Numerical study on concrete-filled aluminium circular hollow section columns

Feng Zhou
Department of Building Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China

Ben Young
Department of Civil Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong, China

Abstract

A numerical study on concrete-filled aluminium circular hollow section columns is presented. A nonlinear finite element model was developed in this study. The model was verified against test results. The finite element model was used for a parametric study and investigated the diameter-to-thickness ratio of the aluminium hollow sections and the concrete strength. The aluminium tubes of high strength material using the nominal concrete cylinder strengths of 70 and 100 MPa were investigated. The results obtained from the numerical study were compared with the design strengths calculated from the American and Australian/New Zealand specifications for aluminium and concrete structures. Design equations for concrete-filled aluminium circular hollow section columns are proposed. It is shown that the proposed design equations accurately predicted the column strengths.

Keywords: Aluminium tubes, Circular hollow sections, Composite columns, Finite element analysis.

1 Introduction

Concrete-filled aluminium tube columns can effectively take advantages of these two materials to provide both high strength and high stiffness. These findings have been reported by Zhou and Young (2008) for concrete-filled aluminium square and rectangular hollow section (SHS and RHS) stub column tests and Zhou and Young (2009) for concrete-filled aluminium circular hollow section (CHS) stub column tests.

Beside the experimental investigation, numerical investigation can also provide a good understanding of the structural behaviour of concrete-filled aluminium CHS columns. The CHS tube could provide confinement to the concrete infill for concrete-filled aluminium CHS columns. When concrete is subjected to lateral confining pressure, the uniaxial compressive strength and the corresponding strain are much higher than those of unconfined concrete. On the other hand, the CHS tube is stiffened by the concrete infill, which can prevent the inward buckling of the tube, hence increase the strength of the column. Therefore, the interface between the aluminium CHS tube and the concrete infill in the composite column have to be considered in the numerical modelling. Numerical investigation of concrete-filled steel tube columns has been reported by Hu et al. (2003), Ellobody and Young (2006), Ellobody et al. (2006) and many other researchers.

This paper presents the numerical simulation of concrete-filled aluminium CHS columns using finite element program ABAQUS (2007). The composite action between the aluminium tube and concrete infill has been carefully considered in the finite element model (FEM). The results obtained from the finite element analysis (FEA) were verified against the test results reported by Zhou and

Young (2009). An extensive parametric study was performed to investigate the effects of cross-section sizes and material properties on the strengths of concrete-filled aluminium CHS columns. The reliability of the design rules in the American specifications (AA 2005; ACI 2008) and Australian/New Zealand standards (AS/NZS 1997; AS3600 2001) for aluminium and concrete structures was evaluated using reliability analysis by comparing with the concrete-filled aluminium CHS column strengths predicted from the FEA (P_{FEA}) and column strengths obtained from the tests (P_{Exp}) reported by Zhou and Young (2009). Furthermore, design equations for concrete-filled aluminium CHS columns were proposed based on the results obtained from the numerical investigation in this study and the test results reported by Zhou and Young (2009). The proposed design equations considered the composite action between the aluminium CHS tube and the concrete infill.

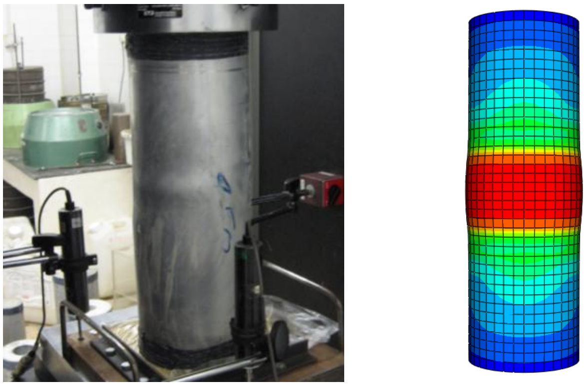
2 Finite element model

There are three main components in the finite element model that need special attention to simulate the structural behaviour of concrete-filled aluminium circular hollow section (CHS) columns. These components are the aluminium CHS tube, concrete infill and the interface between the aluminium tube and the concrete infill. The non-linear finite element analysis program ABAQUS (2007) was used to simulate the structural behaviour of concrete-filled aluminium CHS columns.

