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Behaviour and design of composite columns incorporating compact high-strength steel plates

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ABSTRACT

Concrete filled steel tubular columns (CFSTCs) are finding increasing use in modern construction practice throughout the world. The efficiency of CFSTCs can be further improved if high-strength materials are used. High-strength steel provides attractive alternatives to normal-strength steel for multi-storey and high-rise construction applications. This paper presents an extensive experimental investigation into the axial load behaviour of square composite columns incorporating compact high-strength steel plates. The test parameters include the concrete strength ($f'_c = 21$–55 N/mm^2), depth-to-thickness ratios in the range of 16–40, as well as length-to-depth ratios in the range of 2.60–2.85. Furthermore, a simplified confining pressure versus depth-to-thickness ratio model, appropriate confined concrete constitutive models, and an accurate finite element model which incorporates the effects of initial local imperfections and residual stresses has been developed using the commercial program ABAQUS. The predictions of the behaviour, ultimate strengths, and failure modes are compared with the experimental results to verify the accuracy of the models developed. Additionally, comparisons with the prediction of axial load capacity by using the Australian Standards, Eurocode 4, and American Institute of Steel Construction code provisions for composite columns are also carried out.

1. Introduction

Concrete filled steel tubular columns (CFSTCs) have been extensively used in the construction of building structures, bridges and other industrial structures. These CFSTCs have demonstrated significant benefits over steel hollow sections and reinforced concrete columns, such as high axial load capacity, high ductility performance, and large energy absorption capability. The enhanced mechanical properties of CFSTCs can be explained in terms of composite action between the steel hollow section and the concrete core. Due to the discrepancy of Poisson's ratios between steel and concrete, the volume increase of the concrete core due to the propagation of cracks is constrained by the exterior steel hollow section. Consequently, both the strength and ductility of the concrete are enhanced. On the other hand, the inward local buckling of the steel hollow section is prevented by the in-filled concrete. If CFSTCs are constructed from high-strength materials, greater mechanical and economical advantages can be achieved. High-strength CFSTCs present improved damping and stiffness characteristics when compared with normal-strength CFSTCs. High-strength CFSTCs generally require a smaller cross-section to resist the applied loads. Despite, the significant benefits, the use of high-strength CFSTCs in the building industry is still restricted by the lack of understanding of their structural behaviour and insufficient recommendations in design codes [1].

Uy [2,3] presented the results of steel and composite sections using high-strength structural steel of nominal yield stress 690 N/mm^2 and normal-strength of concrete of 20 N/mm^2. These sections were constructed as stubby columns and were subjected to concentric axial compression. Uy [4] conducted an extensive experimental test programme on short concrete filled steel box columns, which incorporated high-strength structural steel of Grade 690 N/mm^2. The experiments were then used to calibrate a refined cross-sectional analysis method, which considered both the nonlinear material properties of the steel and concrete coupled with the measured residual stress distributions in the steel. Uy et al. [5] conducted further research on high-strength steel box columns filled with concrete. This study consisted of three short columns and three slender columns to consider both the strength and stability aspects of steel–concrete composite high-strength columns. Sakino et al. [6] studied sixteen specimens with steel yield strengths between 507 and 853 N/mm^2 to investigate the behaviour of centrally loaded short CFSTCs, and proposed formulae for estimating the ultimate axial compression capacities of CFSTCs.

Mursi and Uy [7–9] carried out further experimental work on high-strength steel slender columns loaded uniaxially and biaxially and considered the applicability of existing codes of practice to incorporate high-strength steel and normal-strength concrete. Their findings showed that existing codes of practice were quite conservative in coping with

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these structural forms. However, due to the limitations in test equipment capacity this could not be extended to the use of high-strength concrete. This is one of the central tenets of this paper to study the behaviour of composite columns composed of high-strength steel and high-strength concrete. Liew and Xiong [10] also recently conducted a very comprehensive study on ultra-high-strength concrete up to 200 N/mm^2 compressive strength of concrete with steel tubes of yield strength of about 450 N/mm^2.

In order to fully utilise the benefits of high-strength CFSTCs, further research needs to consider the nonlinear behaviour of these terms and to develop design provisions for their practical use. In this paper, a set of experiments will be described which studies loading of the hollow steel columns and the loading of the composite columns composed of compact high-strength steel plates. The local and post-local buckling results of each of these sets of tests will be compared.

