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Abstract

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Numerical simulations of circular high strength concrete-filled aluminum tubular short columns incorporating new concrete confinement model

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ABSTRACT

Concrete-filled aluminum tubular (CFAT) columns have the advantages of a lightweight, high resistance to corrosion, good appearance and ease of maintenance over concrete-filled steel tubular (CFST) columns. However, experimental and computational studies on the performance of CFAT columns have rarely been reported. This paper concerns with the fiber-based numerical analysis, structural behavior, and design of circular high strength CFAT stub columns loaded concentrically. A new concrete confinement model for computing the lateral pressures on the concrete core in CFAT circular columns is proposed and implemented in the computational model. The numerical analysis procedure is given for the determination of the nonlinear load-strain behavior of CFAT stub columns. The available experimental results of circular CFAT columns are used to assess the accuracy of the developed model. The computer model is employed to ascertain the significance of various geometric parameters in addition to material strengths on the responses of CFAT stub circular columns. The design equation based

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on Liang-Fragomeni's expression is proposed for quantifying the ultimate axial strengths of axially compressed CFAT short columns. The verification reveals that the computer modeling approach accurately quantifies the ultimate loads and nonlinear load-strain performance of CFAT columns with circular sections. The proposed design equation yields good calculations of the ultimate axial strengths of CFAT columns.

Keywords Concrete-filled aluminum tubes; Composite columns; Aluminum contribution ratio; Fiber element modeling; Nonlinear analysis.

1. Introduction

Concrete-filled steel tubular (CFST) columns have high performance in terms of strength, earthquake resistance, ductility and stiffness, and are therefore often used in composite buildings [1]. Due to its lightweight and high corrosion resistance, aluminum has been widely used in the construction of high-rise buildings, such as the Empire State Building in New York, 30 St Mary Axe in London, and the Bank of China headquarters in Hong Kong. The weight of CFST columns could significantly be reduced by replacing the steel tubes with aluminum ones. Circular concrete-filled aluminum tubular (CFAT) columns as schematically shown in Fig. 1 have the advantages of a lightweight, high corrosion resistance, good appearance, and ease of maintenance in comparisons with CFST columns. However, the welding of aluminum requires a special process which limits the use of aluminum for the structural application. In addition, the cost of aluminum is two times higher than that of steel. As depicted in Fig. 2, the stress-strain response of aluminum significantly differs from that of structural steels. Unlike the mild steel, aluminum exhibits the rounded stress-strain curve without a well-defined yield strength. Therefore, the 0.2% proof stress is usually used to represent the aluminum yield strength. The

elastic modulus of aluminum material is remarkably lower than that of structural steel. Because of the material characteristics of aluminum, the structural behavior of CFAT columns is different from that of CFST columns. Therefore, to quantify the behavior of circular CFAT short columns, further computational studies are necessary and important.

Extensive studies have been performed to ascertain the responses of CFST columns fabricated by carbon and stainless steel tubes [2–8]. However, only a few experimental studies on square, rectangular and circular CFAT stub columns and double-skin concrete-filled aluminum tubular (DCFAT) columns of circular sections loaded concentrically were conducted by Zhou and Young [9–11]. The filled concrete had the compressive strengths of 40 MPa, 70 MPa, and 100 MPa, which were used to assess the influences of concrete strength on the nonlinear responses of short CFAT and DCFAT columns. For rectangular and square cross-sections, the depth-to-thickness ratio ranged from 8.2 to 63.8 while the diameter-to-thickness (D/t) ratio of circular sections varied from 9.7 to 59.2. The failure modes of CFAT columns with slender sections were the outward local buckling and splitting of aluminum tubes and crushing of concrete near the buckled regions. It was found that the initial stiffness of a CFAT column was higher than that of the corresponding hollow aluminum tubular column.

Computational models developed using the commercial finite element (FE) software Abaqus and the efficient fiber approach have been well established by a number of investigators for determining the structural responses of CFST columns to design actions [12–18]. The CFAT columns are relatively new composite columns, which have received very limited attention. Wang et al. [19] presented a numerical study on the behavior of concentrically loaded circular CFAT stub columns. They utilized the computer program Abaqus to create FE models to predict the behavior of CFAT stub columns loaded axially to failure. The measured stress-

strain response of aluminum material was directly adopted in the finite element analysis. Patel et al. [20] developed a computational model implementing the method of fiber analysis, which can predict the structural performance of concentrically compressed circular DCFAT stub columns. The modeling approach considered the double-skin confinement to capture the interaction effect of aluminum tubes and sandwiched concrete. The nonlinear stress-strain laws proposed by Abdella [21] based on Ramberg and Osgood equation [22] were employed to simulate the behavior of aluminum material. The computer modeling technique developed was shown to simulate well the structural behavior of DCFAT columns. The numerical results indicated that the use of aluminum tube instead of a steel one could approximately reduce the column weight by 22.5%. It was also reported that the current design provisions for circular CFST columns either overestimated or underestimated the ultimate loads of circular DCFAT columns while Liang's design equation [23] produced accurate design strengths.

It has been found that only one numerical study has been undertaken on the performance of circular short CFAT columns [19]. To bridge this knowledge gap, this paper presents the numerical analysis, behavior, and design of concentrically compressed circular high strength CFAT stub columns incorporating a new confinement model. A computational model using the approach of fiber elements is proposed that calculates the load-strain responses of short circular CFAT columns loaded concentrically to failure. The verification of the fiber-based nonlinear simulation model is undertaken. The significance of geometric parameters in addition to material strengths on the nonlinear axial load-strain behavior, strain ductility index and aluminum contribution ratio is examined. The Liang-Fragomeni equation [13] proposed for circular CFST columns to the design of circular CFAT stub columns is assessed.

