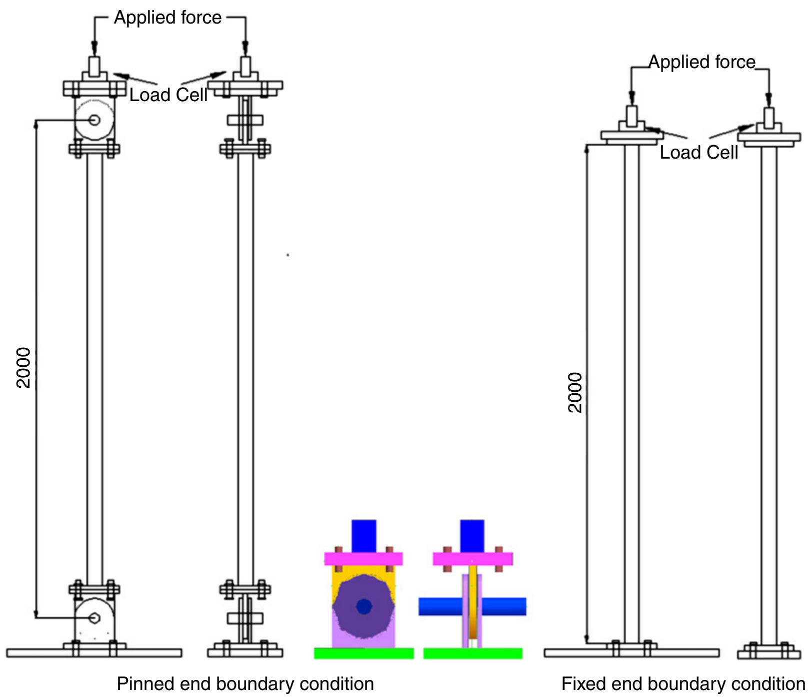

Fig. 1. The setup of columns.

members with pinned or fixed end boundary conditions. However, the behaviors of members with more realistic boundary conditions such as constitutive members in a truss have not been considered in previous research. The traditional linear analysis method of design assumes an effective length factor for different boundary conditions of a chord or a web member in a truss and assesses various factors to compensate for buckling and second-order effects in the determination of buckling strength of individual members. Unfortunately, the accuracy on determination of the effective length highly affects the reliability of these methods. For simple end conditions like pinned and fixed end, previous methods can give an accurate design solution as shown in the following example. However, for more complicated and practical structures like trusses, the accurate determination on the effective length is difficult and sometime impossible. This paper reports the accuracy of design methods in several international codes for the prediction of capacities of steel and CFS tubes as composing members in a truss under pinned and fixed end conditions.

Design codes such as AISC LRFD [11], EC 4 [10] and CoPHK [13] propose the use of second-order analysis and design methods because of the accuracy, reliability and convenience. The superiorities of second-order analysis and design method in comparison with the first-order analysis and design method have been reported in literature by different researchers such as Chen [17] and Chan et al. [18]. Using this design method, nonlinear effects such as the P-Δ and P-δ moments, member and frame imperfections are included in the analysis process. The new design method not only enhances the accuracy of the design output, but it also reduces design time and effort. The Pointwise Equilibrium Polynomial (PEP) element proposed by Chan and Zhou [19] is used here for its simplicity and computational stability and efficiency allowing modeling of one member by one element. The accuracy of using the PEP element on various forms of steel structures have been verified on various structural forms such as dome structures [20], angle trusses in both elastic [21] and plastic analysis [22,23], scaffolding systems [24] and pre-stressed stayed column [25]. In this paper, the design method of second-order analysis with the PEP element would be applied to predict the resistance of steel and CFS tubes used as isolated columns and as members of trusses.

2. Experimental work

2.1. General

Tests for columns and trusses were carried out. For the column tests, four specimens of two bare steel tubes and two CFS tubes were tested. Square hollow section steel tubes of 60 × 60 × 3 mm cross-section were used and the average width, depth and thickness are listed in Table 1. Two boundary conditions as pinned and fixed ends were set up in the test as indicated in Fig. 1. The specimen length for the fixed end condition is 2 m and for the pinned end condition is 1.74 m.

Two trusses with members composed of bare steel tubes (named as steel truss) and CFS tubes (named as composite truss) were tested with the mean dimensions of truss members are listed in Table 1. The same cross-sections used for the isolated columns tests were adopted in the construction of the trusses and the dimensions of the trusses are provided in Fig. 2. Steel trusses were composed of steel tubes for all members and the composite trusses were composed of CFS tubes in the compressive members and bare steel tubes in the tensile members. Each of these three-dimensional trusses consisted of 19 members which included the 14 main members of 2 m length and 5 tie members of 0.8 m length