buckling, the test continued until excessive deformation of the column was observed. After the test, the specimens were removed, photographed and carefully examined.

Figure 1: Test arrangement and instrumentations

Concrete Properties

Three nominal concrete strengths – C30, C60 and C100 were studied. The concrete was produced using commercially available materials with normal mixing and curing techniques; the three mix designs are shown in Table 2 together with the cube and cylinder strength at test day. The strength development of the concrete was monitored over a duration of 28 days by conducting periodic cube and cylinder tests – the results of the cube tests are illustrated in Figure 2. Additionally, at the time of each series of stub column tests, two further standard cube tests and two standard cylinder tests were performed.

Table 2: Concrete mix proportions (% by weight) and the compressive strength (test day)

Grade	Cement	Fines	Coarse	w/c ratio	Silica fume	Super-plasticiser	f_{cu} (N/mm^2)	f_{ck} (N/mm^2)
C30	1.0	2.5	3.5	0.65	0	0	36.9	30.5
C60	1.0	2.0	3.3	0.40	0	0	59.8	55.3
C100	1.0	1.5	2.5	0.30	0.1	0.03	98.4	102.2

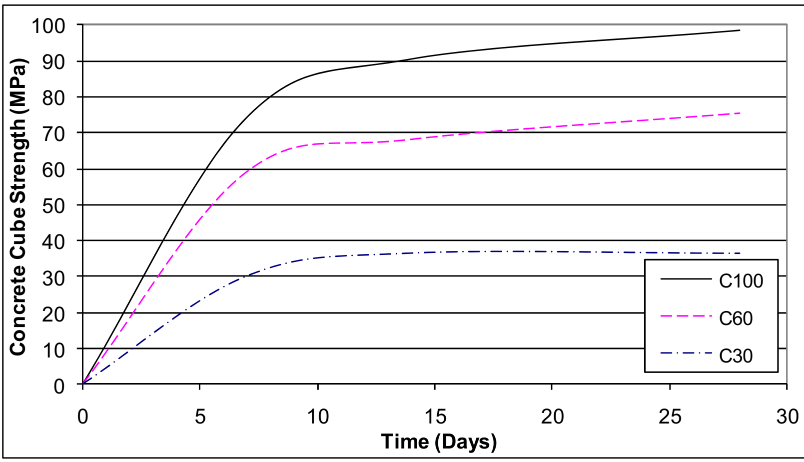

Figure 2: Concrete development strength

Steel Properties

Coupons were cut from the EHS and tested to [EN10002-1 2001] to determine the tensile strength. The coupons were cut form the in the region of maximum radius of curvature (i.e. the flattest portion of the section) and milled to specification. Some flattening of the ends occurred while gripping the specimen but this was well away from the ‘neck’ of the sample. The results from the coupon tests are summarized in Table 3.

Table 3: Steel properties of the EHS

Specimens	Young’s modulus E (N/mm^2)	Yield stress f_y (N/mm^2)	Ultimate strength f_u (N/mm^2)
150×75×4	217500	376.5	513
150×75×5	217100	369.0	505
150×75×6.3	216500	400.5	512

TEST RESULTS

All the specimens were tested under axial compression until failure. The typical failure modes of the composite specimens are shown in Figure 3. For the unfilled EHS, both inward and outward local buckling was observed in the deformed specimen while for the filled tubes, although inward buckling was prevented by the concrete core, outward local buckling is clearly evident in the deformed specimens.

Figure 3: Typical failure mode of the composite EHS

The load vs. end shortening curves from the EHS stub column tests are shown in Figures 4 to 6. The results show the clear advantage of composite EHS columns over their bare (unfilled) EHS counterparts. Overall, it may be observed from Figures 4 to 6 that the stockier EHS tubes with lower concrete strengths have more ductility, though enhancements in load carrying capacity beyond that of the bare steel sections due to concrete filling are more significant for slender sections with higher concrete strengths. The ultimate loads from the stub columns tests $N_{u,Test}$ are presented in Tables 4 with the composite factor, ϕ. The level of strength enhancement (beyond that of the unfilled tubes) can be represented by the composite factor, ϕ, the definition of which is given by Eq. (1). This index provides a quantitative measure of the benefit arising from concrete-filling.

$$\phi = \frac{N_{\text{u,filled}}}{N_{\text{u,unilled}}} \tag{1}$$

Where,

$N_{u,filled}$ is the ultimate resistance of the concrete-filled elliptical test specimens;
$N_{u,\ unfilled}$ is the ultimate test resistance of the corresponding empty EHS.