2. Formulation of computational model

2.1. Basic theory

The basic theory underlying the computational model is based on the method of fiber elements, which is employed to divide the column cross-section into fiber elements [1,24]. The analysis method has been proved to be accurate and computationally efficient for modeling the behavior of inelastic composite sections with the ability to handle gradual yielding and local buckling [16,17]. Liang's discretization technique [23] developed for a circular steel cross-section filled with concrete is employed herein. In this technique, the origin of the coordinate system is located at the section centroid. The aluminum tube wall is discretized into several circumferential layers n_{af} through its thickness. The number of layers n_{af} is specified by the user. The number of aluminum regions n_{ar} is determined from the specified circumference layers n_{af} using the equation $n_{ar} = (\pi D) / (t / n_{af})$, where D is the outer diameter of the tube and t its thickness. The discretization of the cross-section results in circular sector elements as presented in Fig. 3.

The assumptions underlying the fiber model are summarized as: (a) there is no slippage between the concrete and aluminum tube; (b) concrete confinement is considered explicitly in the stress-strain laws of concrete; (c) the local buckling of circular CFAT columns is not considered as practical circular CFAT columns usually have a diameter-to-thickness ratio less than 150 for which local buckling would not occur before the ultimate load of the columns is attained [25]; (d) the failure occurs if the extreme compressive strain of concrete exceeds the prescribed ultimate strain; (e) the influence of concrete shrinkage as well as creep is neglected; (f) CFAT columns are exposed to room temperature.

In the method of fiber analysis, each element represents either a steel fiber or a concrete fiber and can be given the material properties of either steel or concrete. The longitudinal stresses are computed from axial strains by means of applying the uniaxial material constitutive laws. The internal axial force (P) in the cross-section is determined by integrating the fiber stresses over the entire cross-section as

$$P = \sum_{i=1}^{na} A_{a,i} \sigma_{a,i} + \sum_{j=1}^{nc} A_{c,j} \sigma_{c,j} \quad (1)$$

in which na , nc are the numbers of aluminum and concrete elements, respectively; $A_{a,i}$, $A_{c,j}$ the elemental areas of aluminum and concrete fibers, respectively; and $\sigma_{a,i}$, $\sigma_{c,j}$ the elemental stresses of aluminum and concrete fibers, respectively.

2.2. Computer simulation procedure

The analysis of a circular CFAT column firstly discretizes the cross-section into small fiber elements. The area and coordinates of each fiber element are then computed. After that, the axial strain is increased incrementally from zero to the prescribed ultimate concrete strain. Since the force-control method, in which the axial force increases from zero to the ultimate load, cannot capture the post-peak behavior of circular CFAT columns, the strain-control technique is employed in the present study. For each strain increment, the stress in each fiber is computed by using the nonlinear stress-strain relations of aluminum and concrete, which are given in Section 3. The above computation process is repeated until the axial load-strain responses of CFAT circular columns are completely determined. The computer flowchart that

models the load-axial strain responses of CFAT columns is demonstrated in Fig. 4, where $P_{\max}$ is the ultimate axial strength of a CFAT column.

2.3. Contribution ratios of aluminum tube and concrete

The contribution ratio can be used to study the economic design of circular CFAT short columns [26]. The aluminum and concrete contributions to the ultimate axial strength of a circular CFAT short column are evaluated by the contribution ratios. Liang [26] proposed the equations for computing the contribution ratios as follows:

$$R_a = \frac{P_{u,a}}{P_u} \quad (2)$$

$$R_c = \frac{P_{u,c}}{P_u} \quad (3)$$

in which R_a and R_c represent the aluminum and concrete contribution ratios, respectively; $P_{u,a}$ and $P_{u,c}$ denote the axial load of aluminum tube and concrete at the strain where CFAT column attains the ultimate axial strength, respectively; and P_u stands for the ultimate axial load a circular CFAT short column.

3. Material constitutive laws

3.1. Stress-strain relation of aluminum

Ramberg and Osgood [22] developed an equation that describes the stress-strain relationship

of aluminum as a function of three parameters, including the 0.2% proof stress $\sigma_{0.2}$, Young's modulus E_0 , and nonlinearity index n . The Ramberg-Osgood equation [22] expresses the strain as a function of stress. The strain-control procedure given in Section 2.2 requires the calculation of stresses using given strains [27]. Abdella [21] mathematically inverted the stress-strain equation proposed by Ramberg and Osgood [22] for aluminum. The inversion allows the stress to be computed directly from the strain. The stress-strain model given by Abdella [21] is implemented in the proposed computational model, and it is divided into two stages based on the strain range as shown in Fig. 5. In the first stage, the stress is calculated from strain by

$$\sigma_a = \frac{\sigma_{0.2} r (\varepsilon_a / \varepsilon_{0.2})}{1 + (r-1) (\varepsilon_a / \varepsilon_{0.2})^p} \quad \text{for } 0 \leq \varepsilon_a \leq \varepsilon_{0.2} \quad (4)$$

$$r = \frac{E_0 \varepsilon_{0.2}}{\sigma_{0.2}} \quad (5)$$

$$p = \frac{r(1-r_2)}{r-1} \quad (6)$$

$$r_2 = \frac{E_{0.2} \varepsilon_{0.2}}{\sigma_{0.2}} \quad (7)$$

in which ε_a denotes the aluminum strain, σ_a the stress at the strain ε_a , E_0 the Young's modulus of aluminum, $\sigma_{0.2}$ the 0.2% proof stress of aluminum, and $\varepsilon_{0.2}$ the strain at the stress $\sigma_{0.2}$, which is defined as [22]