The numerical analysis was performed over a range of diameter-to-thickness (D/t) ratio for the aluminium tubular sections that included from compact sections to slender sections. Types of elements for composite columns were chosen from element library in the ABAQUS (2007). The element of C3D8, a three-dimensional eight-node solid element, was used for compact sections. The element of S4R, a four-node doubly curved thin or thick shell element with reduced integration, was used for slender sections. In this study, the aluminium tubes were stiffened by the concrete infill, which prevented the inward buckling of the tubes. Hence, fine mesh of C3D8 element was used to model both the concrete infill and the aluminium tubes for the composite columns. The finite element mesh used in the model was investigated by varying the size of the elements in order to provide both accurate results and less computational time. It is found that a mesh size of 1(length): 1(width): 1(depth), for most of the elements, achieved accurate results. The typical finite element mesh of the concrete-filled aluminium CHS columns is shown in Figure 1.

Following the test procedure conducted by Zhou and Young (2009), the top and bottom surfaces of the concrete-filled aluminium CHS columns were restrained against all degrees of freedom except for the displacement at the loaded end, which is the top surface, in the direction of the applied load. The loading method used in the finite element model (FEM) was identical to that used in the tests. The displacement control method was used for the analysis of the concrete-filled aluminium CHS columns. Vertical compressive uniform loads were applied to the specimen by specifying a displacement to each node of the loaded end in the top surface. Generally, a displacement of 20 mm was specified.

The measured stress-strain curves reported by Zhou and Young (2009) for the aluminium CHS tubes were used in the analysis. The Misses yield criterion with associated plastic flow is used in the multiaxial stress state. The aluminium alloy is assumed to have isotropic hardening behaviour. The material behaviour provided by ABAQUS (using the *PLASTIC option) allows a multi-linear stress–strain curve to be used. The first part of the multi-linear curve represents the elastic part up to the proportional limit stress with measured Young’s modulus and Poisson’s ratio equal to 0.33. Since the analysis involves large in-elastic strains, the nominal (engineering) static stress-strain curve was converted to a true stress and logarithmic plastic strain curve. The true stress (σ_{true}) and plastic true strain (ε^{pl}_{true}) are specified in ABAQUS (2007).



(a) Experimental (b) FEA

Figure 1. Comparison of experimental and finite element analysis failure modes

The aluminium CHS tube could provide confinement to the concrete infill for the concrete-filled aluminium CHS columns. The confinement model for concrete infill used by Ellobody et al. (2006) was adopted in this study. The concrete in the composite columns is usually subjected to triaxial compressive stress, and the failure of concrete is dominated by the compressive failure surface expanding with increasing hydrostatic pressure. Hence, a linear Drucker-Prager yield criterion was used with associate flow and isotropic hardening rule. The material angle of friction (β_{cc}) and the ratio of flow stress in triaxial tension to that in compression (K) were taken as 20° and 0.8, respectively, as recommended by Wu (2000).

The interfaces between the aluminium tube and the concrete infill were modeled using the contact pair. The "surface-to-surface contact" option was used. The concrete infill was defined as the master element, while the aluminium tube was defined as the slave element of the interface elements in the FEM. Along the normal direction to the interface, the "hard contact" relation was used. The contact pair allows the surfaces to separate under the influence of a tensile force. However, the two contact surfaces are not allowed to penetrate each other. Along the tangential direction to the interface, "Penalty" option was used and a friction coefficient of 0.25 was also used in the analysis.