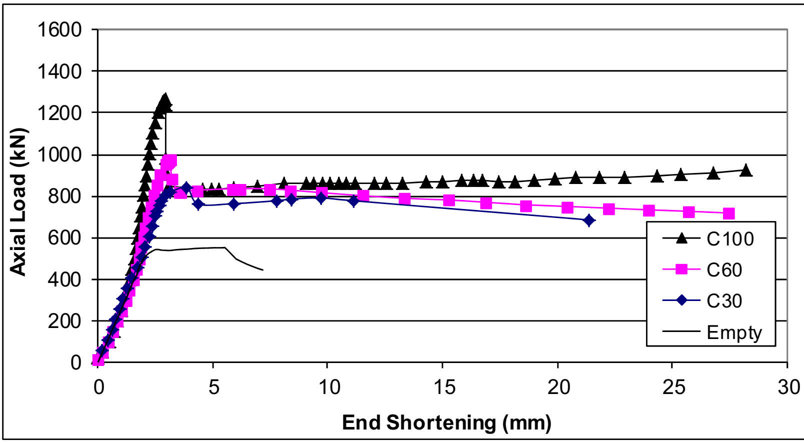

Figure 4: Axial load vs. end shortening curves for 150×75×4 EHS composite columns

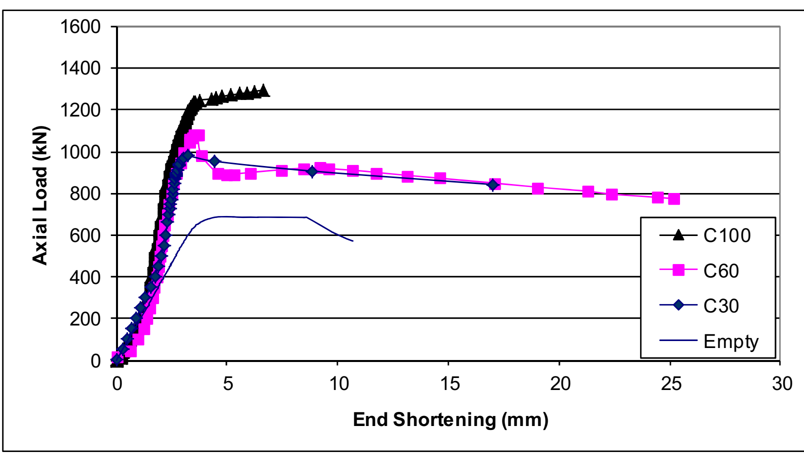

Figure 5: Axial load vs. end shortening curves for 150×75×5 EHS composite columns

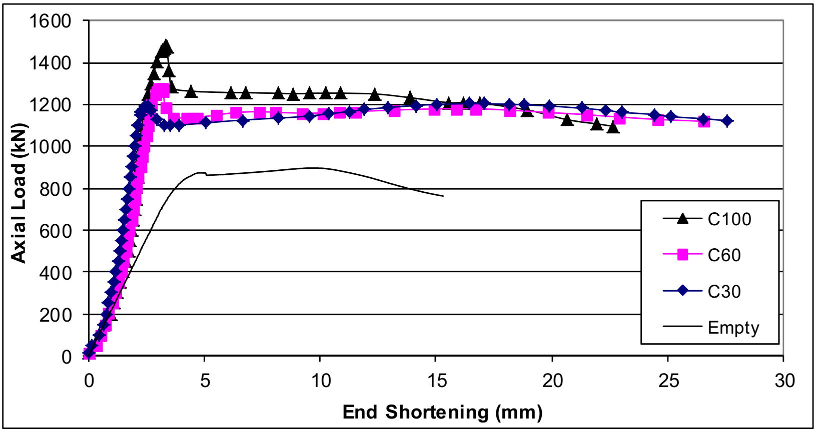

Figure 6: Axial load vs. end shortening curves for 150×75×6.3 EHS composite columns

Table 4: Summary of test results and composite factor, ϕ

Reference	$N_{u,\,Test}$	Composite factor, ϕ
150×75×4	550.0	1.00
150×75×4-C30	838.6	1.52
150×75×4-C60	974.2	1.77
150×75×4-C100	1264.6	2.30
150×75×5	688.9	1.00
150×75×5-C30	981.4	1.42
150×75×5-C60	1084.1	1.57
150×75×5-C100	1296.0	1.88
150×75×6.3	871.8	1.00
150×75×6.3-C30	1202.9	1.38
150×75×6.3-C60	1280.1	1.47
150×75×6.3-C100	1483.2	1.70

Figure 7 shows the relationship between the composite factor, ϕ and the cube strength of the concrete f_{cu} for the three different tube thicknesses. The results show that, as expected, the concrete contribution ratio increases for the higher concrete strengths, and that the level of enhancement is more significant for the thinner tubes; the 4mm elliptical tube shows a doubling in capacity with the C100 concrete infill.