$$\varepsilon_{0.2} = 0.002 + \frac{\sigma_{0.2}}{E_0} \quad (8)$$

In Eq. (7), $E_{0.2}$ stands for the tangent modulus of aluminum, which is computed by [22]

$$E_{0.2} = \frac{E_0}{1 + 0.002(nE_0/\sigma_{0.2})} \quad (9)$$

In the second stage, the aluminum stress is determined using the expressions proposed by Abdella [21] as

$$\sigma_a = \sigma_{0.2} \left[1 + \frac{r_2 (\varepsilon_a / \varepsilon_{0.2} - 1)}{1 + (r^* - 1) \left(\frac{\varepsilon_a / \varepsilon_{0.2} - 1}{\varepsilon_{au} / \varepsilon_{0.2} - 1} \right)^{p^*}} \right] \quad \text{for } \varepsilon_{0.2} < \varepsilon_a \leq \varepsilon_{au} \quad (10)$$

$$r^* = \frac{E_{0.2} (\varepsilon_{au} - \varepsilon_{0.2})}{(\sigma_{au} - \sigma_{0.2})} \quad (11)$$

$$p^* = \frac{r^* (1 - r_u)}{r^* - 1} \quad (12)$$

$$r_u = \frac{E_u (\varepsilon_{au} - \varepsilon_{0.2})}{\sigma_{au} - \sigma_{0.2}} \quad (13)$$

The slope E_u was proposed by Abdella [21] as

$$E_u = \frac{E_{0.2}}{1 + (r^* - 1)m} \quad (14)$$

where m is the strain hardening parameter which was proposed by Rasmussen [28] as

$$m = 1 + 3.5 \frac{\sigma_{0.2}}{\sigma_{au}} \quad (15)$$

where σ_{au} denotes the ultimate stress of aluminum, which was obtained from the tension coupon test conducted by Zhou and Young [10]. In Fig. 5, ε_{au} is the strain at the stress σ_{au} .

3.2. Stress-strain relation of confined concrete

The lateral expansion of concrete in a circular CFAT column is restrained by the aluminum tube under increasing axial compression. It has been well established that the circular tube effectively confines the concrete in a CFST column with a circular section so that both the ductility and compressive strength of the filled concrete improve. The nonlinear stress-strain relationship depicted in Fig. 6 suggested by Liang and Fragomeni [13] is implemented in the computational model proposed to simulate the nonlinear response of confined concrete in CFAT columns of circular sections. The equation given by Mander et al. [29] is used to express the branch OA as

$$\sigma_c = \frac{f'_{cc} \lambda \left(\varepsilon_c / \varepsilon'_{cc} \right)}{\lambda - 1 + \left(\varepsilon_c / \varepsilon'_{cc} \right)^\lambda} \quad \text{for } 0 \leq \varepsilon_c \leq \varepsilon'_{cc} \quad (16)$$

where σ_c stands for the concrete stress in compression, ε_c the strain at stress σ_c , f'_{cc} and ε'_{cc} the axial compressive strength and strain of the confined concrete respectively, and λ is expressed by

$$\lambda = \frac{E_c}{E_c - (f'_{cc} / \varepsilon'_{cc})} \quad (17)$$

where E_c stands for the concrete elastic modulus, which is determined as [30]

$$E_c = 3320\sqrt{\gamma_c f'_c} + 6900 \text{ (MPa)} \quad (18)$$

where f'_c is the axial compressive strength of filled concrete, and γ_c the concrete strength reduction parameter derived by Liang [24] to consider the scale effect, given by

$$\gamma_c = 1.85 D_c^{-0.135} \quad (0.85 \leq \gamma_c \leq 1.0) \quad (19)$$

where D_c is the concrete diameter shown in Fig. 1 and the unit for D_c is mm.

The linear branches AB and BC shown in Fig. 6 are simulated using the following equations:

$$\sigma_c = \begin{cases} \beta_{cc} f'_{cc} + (f'_{cc} - \beta_{cc} f'_{cc}) \left(\frac{\varepsilon_c - 0.02}{\varepsilon'_{cc} - 0.02} \right) & \text{for } \varepsilon'_{cc} < \varepsilon_c \leq 0.02 \\ \beta_{cc} f'_{cc} & \text{for } \varepsilon_c > 0.02 \end{cases} \quad (20)$$

in which β_{cc} represents the strength degradation parameter. The following expressions presented by Hu et al. [12] are used to determine β_{cc} :

$$\beta_{cc} = \begin{cases} 1.0 & \text{for } 22 \leq \frac{D}{t} \leq 40 \\ 1.3491 + 0.0000339 \left(\frac{D}{t} \right)^2 - 0.010085 \left(\frac{D}{t} \right) & \text{for } 40 < \frac{D}{t} \leq 150 \end{cases} \quad (21)$$

It would appear from Eq. (21) that for small D/t ratios varying from 22 to 40, the aluminum tube offers strong confinement to the concrete so that its strength does not degrade. However, for the D/t ratio greater than 40, the aluminum tube provides less confinement to the concrete that exhibits softening behavior as depicted in Fig. 6.