3 Verification of finite element model

3.1 Summary of experimental investigation

An experimental investigation of concrete-filled aluminium circular hollow section (CHS) columns performed by Zhou and Young (2009) was used to verify the developed finite element model (FEM) in this study. Ten series of CHS tubes (CHS1 – CHS10) fabricated by extrusion using 6061-T6 heat-treated aluminium alloy (high strength material) with concrete infill were tested. The nominal section sizes (D×t) of the series CHS1, CHS2, CHS3, CHS4, CHS5, CHS6, CHS7, CHS8, CHS9 and CHS10 are 38×4, 50×3, 60×2.5, 76×2, 100×2, 120×2.5, 150×2.5, 150×5, 160×4 and 180×3.5 mm, respectively, where D is the diameter and t is the thickness of the sections. The measured diameter-to-thickness (D/t) ratio of the CHS tubes ranged from 9.7 to 59.7. The column lengths (L) were chosen so that the length-to-diameter ratio (L/D) for the concrete-filled aluminium CHS stub columns generally remained at a constant value of 3 to prevent overall column buckling. The column specimens were tested using three different nominal concrete cylinder strengths of 40, 70 and 100 MPa. Table 1 summarizes the measured dimensions and material properties of the tested specimens. The details of the experimental investigation are reported in Zhou and Young (2009).

Table 1. Summary of the test program and compared with finite element analysis results

specimen	D (mm)	t (mm)	D/t	f_y (MPa)	f_c (MPa)	P_{Exp}(kN)	P_{FEA}(kN)	P_{Exp}/P_{FEA}
CHS1-C40	38.0	3.89	9.8	242.4	44.8	158.9	165.7	0.96
CHS1-C70	38.0	3.90	9.7	242.4	70.2	167.2	173.3	0.96
CHS1-C100	38.0	3.92	9.7	242.4	106.0	171.5	189.3	0.91
CHS2-C40	50.0	3.13	16.0	238.4	44.8	217.0	238.8	0.91
CHS2-C70	50.0	3.12	16.0	238.4	70.2	238.9	251.3	0.95
CHS2-C100	50.0	3.13	16.0	238.4	106.0	327.5	301.2	1.09
CHS3-C40	60.0	2.55	23.5	237.8	44.8	244.1	250.2	0.98
CHS3-C70	60.0	2.54	23.6	237.8	70.2	292.4	307.3	0.95
CHS3-C100	59.9	2.53	23.7	237.8	106.0	412.6	412.7	1.00
CHS4-C40	76.1	2.06	36.9	237.0	44.8	329.9	356.0	0.93
CHS4-C70	76.0	2.06	36.9	237.0	70.2	415.7	451.9	0.92
CHS4-C100	76.0	2.05	37.1	237.0	106.0	611.4	592.0	1.03
CHS5-C40	99.7	2.02	49.4	244.3	44.8	543.6	506.7	1.07
CHS5-C70	99.8	2.06	48.4	244.3	70.2	712.0	687.2	1.04
CHS5-C100	100.0	2.05	48.8	244.3	106.0	995.8	942.9	1.06
CHS6-C40	119.8	2.49	48.1	253.1	44.8	822.8	747.6	1.10
CHS6-C70	120.0	2.55	47.1	253.1	70.2	1010.3	1011.4	1.00
CHS6-C100	119.9	2.48	48.3	253.1	106.0	1388.7	1366.9	1.02
CHS7-C40	150.1	2.53	59.3	267.9	44.8	1111.1	1124.6	0.99
CHS7-C70	150.1	2.54	59.1	267.9	70.2	1496.4	1540.0	0.97
CHS7-C100	149.9	2.53	59.2	267.9	106.0	2057.8	2120.4	0.97
CHS8-C40	150.2	5.03	29.9	216.9	44.8	1481.9	1532.9	0.97
CHS8-C70	150.2	5.04	29.8	216.9	70.2	1740.6	1845.0	0.94
CHS8-C100	150.2	5.03	29.9	216.9	106.0	2666.1	2491.9	1.07
CHS9-C40	160.1	4.03	39.7	254.2	44.8	1494.1	1538.3	0.97
CHS9-C70	160.5	4.07	39.4	254.2	70.2	1974.4	1988.4	0.99
CHS9-C100	160.5	4.06	39.5	254.2	106.0	2797.3	2627.8	1.06
CHS10-C40	180.0	3.71	48.5	264.9	44.8	1690.2	1721.7	0.98
CHS10-C70	180.4	3.69	48.9	264.9	70.2	2274.2	2296.7	0.99
CHS10-C100	180.5	3.75	48.1	264.9	106.0	3139.2	3119.6	1.01
							Mean, P_m	0.99
							COV	0.053