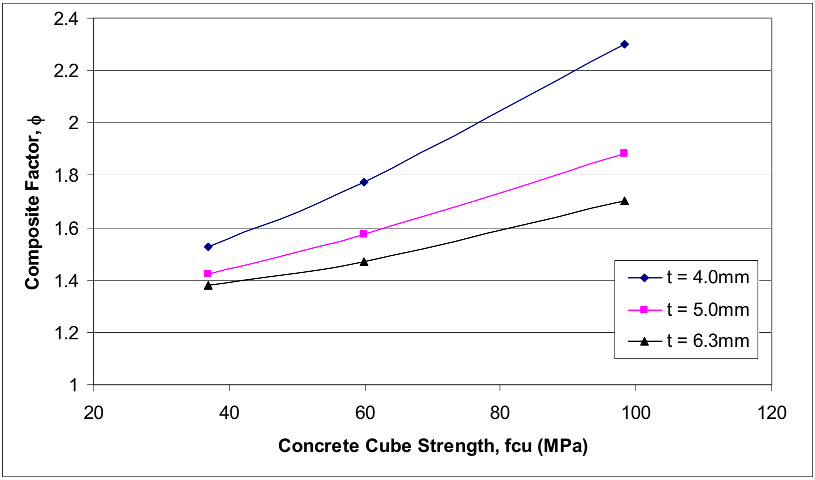

Figure 7: Composite factor vs. concrete cube strength curves

DESIGN CODE

Concrete-filled elliptical hollow sections are not explicitly covered by current design codes. The test results obtained in the present study have been combined with those reported by [Zhao et al., 2007] and compared with existing design guidance for the circular concrete-filled tubes. The codes considered are [EN 1994-1-1 2004] and [AISC 360-05 2005] respectively abbreviated to EC4, and AISC in this paper. The principal differences between the codes relate to the factors that are applied to the individual steel and concrete contributions to the composite resistance. Following the comparisons, design recommendations are made for concrete-filled elliptical hollow sections.

EC4 covers concrete encased and partially encased steel sections and concrete-filled tubes with and without reinforcement. The compressive resistance $N_{u,EC4}$ of concrete-filled steel tubes is given by Eq. (2). This is the latest design code that takes into account increases in concrete capacity due to confinement by the steel sections.

$$N_{u,EC4} = \eta_a A_a f_{yd} + A_c f_{cd}\left(1 + \eta_c \frac{t}{d}\frac{f_y}{f_{ck}}\right) \qquad (2)$$

Where,

$N_{u,EC4}$	Ultimate axial capacity of the composite column
f_{cd}	Design compressive strength of the concrete
f_{ck}	Cylinder strength of concrete
f_y	Yield strength of the steel tube
f_{yd}	Design strength of the steel tube

d	Larger diameter of the elliptical steel section
t	Thickness of steel tube
η_c	Coefficient of concrete confinement
η_a	Coefficient of steel confinement

In the AISC code, the compressive resistance of concrete-filled circular hollow sections $N_{u,AISC}$ is given by Eq. (3). The 0.95 factor on the concrete contribution in Eq. (3) reflects the superior performance of concrete-filled CHS over their rectangular counterparts.

$$N_{u,\mathrm{AISC}} = A_s f_y + 0.95 A_c f_{ck} \quad (3)$$

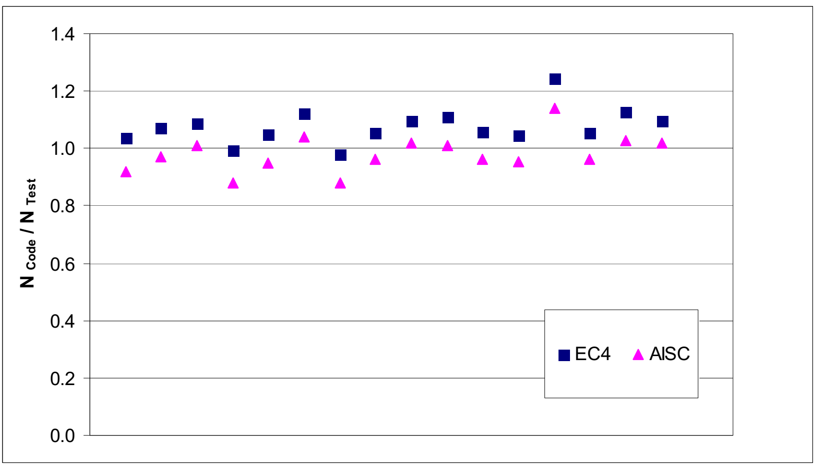

Figure 8: Comparison of code prediction

All the test results presented in this paper have been combined with those reported by [Zhao et al. 2007] and compared with the predictions from the aforementioned design codes. The comparisons, shown in Figure 8 and Table 5 reveal that the ultimate test loads from the 16 concrete-filled EHS specimens are generally over-predicted by the EC4 formulations for concrete-filled CHS by 8% and underestimated by 2% by the corresponding AISC concrete-filled CHS formulations. On the basis of the comparisons, it is recommended that the AISC expression for concrete-filled CHS (Eq. (3)) is most suitable for predicting the resistance of concrete-filled EHS. However, it is clear that the level of confinement and hence the resistance of concrete-filled EHS are related to the aspect ratio of the section and further research to investigate this feature is ongoing.