3.3. Proposed concrete confinement model

The compressive strength (f'_{cc}) and its corresponding strain (ϵ'_{cc}) of confined concrete are determined by employing the equations given by Mander et al. [29] with the factor γ_c proposed by Liang [24] to account for the scale effect. The equations are expressed by

$$f'_{cc} = \gamma_c f'_c + 4.1 f_{rp} \quad (22)$$

$$\epsilon'_{cc} = \epsilon'_c \left(1 + 20.5 \frac{f_{rp}}{\gamma_c f'_c} \right) \quad (23)$$

where f_{rp} represents the lateral pressure on the concrete, and ϵ'_c the strain at stress f'_c , which can be determined by the expressions suggested by Liang [24] as

$$\varepsilon'_c = \begin{cases} 0.002 & \text{for } \gamma_c f'_c \leq 28 \text{ MPa} \\ 0.002 + \frac{\gamma_c f'_c - 28}{54000} & \text{for } 28 < \gamma_c f'_c \leq 82 \text{ MPa} \\ 0.003 & \text{for } \gamma_c f'_c > 82 \text{ MPa} \end{cases} \quad (24)$$

The Young's modulus of aluminum is 70 GPa, which is significantly lower than that of steel with 200 GPa. Therefore, the lateral confining pressure exerted by the aluminum tube is different from that offered by the carbon steel tube. It is important to develop a new confinement model for quantifying the lateral pressures on the concrete in circular CFAT columns to accurately determine f'_{cc} and ε'_{cc} . The lateral confining pressure on the concrete in a circular CFAT column depends on the diameter-to-thickness D/t ratio and 0.2% proof strength $\sigma_{0.2}$ of the aluminum tube. The regression analysis based on the multiple polynomial method was used to fit a surface to the experimental lateral confining pressures. Figure 7 depicts the surface fitting based on the experimental results [10]. A new concrete confinement model for predicting the lateral pressure f_{rp} on the concrete confined by circular aluminum tubes is proposed herein as

$$\begin{aligned} f_{rp} = & 0.00249 \left(\frac{D}{t} \right) \sigma_{0.2} - 0.002297 \left(\frac{D}{t} \right)^2 + 0.001269 \sigma_{0.2}^2 \\ & - 0.5329 \left(\frac{D}{t} \right) - 0.7214 \sigma_{0.2} + 104.24 \end{aligned} \quad (25)$$

The proposed confinement model has been implemented in the constitutive laws for confined concrete, which have been found to simulate well the ultimate strengths of CFAT columns as demonstrated in Section 4. The comparison of lateral pressures on concrete confined by the aluminum and carbon steel tubes are given in Section 5.1. The lateral confining pressure

induced by the steel tube to the concrete core in a CFST column can be determined using the equation proposed by Liang and Fragomeni [13].

4. Comparisons of computations against test data

4.1. Ultimate loads

Experimental results given by Zhou and Young [10] on concentrically compressed circular CFAT short columns were used to verify the developed numerical model. Table 1 provides the dimensions of tested columns and material strengths of aluminum and concrete. The nonlinearity index (n) for aluminum was not given by Zhou and Young [10] and was taken as 5.0 for the verification of the model. The diameter-to-thickness (D/t) ratios of the tested specimens varied from 9.7 to 59.2. Equation (21) applies to D/t ratios ranging from 22 to 150. For the analysis of the tested specimens with a D/t ratio less than 22, the factor β_{cc} was taken as 1.0. In Table 1, $P_{u,exp}$ stands for the experimental ultimate load, and $P_{u,num}$ represents the numerical ultimate load. The mean, standard deviation (SD), and coefficient of variation (COV) of the $P_{u,num}/P_{u,exp}$ ratios are 0.996, 0.056 and 0.056, respectively. The statistical analysis confirms that the computer model accurately quantifies the ultimate loads of CFAT short circular columns loaded axially.

4.2. Axial load-strain responses

The numerically computed load-strain responses of concentrically loaded CFAT short columns of circular sections are compared against test data given by Zhou and Young [10]. Figure 8

provides the experimental and numerical load-strain responses of Specimens CHS2C40, CHS2C70, CHS7C40, and CHS7C70. As can be found from Fig. 8, the computer model accurately captures the initial stiffness, ultimate loads and post-peak responses of the tested columns except Specimen CHS7C70. This discrepancy is mainly induced by the uncertainty of the actual concrete compressive strength of the tested columns. The comparison reveals that the computational model accurately ascertains the nonlinear load-axial strain behavior of concentrically compressed short CFAT columns.

5. Behavior of circular CFAT short columns

The numerical technique developed was utilized to examine the influences of aluminum and concrete strengths, and geometric properties on the ultimate axial loads, performance indices, and load-strain responses of circular CFAT columns. The Young's modulus (E_0) and nonlinearity index (n) of aluminum were taken as 69 GPa and 5.0, respectively. The ultimate strain of concrete (ε_{cu}) was specified as 0.04 in the numerical analyses. The axial strength and strain ductility of CFAT columns were evaluated using the performance indices in term of strain ductility [13]. The strain ductility index (PI_{ac}) of a CFAT column was determined by $PI_{sd} = \varepsilon_{u.90} / \varepsilon_{y.75}$, where $\varepsilon_{y.75}$ was equal to $\varepsilon_{0.75} / 0.75$ and $\varepsilon_{0.75}$ was the strain at $0.75P_u$ in the ascending load-strain branch [13]. For columns exhibiting strain-softening behavior, the strain $\varepsilon_{u.90}$ was taken as the strain at $0.90P_u$. For columns displaying strain hardening behavior, the strain $\varepsilon_{u.90}$ was specified as the ultimate concrete strain ε_{cu} [13]. The range of parameters is selected for reflecting the use of CFAT columns in high-rise buildings.

5.1. Comparison of confining pressures by steel and aluminum tubes

The lateral confining pressures exerted by the carbon steel tube of a circular CFST column were predicted using the concrete confinement model developed by Hu et al. [12] and Tang et al. [31]. The concrete confinement induced by the aluminum tube in a circular CFAT column was determined by the proposed Eq. (25) of this paper. The comparison of the confining pressures by the aluminum and carbon steel tubes is given in Table 2. As shown, the lateral pressure provided by the aluminum tube is lower than that exerted by the carbon steel tube. This is because the Young's modulus of aluminum is three times lower than that of carbon steel. It should be noted that Tang et al. [31] model might give negative confining pressures on the concrete in CFST columns with for small D/t ratios.