3.2 Comparison of finite element analysis results with experimental results

In the verification of the developed FEM, a total of thirty concrete-filled aluminium CHS columns tested by Zhou and Young (2009) were analyzed. A comparison between the experimental results and the finite element results was carried out. The main objective of this comparison is to verify and check the accuracy of the finite element model. The comparison of the test results (P_{Exp}) with the column strengths (P_{FEA}) predicted from the FEA is shown in Table 1. It is shown that the finite element results agreed well with the test results. A maximum difference of 10% was observed between the experimental and numerical results for specimen CHS6-C40. The mean value of the P_{Exp}/P_{FEA} ratio is 0.99 with the corresponding coefficient of variation (COV) of 0.053, as shown in Table 1. The failure mode of concrete-filled aluminium CHS column was also verified against the finite element model, as shown in Figure 1. It is shown that both the ultimate loads and the failure modes reflect good agreement between the experimental and finite element results.

4 Parametric study

It is shown that the developed finite element model (FEM) closely predicted the failure loads of the concrete-filled aluminium circular hollow section (CHS) columns. Hence, parametric study was carried out to study the effects of cross-section sizes and material properties on the concrete-filled aluminium CHS column strengths. Two Series were analyzed on aluminium CHS tubes of high strength material (T6) using the nominal concrete strengths of 70 and 100 MPa in the parametric study. The two series analyzed in this study were T6-C70 and T6-C100. The T6 stand for the high strength material type of aluminium CHS tubes. The letter "C" in the series label defines the concrete strength followed by the value of the nominal concrete cylinder strength in MPa. Each series consists of 24 different section sizes. The overall depth-to-thickness (D/t) ratio of the sections ranged from 10 to 160. The cross-section dimensions and concrete-filled aluminium CHS column strengths (P_{FEA}) predicted from the finite element analysis (FEA) are summarized in Table 2.

The measured material properties of the aluminium CHS tubes and concrete infill were used in the parametric study. The nonlinear stress-strain curve of the high strength aluminium CHS tube (series CHS7) tested by Zhou and Young (2009) having the yield stress of 267.9 MPa was used in the parametric study for high strength (T6) aluminium tubes. The measured compressive concrete cylinder strengths of 70.2 and 106.0 MPa reported by Zhou and Young (2009) were used in the parametric study for the concrete infill.

Table 2. Specimen dimensions and column strengths of the parametric study

Section	Diameter D (mm)	Thickness t (mm)	D/t	Length L(mm)	P_{FEA-T6} (kN)	
					C70	C100
D80-1	80	0.5	160.0	240	377.8	551.7
D80-2	80	0.6	133.3	240	382.5	555.9
D80-3	80	0.8	100.0	240	403.8	557.3
D80-4	80	1.0	80.0	240	417.5	586.5
D80-5	80	1.4	57.1	240	441.5	608.5
D80-6	80	2.0	40.0	240	502.1	662.0
D80-7	80	4.0	20.0	240	675.3	814.8
D80-8	80	8.0	10.0	240	894.4	971.6
D200-1	200	1.3	153.8	600	2381.0	3462.8
D200-2	200	1.6	125.0	600	2440.3	3537.1
D200-3	200	2.0	100.0	600	2534.0	3599.6
D200-4	200	2.5	80.0	600	2622.7	3681.9
D200-5	200	3.3	60.6	600	2717.3	3769.9
D200-6	200	5.0	40.0	600	3137.7	4140.3
D200-7	200	10.0	20.0	600	3708.4	4595.6
D200-8	200	20.0	10.0	600	5574.0	6021.4
D300-1	300	2.0	150.0	900	5388.8	7832.6
D300-2	300	2.3	130.4	900	5497.1	7920.3
D300-3	300	3.0	100.0	900	5669.7	8070.1
D300-4	300	3.8	78.9	900	5885.0	8213.9
D300-5	300	5.0	60.0	900	6128.3	8470.9
D300-6	300	7.5	40.0	900	7030.1	9283.5
D300-7	300	15.0	20.0	900	9428.8	11410.6
D300-8	300	20.0	15.0	900	10537.2	12253.2