Table 5: Comparison between test results and codes prediction

Reference	$N_{u,\,Test}$ (kN)	$N_{u,\,EC4}$ (kN)	$\frac{N_{u,EC4}}{N_{u,Test}}$	$N_{u,AISC}$ (kN)	$\frac{N_{u,AISC}}{N_{u,Test}}$
150×75×4-C30	838.6	871.7	1.04	770.1	0.92
150×75×4-C60	974.2	1046.6	1.07	947.3	0.97
150×75×4-C100	1264.6	1379.1	1.09	1279.0	1.01
150×75×5-C30	981.4	977.8	1.00	865.6	0.88
150×75×5-C60	1084.1	1140.7	1.05	1030.8	0.95
150×75×5-C100	1296.0	1459.2	1.13	1350.4	1.04
150×75×6.3-C30	1202.9	1184.6	0.98	1059.5	0.88
150×75×6.3-C60	1280.1	1354.2	1.06	1230.5	0.96
150×75×6.3-C100	1483.2	1630.1	1.10	1511.2	1.02
150×75×4-C60*	1075	1193.1	1.11	1087.9	1.01
150×75×5-C60*	1163	1229.5	1.06	1118.4	0.96
150×75×6.3-C60*	1310	1370.3	1.05	1247.8	0.95
200×100×5-C60*	1598	1991.3	1.25	1819.4	1.14
200×100×6.3-C60*	2068	2181.4	1.05	1989.5	0.96
200×100×8-C60*	2133	2404.7	1.13	2193.3	1.03
200×100×10-C60*	2290	2514.9	1.10	2331.2	1.02
*Test reported by [Zhao et al.,		Mean	1.08	Mean	0.98
		SD	0.061	SD	0.064

CONCLUSIONS

A total of 12 tests – 9 compositely loaded and 3 unfilled elliptical hollow sections have been performed to investigate the compressive behaviour of concrete-filled elliptical hollow sections. The compressive response was found to be sensitive to both steel tube thickness and concrete strength, with higher tube thickness resulting in higher load-carrying capacity and enhanced ductility, and higher concrete strengths improving load-carrying capacity but reducing ductility. The experimental results from the present study were combined with an additional 7 experimental results from literature, and compared with existing code provisions for circular hollow sections. From the comparisons, it may be concluded that existing design rules for concrete-filled CHS may be safely applied to EHS, and that the AISC design expression for CHS provide an accurate prediction of composite EHS behaviour.

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SEISMIC PERFORMANCE OF COMPOSITE *EWECS* COLUMNS IN NEW HYBRID STRUCTURAL SYSTEM

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ABSTRACT

This paper presents the results of experimental and analytical studies on Engineering Wood Encased Concrete-Steel (EWECS) composite columns. A total of four specimens with the scale of about two-fifth were tested under combined constant axial load and lateral load reversals. Variables investigated include the type of woody shell connection between column and loading stub and the presence of shear studs. The test results indicated that EWECS columns had excellent hysteretic behavior without severe damage even at large story drift of 0.04 radian. The results also showed that EWECS columns with the type of column-stub connection consisting of woody shell and wood panel attached to stub showed high performance in both capacity and damage limit. In addition, the presence of shear studs on EWECS columns improved the deformation capacity of the column and reduced the damage of woody shell. An analytical study was also performed using fiber section analysis to simulate the behavior of the composite columns.

INTRODUCTION

A new type of hybrid structural system called engineering wood encased concrete-steel (EWECS) structural system has been developed by the authors to solve a problem on the limitation of story number for unfireproof wooden structures that is limited to not more than three stories based on the Building Standard Law of Japan. The proposed structural system consists of EWECS columns and engineering wood encased steel (EWES) beams, as shown in Figure 1. For the first stage of the research program, composite EWECS columns were investigated. The composite column consists of concrete encased steel (CES) core with an exterior woody shell (Figure 1).

Both economical and structural benefits are realized from this type of composite column due to the use of woody shell as column cover. During construction, the woody shell acts as forming for the composite column, decreasing the labor and materials required for construction and, consequently, reducing the construction cost and time. From the structural point of view, the shell improves the structural behavior of the column through its action to provide core confinement and resistance to