5.2. Load distributions in CFAT columns

The load distribution analysis was conducted to quantify the contribution of aluminum tube and concrete to the fundamental performance of circular CFAT short columns. Columns C1-C4 given in Table 3 were analyzed to study the effects of diameter-to-thickness D/t ratio on the axial load distributions in circular CFAT columns. Figure 9 depicts the axial load-strain curves of aluminum tubes and concrete of circular CFAT columns with various D/t ratios. It appears that the concrete carries a large amount of the axial load regardless of the D/t ratio. The aluminum and concrete contributions as a function of the D/t ratio are shown in Fig. 10. It can be noted that the increase of the D/t ratio generally decreases the contribution of aluminum tube to the ultimate axial load of circular CFAT columns. However, the concrete

contribution increases as the ratio of D/t increases. It can be concluded that the CFAT column with a large D/t ratio is economical.

Columns C5-8 given in Table 3 were numerically studied to examine the influence of aluminum proof strength on the aluminum tube and concrete load distribution in circular CFAT columns. Figure 11 illustrates the axial load-strain responses of aluminum tube and concrete in circular CFAT columns with various 0.2% proof strengths. The same trend is observed for the effect of aluminum proof strength on the concrete contribution in carrying the axial load. However, the aluminum contribution to the ultimate axial strength of circular CFAT columns slightly increases with increasing the aluminum proof strength as demonstrated in Fig. 12. With the 270 MPa proof strength, the concrete and aluminum contribution ratios are 0.72 and 0.28, respectively. It indicates that the CFAT columns should be made from the aluminum tubes with a high proof strength.

The developed model was utilized to simulate Columns C9-C12 provided in Table 3 for evaluating the effect of concrete strength on the load distribution of the concrete and aluminum in CFAT columns. The axial load-strain curves of aluminum tube and concrete for various concrete strengths are presented in Fig. 13. It demonstrates that the concrete contribution is higher than the aluminum tube in carrying the axial load. The concrete and aluminum contribution ratios as a function of concrete compressive strength are depicted in Fig. 14. It is interesting to note that the concrete contribution increases significantly with increasing the concrete strengths. With 100 MPa concrete, the concrete contribution ratio is 0.84 compared to 0.16 for aluminum contribution ratio.

5.3. Influence of diameter-to-thickness ratio

Inelastic analyses on Columns C1-C4 listed in Table 3 were undertaken by using the developed fiber model to assess the influence of D/t ratio on the performance of CFAT columns. The various D/t ratios for the same tube diameter were calculated by altering the thickness. The computed load-strain curves of these columns are provided in Fig. 15. It appears that the D/t ratio has a minor influence on the initial stiffness of short CFAT columns. Nevertheless, it has a considerable influence on the column ultimate strength. The ultimate strength decreases when increasing the D/t ratio or the tube thickness. As the D/t ratio is changed from 60 to 70, 80 and 100, the reductions in the column ultimate strength are found to be 10%, 12% and 16%, respectively. The strain ductility indices PI_{sd} have been plotted against the D/t ratios ranging from 60 to 100 in Fig. 16. The significant reduction in the ductility index is found when increasing the D/t ratio from 60 to 70. As the D/t ratio increases from 70 to 100, the ductility reduction is less. This is because the CFAT column with a large D/t ratio exhibits more significant strain-softening behavior.

5.4. Influence of aluminum proof stress

The sensitivities of the initial stiffness, ductility index and ultimate axial load of CFAT columns to the aluminum proof stress were examined. The proof stresses ranging from 220 MPa to 270 MPa were considered. The fiber-based model was employed to simulate Columns C5-C8 listed in Table 3. Figure 17 demonstrates the comparison of the load-strain responses of CFAT columns with 220 MPa and 270 MPa aluminum proof stress. As appeared from the figure, the ultimate load of the CFAT column with the proof stress of 270 MPa is 13% higher than that of the one with proof stress of 220 MPa. Figure 18 presents the strain ductility-aluminum proof stress responses. It is demonstrated that the strain ductility index PI_{sd} decreases with an

increase in the proof stress. The index PI_{sd} is reduced from 14.9 to 12.3 by increasing $\sigma_{0.2}$ from 220 MPa to 270 MPa.

5.5. Influence of concrete strength

The structural behavior of Columns C9-C12 listed in Table 3 was simulated using the numerical model to assess the significance of concrete compressive strength on their behavior. The nonlinear structural responses of short CFAT columns with different concrete strengths to axial compression are provided in Fig. 19. Increasing the concrete strength is shown to slightly improve the column initial stiffness, but remarkably increases the ultimate strengths of CFAT columns. For instance, the ultimate strengths are increased by 41%, 66% and 99%, respectively, by changing the concrete strength from 40 MPa to 65 MPa, 80 MPa and 100 MPa. It reveals that high-strength concrete can be used in CFAT columns to improve their strength performance. As illustrated in Fig. 20, the strain ductility index PI_{sd} is shown to decrease as the higher strength concrete is used, which is caused by the brittle behavior of high-strength concrete. The strain ductility indices were obtained as 19.3, 18.1, 16.9 and 15.7 for CFAT columns with concrete strengths of 40 MPa, 65 MPa, 80 MPa, and 100 MPa, respectively.