5 Reliability analysis

The reliability of the concrete-filled aluminium column design rules was evaluated using reliability analysis. The reliability index (β) is a relative measure of the safety of the design. A target reliability index of 2.5 for aluminium structural members is recommended as a lower limit in the AA Specification (2005). The design rules are considered to be reliable if the reliability index is greater than or equal to 2.5. The load combination of 1.2DL + 1.6LL as specified in the American Society of Civil Engineers Standard (ASCE 2005) was used in the reliability analysis, where DL is the dead load and LL is the live load. The statistical parameters are obtained from AA Specification for aluminium column strength, where $M_m = 1.10$, $F_m = 1.00$, $V_M = 0.06$, and $V_F = 0.05$, which are the mean values and coefficients of variation for material properties and fabrication factors. The statistical parameters P_m and V_P are the mean value and coefficient of variation of load ratio, respectively, as shown in Tables 3 and 4. In calculating the reliability index, the correction factor in the AA Specification was used. Reliability analysis is detailed in the AA Specification (2005).

Table 3. Comparison of numerical results with design Strengths for Concrete-filled Aluminium CHS Columns of Series T6-C70

Specimen	D/t	P_{Exp} & P_{FEA} (kN)	(P_{Exp} & P_{FEA}) /P_{AA}	(P_{Exp} & P_{FEA}) /$P_{\mathrm{AS/NZS}}$	(P_{Exp} & P_{FEA}) /P_{P}
CHS1C70	9.7	167.2	1.16	1.26	0.89
CHS2C70	16.0	238.9	1.20	1.28	0.86
CHS3C70	23.6	292.4	1.17	1.23	0.83
CHS4C70	36.9	415.7	1.19	1.21	0.91
CHS5C70	48.4	712.0	1.25	1.26	1.02
CHS6C70	47.1	1010.3	1.21	1.22	0.99
CHS7C70	59.1	1496.4	1.19	1.19	0.96
CHS8C70	29.8	1740.6	1.23	1.28	0.91
CHS9C70	39.4	1974.4	1.26	1.28	0.97
CHS10C70	48.9	2274.2	1.20	1.21	0.98
T6-D80-1-C70	160.0	377.8	1.22	1.22	1.00
T6-D80-2-C70	133.3	382.5	1.21	1.21	0.98
T6-D80-3-C70	100.0	403.8	1.23	1.23	0.99
T6-D80-4-C70	80.0	417.5	1.23	1.23	0.99
T6-D80-5-C70	57.1	441.5	1.22	1.22	0.99
T6-D80-6-C70	40.0	502.1	1.27	1.29	0.98
T6-D80-7-C70	20.0	675.3	1.35	1.43	0.94
T6-D80-8-C70	10.0	894.4	1.32	1.43	1.00
T6-D200-1-C70	153.8	2381.0	1.23	1.23	1.00
T6-D200-2-C70	125.0	2440.3	1.22	1.22	0.99
T6-D200-3-C70	100.0	2534.0	1.23	1.23	0.99
T6-D200-4-C70	80.0	2622.7	1.24	1.24	0.99
T6-D200-5-C70	60.6	2717.3	1.22	1.22	0.98
T6-D200-6-C70	40.0	3137.7	1.27	1.29	0.98
T6-D200-7-C70	20.0	3708.4	1.19	1.26	0.83
T6-D200-8-C70	10.0	5574.0	1.32	1.43	0.99
T6-D300-1-C70	150.0	5388.8	1.23	1.23	1.00
T6-D300-2-C70	130.4	5497.1	1.23	1.23	1.00
T6-D300-3-C70	100.0	5669.7	1.23	1.23	0.99
T6-D300-4-C70	78.9	5885.0	1.23	1.23	0.99
T6-D300-5-C70	60.0	6128.3	1.22	1.22	0.98
T6-D300-6-C70	40.0	7030.1	1.27	1.29	0.98
T6-D300-7-C70	20.0	9428.8	1.34	1.42	0.94
T6-D300-8-C70	15.0	10537.2	1.34	1.43	0.95
		Mean, P_m	1.24	1.27	0.96
		COV, V_p	0.039	0.058	0.051
		Reliability index , β	3.66	3.69	2.53
		Resistance factor , ϕ	0.90	0.90	0.90