Moreover, proper material constitutive models and an accurate finite element method (FEM) model which accounts for the effects of initial local imperfections and residual stresses have been developed by using the commercial program, ABAQUS [11]. The predictions of the behaviour, ultimate strengths, and failure modes are compared with the experimental results to verify the accuracy of the presented models. Likewise, comparisons are also made with the strength models for axial load capacity by using the Australian Standards AS3600 [12] & AS4100 [13], AS5100 [14], Eurocode 4 (EC4) [15] and the American Institute of Steel Construction (AISC) [16] models for steel hollow and composite sections.

2. Experiments

This section outlines the test programme undertaken which includes column tests and extensive material property tests. The test set-up for the columns will be described and the results will then be presented. A general review and description of the failure modes will then be presented.

2.1. Material properties

2.1.1. Tensile coupon tests

To determine the stress–strain characteristics of the steel plate in tension, four 40 mm tensile coupons were produced from the virgin steel plate and tested in an Instron uniaxial testing machine. Pertinent data for these test coupons is provided in Table 1. Four tests were conducted with a mean value of yield stress of 701 N/mm^2 being established. Although high-strength steel is not considered to have a defined strain-hardening region, the tests revealed an increase in stress after yielding and the mean ultimate stress of the material in tension was determined to be 754 N/mm^2. Stress–strain diagrams are provided in Fig. 1 and the failure mode of the tensile coupons is illustrated in Fig. 2. The ductility can also be observed both by the pronounced necking of the specimens, which resulted in ultimate strains in excess of 65,000 microstrain (με) in all cases.

Table 1
Tensile coupon tests.

Series	Specimen number	Yield stress, f_y (N/mm^2)	Ultimate stress, σ_u (N/mm^2)	Young's modulus, E_s (N/mm^2)	Yield strain (με)
1 & 2	TC 1	685	731	158,850	4314
	TC 2	699	747	257,196	2719
	TC 3	733	780	203,693	3599
	TC 4	687	758	212,585	3232
	Mean	701	754	208,081	3466
	Standard deviation	22.2	20.6	40,313.4	670.7

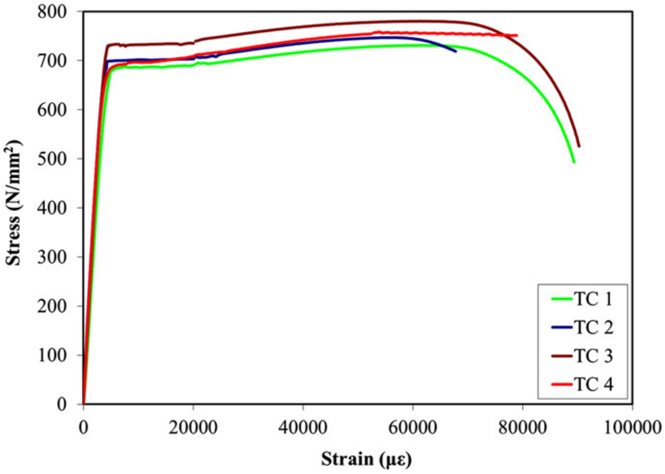

Fig. 1. Tensile coupon tests.

2.1.2. Compressive stub column tests

The stress–strain characteristics can be quite different in tension and compression which can be due to the effects of residual stresses. To try and analyse these differences a series of stub column tests were also undertaken. The compressive properties of the plate were determined by testing four 50 mm and two 70 mm stub columns, with an observed mean yield stress of 761 N/mm^2 which was achieved at a strain of 3455 με. The stub column test results are presented in Table 2. Both the compressive and tensile tests produced average yield strains of 3460 με. Fig. 3 shows the stress–strain diagrams for the tests and a typical specimen is illustrated in Fig. 4.

2.1.3. Concrete cylinder tests

Concrete cylinders were cast and tested to allow the characteristic compressive strength of the concrete to be determined. In total, twelve cylinders were tested in two groups and the relevant parameters and results are summarised in Table 3. The mean compressive strength of the concrete was thus determined at 28 days. The mean compressive strengths of the columns at the time of testing were estimated as 21.0 and 54.5 N/mm^2 for series 1 and 2, respectively.

Fig. 2. Typical failure mode for tensile coupon.