5.6. Comparison of CFST and CFAT columns

The computer simulation method proposed was used to ascertain the responses of short circular CFAT and CFST columns to axial loads. The same dimensions and material strengths of Column C13 listed in Table 3 were used in the computer simulations. The fiber-based computer program written by Liang [23] was employed to compute the load-strain response of the circular CFST column. The simulated load-strain curves for CFST and CFAT columns have

been plotted in Fig. 21. It is interesting to note that the CFAT column has slightly lower ultimate strength and initial stiffness than the CFST column. This is because aluminum has a lower elastic modulus and rounded stress-strain curve. However, both columns exhibit similar post-yield responses.

6. Design of circular CFAT short columns

Liang and Fragomeni [13] developed a formula for the design of concentrically compressed circular short CFST columns including concrete confinement effects. The design equation of Liang and Fragomeni [13] is modified herein by means of replacing the steel yield stress f_y with the aluminum proof stress $\sigma_{0.2}$ and the factor γ_a for aluminum tube as follows:

$$P_{ucal} = (\gamma_c f'_c + 4.1 f_{rp}) A_c + \gamma_a \sigma_{0.2} A_a \quad (26)$$

in which γ_c is determined using Eq. (19), f_{rp} is calculated using Eq. (25) and the factor γ_a is used to consider the effects of D/t ratio and strain-hardening and is proposed herein as

$$\gamma_a = 1.725 \left(\frac{D}{t} \right)^{-0.192} \quad (27)$$

The ultimate axial loads of short circular CFAT columns determined by the modified equation of Liang and Fragomeni [13] are compared against the available test data in Table 4. It is indicated that the ultimate axial loads computed using the modified equations Eqs. (26) and (27) are in good agreement with experimental data, leading to a mean calculated-to-test ratio

of 0.993, an SD of 0.061, and a COV of 0.061. This indicates that the modified design equations provide better strength predictions than codified design methods.

7. Conclusions

The fiber-based computer simulation model has been presented in this paper, which can predict the structural responses of short high strength CFAT columns with circular sections to concentric loads. The computational model incorporates not only the accurate stress-strain laws for aluminum but also the newly developed concrete confinement model for concrete confined by a circular aluminum tube. The basic theory underlying the computational model and the simulation procedure have been described for accurately capturing the axial load-strain performance of CFAT circular short columns. The concluding remarks are given as follows:

- (1) The numerical model using the method of fiber analysis accurately simulates the behavior of circular short CFAT columns loaded concentrically to failure.
- (2) The circular CFAT column has slightly lower initial stiffness than the equivalent circular CFST column because of the low elastic modulus of aluminum.
- (3) Increasing the D/t ratio markedly decreases the axial strength and strain ductility of CFAT columns.
- (4) The ultimate load of CFAT columns is demonstrated to considerably increase by using aluminum tubes with higher proof stress.
- (5) The use of high strength concrete remarkably increases the ultimate axial strength of CFAT columns but reduces the strain ductility and aluminum contribution ratio.
- (6) The modified design model of Liang and Fragomeni [13] yields accurate strength calculations.

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Figures and Tables

Table 1 Comparison of experimental and numerical ultimate axial loads.

Specimen	D (mm)	t (mm)	$\frac{D}{t}$	$\sigma_{0.2}$ (MPa)	σ_{au} (MPa)	E_0 (GPa)	f'_c (MPa)	$P_{u,exp}$ (kN)	$P_{u,num}$ (kN)	$\frac{P_{u,num}}{P_{u,exp}}$	Ref.
CHS1C40	38	3.89	9.8	242.4	278.5	65	44.8	158.9	145.6	0.916	[10]
CHS1C70	38	3.9	9.7	242.4	278.5	65	70.2	167.2	163.9	0.980	
CHS1C100	38	3.92	9.7	242.4	278.5	65	106	171.5	189.8	1.107	
CHS2C40	50	3.13	16	238.4	259.1	66.1	44.8	217	204.2	0.941	
CHS2C70	50	3.12	16	238.4	259.1	66.1	70.2	238.9	242.1	1.013	
CHS2C100	50	3.13	16	238.4	259.1	66.1	106	327.5	296.1	0.904	
CHS3C40	60	2.55	23.5	237.8	261.4	69.8	44.8	244.1	257.8	1.056	
CHS3C70	60	2.54	23.6	237.8	261.4	69.8	70.2	292.4	317.6	1.086	
CHS3C100	59.9	2.53	23.7	237.8	261.4	69.8	106	412.6	401.0	0.972	
CHS4C40	76.1	2.06	36.9	237	256	64.9	44.8	329.9	352.1	1.067	
CHS4C70	76	2.06	36.9	237	256	64.9	70.2	415.7	454.4	1.093	
CHS4C100	76	2.05	37.1	237	256	64.9	106	611.4	599.1	0.980	
CHS5C40	99.7	2.02	49.4	244.3	259.5	65.6	44.8	543.6	515.6	0.948	
CHS5C70	99.8	2.06	48.4	244.3	259.5	65.6	70.2	712	703.9	0.989	
CHS5C100	100	2.05	48.8	244.3	259.5	65.6	106	995.8	959.9	0.964	
CHS6C40	119.8	2.49	48.1	253.1	264.7	66.5	44.8	822.8	764.7	0.929	
CHS6C70	120	2.55	47.1	253.1	264.7	66.5	70.2	1010.3	1031.7	1.021	
CHS6C70-R	119.6	2.48	48.2	253.1	264.7	66.5	70.2	1004	1014.4	1.010	
CHS6C100	119.9	2.48	48.3	253.1	264.7	66.5	106	1388.7	1376.7	0.991	
CHS7C40	150.1	2.53	59.3	267.9	282.9	64.9	44.8	1111.1	1107.9	0.997	
CHS7C70	150.1	2.54	59.1	267.9	282.9	64.9	70.2	1496.4	1500.9	1.003	
CHS7C100	149.9	2.53	59.2	267.9	282.9	64.9	106	2057.8	2042.5	0.993	
CHS8C40	150.2	5.03	29.9	216.9	251.9	65.8	44.8	1481.9	1507.8	1.017	
CHS8C70	150.2	5.04	29.8	216.9	251.9	65.8	70.2	1740.6	1880.7	1.081	
CHS8C100	150.2	5.03	29.9	216.9	251.9	65.8	106	2666.1	2403.9	0.902	
CHS9C40	160.1	4.03	39.7	254.2	272.9	66.6	44.8	1494.1	1492.5	0.999	
CHS9C70	160.5	4.07	39.4	254.2	272.9	66.6	70.2	1974.4	1939.0	0.982	
CHS9C100	160.5	4.06	39.5	254.2	272.9	66.6	106	2797.3	2550.3	0.912	
CHS10C40	180	3.71	48.5	264.9	287.1	68.7	44.8	1690.2	1755.6	1.039	
CHS10C70	180.4	3.69	48.9	264.9	287.1	68.7	70.2	2274.2	2300.7	1.012	
CHS10C100	180.5	3.75	48.1	264.9	287.1	68.7	106	3139.2	3085.9	0.983	
Mean										0.996	
Standard deviation (SD)										0.056	
Coefficient of variation (COV)										0.056	