Table 4. Comparison of numerical results with design Strengths for Concrete-filled Aluminium CHS Columns of Series T6-C100

Specimen	*D/t*	P_{Exp} & P_{FEA} (kN)	(P_{Exp} & P_{FEA}) /P_{AA}	(P_{Exp} & P_{FEA}) /$P_{\mathrm{AS/NZS}}$	(P_{Exp} & P_{FEA}) /P_{P}
CHS1C100	9.7	171.5	1.06	1.13	0.81
CHS2C100	16.0	327.5	1.38	1.45	1.01
CHS3C100	23.7	412.6	1.33	1.39	0.98
CHS4C100	37.1	611.4	1.35	1.37	1.05
CHS5C100	48.8	995.8	1.32	1.32	1.06
CHS6C100	48.3	1388.7	1.27	1.28	1.01
CHS7C100	59.2	2057.8	1.23	1.23	0.97
CHS8C100	29.9	2666.1	1.48	1.52	1.12
CHS9C100	39.5	2797.3	1.38	1.40	1.08
CHS10C100	48.1	3139.2	1.25	1.26	1.00
T6-D80-1-C100	160.0	551.7	1.20	1.20	1.01
T6-D80-2-C100	133.3	555.9	1.20	1.20	1.00
T6-D80-3-C100	100.0	557.3	1.17	1.17	0.97
T6-D80-4-C100	80.0	586.2	1.21	1.21	1.00
T6-D80-5-C100	57.1	608.5	1.21	1.21	1.00
T6-D80-6-C100	40.0	662.0	1.24	1.26	1.02
T6-D80-7-C100	20.0	814.8	1.31	1.37	0.97
T6-D80-8-C100	10.0	971.6	1.25	1.34	0.98
T6-D200-1-C100	153.8	3462.8	1.20	1.20	1.01
T6-D200-2-C100	125.0	3537.1	1.21	1.21	1.01
T6-D200-3-C100	100.0	3599.6	1.21	1.21	1.01
T6-D200-4-C100	80.0	3681.9	1.21	1.21	1.01
T6-D200-5-C100	60.6	3769.9	1.21	1.21	1.00
T6-D200-6-C100	40.0	4140.3	1.24	1.26	1.02
T6-D200-7-C100	20.0	4595.6	1.18	1.24	0.87
T6-D200-8-C100	10.0	6021.4	1.24	1.33	0.97
T6-D300-1-C100	150.0	7832.6	1.21	1.21	1.02
T6-D300-2-C100	130.4	7920.3	1.21	1.21	1.01
T6-D300-3-C100	100.0	8070.1	1.21	1.21	1.00
T6-D300-4-C100	78.9	8213.9	1.20	1.20	1.00
T6-D300-5-C100	60.0	8470.9	1.20	1.20	1.00
T6-D300-6-C100	40.0	9283.5	1.24	1.25	1.02
T6-D300-7-C100	20.0	11410.6	1.30	1.36	0.96
T6-D300-8-C100	15.0	12253.2	1.29	1.36	0.96
		Mean, P_m	1.25	1.27	1.00
		COV, V_p	0.061	0.070	0.052
		Reliability index , β	3.61	3.65	2.69
		Resistance factor , ϕ	0.90	0.90	0.90