Table 2 Comparison of lateral confining pressures provided by the carbon steel tube and aluminum tube.

Specimen	$P_{u,exp}$ (kN)	Hu et al. model [12]			Tang et al. model [31]			Proposed Eq. (26)		
		f_{rp1} (MPa)	$P_{u,num1}$ (kN)	$\frac{P_{u,num1}}{P_{u,exp}}$	f_{rp2} (MPa)	$P_{u,num2}$ (kN)	$\frac{P_{u,num2}}{P_{u,exp}}$	f_{rp} (MPa)	$P_{u,num}$ (kN)	$\frac{P_{u,num}}{P_{u,exp}}$
CHS1C40	158.9	6.20	150.8	0.949	6.35	151.3	0.952	4.41	145.6	0.916
CHS1C70	167.2	6.20	169.2	1.012	-5.16	151.0	0.903	4.41	163.9	0.980
CHS1C100	171.5	6.20	195.1	1.137	-43.16	176.9	1.031	4.41	189.8	1.107
CHS2C40	217	6.10	212.4	0.979	6.97	217.7	1.003	4.77	204.2	0.941
CHS2C70	238.9	6.10	250.3	1.048	1.82	224.0	0.938	4.77	242.1	1.013
CHS2C100	327.5	6.10	304.3	0.929	-17.56	266.7	0.814	4.77	296.1	0.904
CHS3C40	244.1	5.72	268.9	1.102	6.71	278.5	1.141	4.58	257.8	1.056
CHS3C70	292.4	5.71	328.6	1.124	4.23	314.4	1.075	4.57	317.6	1.086
CHS3C100	412.6	5.69	411.9	0.998	-7.02	356.7	0.865	4.57	401.0	0.972
CHS4C40	329.9	3.06	344.2	1.043	5.60	386.6	1.172	3.53	352.1	1.067
CHS4C70	415.7	3.07	446.7	1.074	4.65	472.9	1.138	3.53	454.4	1.093
CHS4C100	611.4	3.03	591.1	0.967	-1.52	540.6	0.884	3.51	599.1	0.980
CHS5C40	543.6	1.09	492.1	0.905	4.59	600.3	1.104	1.87	515.6	0.948
CHS5C70	712	1.10	676.4	0.950	4.25	773.8	1.087	2.00	703.9	0.989
CHS5C100	995.8	1.10	933.5	0.937	0.12	903.5	0.907	1.95	959.9	0.964
CHS6C40	822.8	1.14	713.7	0.867	4.79	875.4	1.064	2.31	764.7	0.929
CHS6C70	1010.3	1.15	975.3	0.965	4.74	1134.2	1.123	2.44	1031.7	1.021
CHS6C70-R	1004	1.14	963.7	0.960	4.63	1119.1	1.115	2.30	1014.4	1.010
CHS6C100	1388.7	1.14	1326.1	0.955	1.16	1326.9	0.956	2.28	1376.7	0.991
CHS7C40	1111.1	1.10	1048.2	0.943	3.90	1255.8	1.130	1.93	1107.9	0.997
CHS7C70	1496.4	1.11	1437.9	0.961	4.07	1660.9	1.110	1.96	1500.9	1.003
CHS7C100	2057.8	1.11	1980.5	0.962	1.92	2040.8	0.992	1.94	2042.5	0.993
CHS8C40	1481.9	4.08	1409.1	0.951	5.70	1511.4	1.020	5.64	1507.8	1.017
CHS8C70	1740.6	4.09	1782.3	1.024	3.96	1774.2	1.019	5.65	1880.7	1.081
CHS8C100	2666.1	4.08	2305.2	0.865	-4.47	2047.3	0.768	5.64	2403.9	0.902
CHS9C40	1494.1	2.69	1453.8	0.973	5.55	1666.3	1.115	3.21	1492.5	0.999
CHS9C70	1974.4	2.75	1903.0	0.964	5.50	2108.5	1.068	3.24	1939.0	0.982
CHS9C100	2797.3	2.73	2513.4	0.898	1.69	2435.5	0.871	3.23	2550.3	0.912
CHS10C40	1690.2	1.19	1583.8	0.937	4.81	1946.2	1.151	2.93	1755.6	1.039
CHS10C70	2274.2	1.19	2129.6	0.936	5.03	2519.6	1.108	2.90	2300.7	1.012
CHS10C100	3139.2	1.20	2908.0	0.926	2.66	3054.5	0.973	2.97	3085.9	0.983
Mean				0.976			1.019			0.996
Standard deviation (SD)				0.067			0.110			0.056
Coefficient of variation (COV)				0.069			0.108			0.056

Table 3 Geometric and material properties of CFAT columns employed in the parametric study.