6 Comparison of experimental and numerical results with current design strengths

The concrete-filled aluminium CHS column strengths (P_{FEA}) predicted from the finite element analysis (FEA) were compared with the nominal design strengths (P_n) predicted using the American specifications (AA 2005; ACI 2008) and Australian/New Zealand standards (AS/NZS 1997; AS3600

2001) for aluminium and concrete structures. The unfactored design strengths (P_n) of concrete-filled aluminium CHS stub columns were obtained by determining the strength of the aluminium tube (A_aF_L) using the specifications (AA 2005; AS/NZS 1997) for aluminium structures as well as the strength of concrete infill ($0.85A_cf_c$) using the specifications (ACI 2008; AS3600 2001) for concrete structures, as shown in Eq. (1).

$$P_n = A_a F_L + 0.85 A_c f_c \tag{1}$$

where A_a is the full cross-section area of aluminium tube, F_L is the limit state stress calculated using Sections 3.4.7 through 3.4.10 and Sections 4.7.2 and 4.7.4 of the American (AA) Specification (2005), and Sections 3.4.8 through 3.4.11 and Sections 4.7.2 and 4.7.4 of the Australian/New Zealand (AS/NZS) Standard (1997), Ac is the area of concrete and f_c is the concrete cylinder strength. The design rules in the AS/NZS Standard (1997) for calculating the design strengths of aluminium columns are generally identical to those in the AA Specification (2005), except that the AS/NZS Standard reduces the yield load of the column using a coefficient k_c which is not included in the AA Specification. The American Specification (ACI 2008) and Australian Standard (AS3600 2001) for concrete structures generally use the same formula to calculate the strength of the concrete infill.

The concrete-filled aluminium CHS column strengths (P_{FEA}) predicted from FEA together with the test strengths (P_{Exp}) reported by Zhou and Young (2009) were compared with design strengths (P_{AA} and $P_{AS/NZS}$), as shown in Tables 3 and 4. For the American specifications (AA 2005; ACI 2008), the mean values of the (P_{Exp} and P_{FEA})/P_{AA} ratio are 1.24 and 1.25 with the corresponding coefficients of variation (COV) of 0.039 and 0.061, and the reliability index (β) are 3.66 and 3.61 for series T6-C70 and T6-C100, respectively. For the Australian/New Zealand standards (AS/NZS 1997; AS3600 2001), the mean values of the (P_{Exp} and P_{FEA})/P_{AA} ratio are 1.27 and 1.27 with the corresponding COV of 0.058 and 0.070, and the reliability index (β) are 3.69 and 3.65 for series T6-C70 and T6-C100, respectively. It is shown that the American and AS/NZS specifications are generally conservative and reliable for the concrete-filled aluminium CHS stub columns having nominal concrete cylinder strengths of 70 and 100 MPa with the D/t ratio of the CHS tubes ranging from 9 to 160.

7 Proposed design equations

The aluminium CHS tube provides confinement to the concrete infill for the composite columns. On the other hand, the aluminium tube is stiffened by the concrete infill, which can prevent the inward buckling of the aluminium tube and increase the stability and strength of the column as a composite system. These enhancements of concrete-filled aluminium CHS columns due to the composite action between the constituent elements are not considered in the current American and Australian/New Zealand design rules. In this study, the ultimate strengths (P_p) of the concrete-filled aluminium CHS columns are proposed, as shown in Eqs (2) - (4).

$$P_p = A_a f_y + 0.85 A_c f_c + \eta A_c f_y \tag{2}$$

in which,

$$\eta = 0.31 - 0.0055\frac{D}{t} \qquad \text{for} \quad 9 \le \frac{D}{t} \le 50\left(1 - 0.377\frac{f_c}{f_y}\right) \tag{3}$$

$$\eta = 0.045 - 0.0002\frac{D}{t} + 0.1\left(\frac{f_c}{f_y}\right) \qquad \text{for} \quad 50\left(1\text{-}0.377\frac{f_c}{f_y}\right) < \frac{D}{t} \le 160 \tag{4}$$

where P_p is the proposed column strength of concrete-filled aluminium CHS; A_a is the full cross-section area of aluminium tube; f_y is the aluminium yield stress (0.2% proof stress); A_c is area of concrete; f_c is the concrete cylinder strength; D is the outer diameter of CHS tube; and t is the thickness of aluminium CHS tube. The ultimate strengths of concrete-filled aluminium CHS columns are influenced not only by its constituent material properties such as the compressive cylinder strength of the concrete (f_c) and the yield stress (f_y) of the aluminium tube, but also the confining pressure on the concrete infill which depends on the overall depth-to-thickness (D/t) ratio of the aluminium CHS tube. The limitations of the Eqs (2) - (4) are $9 \leq D/t \leq 160$ and $f_c \leq 106$ MPa.

8 Comparison of experimental and numerical results with proposed design strengths

The unfactored design strengths calculated using the proposed design equations (2) - (4) were compared with the concrete-filled aluminium column strengths obtained from the tests (P_{Exp}) reported by Zhou and Young (2009) and the column strengths (P_{FEA}) predicted by the FEA obtained from this study. The proposed design strengths were calculated using the measured cross-section dimensions and measured material properties. The resistance factor $\phi = 0.90$ for composite columns was obtained from reliability analysis. The load combination of 1.2DL + 1.6LL was used to determine the reliability index (β), as shown in Tables 3 and 4.

The proposed design strengths are generally conservative and reliable for the concrete-filled aluminium CHS columns. The mean values of the (P_{Exp} and P_{FEA})/P_{AA} ratio are 0.96 and 1.00 with the corresponding COV of 0.051 and 0.052, and the values of β are 2.53 and 2.69 for series T6-C70 and T6-C100, respectively, as shown in Tables 3 and 4. The reliability indices (β) are greater than the target value for all the specimens. It is also shown that the proposed design strengths are more accurate than the current design strengths.

9 Conclusions

A finite element model (FEM) of concrete-filled aluminium circular hollow section (CHS) columns including geometric and material non-linearities has been developed and presented in this paper. The developed FEM was verified against experimental results. It is shown that the FEM closely predicted the structural behaviour of concrete-filled aluminium CHS columns. Hence, a parametric study was carried out to study the effects of cross-section sizes and material properties of concrete-filled aluminium CHS column strengths.

The reliability of the concrete-filled aluminium column design rules in the current American and Australian/New Zealand specifications for aluminium and concrete structures was evaluated using reliability analysis. The composite column strengths obtained from the finite element analysis and the tests were compared with the design strengths. It is shown that the American and Australian/New Zealand specifications are generally conservative and reliable for the concrete-filled aluminium CHS stub columns having nominal concrete cylinder strengths of 70 and 100 MPa.

The current American and Australian/New Zealand design rules do not consider the benefits of composite action due to the confinement in the concrete-filled aluminium CHS columns. Therefore, composite column design equations are proposed in order to predict the ultimate strengths of concrete-filled aluminium CHS columns. The column strengths calculated using the proposed design equations are generally conservative and reliable for all the specimens considered in this study. It should be noted that the proposed design strengths are more accurate than the current design strengths. The proposed design equations are capable of producing reliable limit state design when calibrated with the resistance factor $\phi = 0.90$.

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