Parameter	Specimen	D (mm)	t (mm)	$\frac{D}{t}$	$\sigma_{0.2}$ (MPa)	σ_{au} (MPa)	f'_c (MPa)
D/t ratio	C1	400	6.7	40	260	290	65
	C2	400	5.7	60	260	290	65
	C3	400	5	80	260	290	65
	C4	400	4	100	260	290	65
Aluminum proof stress	C5	500	10	50	220	250	50
	C6	500	10	50	240	260	50
	C7	500	10	50	250	260	50
	C8	500	10	50	270	280	50
Concrete strength	C9	600	10	60	250	260	40
	C10	600	10	60	250	260	65
	C11	600	10	60	250	260	80
	C12	600	10	60	250	260	100
CFST and CFAT columns	C13	700	10	70	270	280	80

Table 4 Verification of the design model.

Specimen	$\frac{D}{t}$	γ_c	f'_c (MPa)	f_{rp} (MPa)	γ_a	$\sigma_{0.2}$ (MPa)	P_u (kN)	P_{ucl} (kN)	$\frac{P_{ucl}}{P_u}$
CHS1C40	9.8	1.000	44.8	4.410	1.114	242.4	158.9	157.6	0.992
CHS1C70	9.7	1.000	70.2	4.410	1.114	242.4	167.2	176.1	1.053
CHS1C100	9.7	1.000	106	4.408	1.115	242.4	171.5	202.1	1.178
CHS2C40	16.0	1.000	44.8	4.768	1.013	238.4	217	208.0	0.959
CHS2C70	16.0	1.000	70.2	4.767	1.013	238.4	238.9	245.9	1.029
CHS2C100	16.0	1.000	106	4.768	1.013	238.4	327.5	300.0	0.916
CHS3C40	23.5	1.000	44.8	4.576	0.941	237.8	244.1	253.4	1.038
CHS3C70	23.6	1.000	70.2	4.572	0.940	237.8	292.4	313.2	1.071
CHS3C100	23.7	1.000	106	4.569	0.940	237.8	412.6	396.5	0.961
CHS4C40	36.9	1.000	44.8	3.529	0.863	237	329.9	339.1	1.028
CHS4C70	36.9	1.000	70.2	3.534	0.863	237	415.7	441.5	1.062
CHS4C100	37.1	1.000	106	3.514	0.862	237	611.4	586.2	0.959
CHS5C40	49.4	0.999	44.8	1.868	0.816	244.3	543.6	500.4	0.921
CHS5C70	48.4	0.999	70.2	2.004	0.819	244.3	712	690.1	0.969
CHS5C100	48.8	0.999	106	1.955	0.818	244.3	995.8	948.9	0.953
CHS6C40	48.1	0.975	44.8	2.313	0.820	253.1	822.8	741.0	0.901
CHS6C70	47.1	0.975	70.2	2.441	0.823	253.1	1010.3	1009.6	0.999
CHS6C70-R	48.2	0.975	70.2	2.299	0.820	253.1	1004	993.3	0.989
CHS6C100	48.3	0.975	106	2.284	0.819	253.1	1388.7	1359.2	0.979
CHS7C40	59.3	0.945	44.8	1.932	0.788	267.9	1111.1	1077.7	0.970
CHS7C70	59.1	0.945	70.2	1.964	0.788	267.9	1496.4	1477.3	0.987
CHS7C100	59.2	0.945	106	1.942	0.788	267.9	2057.8	2029.0	0.986
CHS8C40	29.9	0.949	44.8	5.638	0.899	216.9	1481.9	1459.7	0.985
CHS8C70	29.8	0.949	70.2	5.646	0.899	216.9	1740.6	1832.7	1.053
CHS8C100	29.9	0.949	106	5.638	0.899	216.9	2666.1	2355.7	0.884
CHS9C40	39.7	0.939	44.8	3.213	0.851	254.2	1494.1	1430.1	0.957
CHS9C70	39.4	0.939	70.2	3.236	0.852	254.2	1974.4	1876.4	0.950
CHS9C100	39.5	0.939	106	3.229	0.851	254.2	2797.3	2487.7	0.889
CHS10C40	48.5	0.923	44.8	2.933	0.819	264.9	1690.2	1694.1	1.002
CHS10C70	48.9	0.923	70.2	2.896	0.817	264.9	2274.2	2245.6	0.987
CHS10C100	48.1	0.923	106	2.969	0.820	264.9	3139.2	3037.3	0.968
C1	40.0	0.850	65	3.368	0.850	260	8880.6	10538.4	1.187
C2	59.7	0.850	65	1.112	0.787	260	8007	8714.0	1.088
C3	80.0	0.850	65	0.000	0.744	260	7790.9	7799.9	1.001
C4	100.0	0.850	65	0.000	0.713	260	7496.7	7589.8	1.012
C5	50.0	0.850	50	1.957	0.814	220	12277.8	11899.0	0.969
C6	50.0	0.850	50	1.694	0.814	240	12339.2	11954.4	0.969
C7	50.0	0.850	50	1.943	0.814	250	12652.5	12264.5	0.969
C8	50.0	0.850	50	3.202	0.814	270	13910.7	13449.6	0.967
C9	60.0	0.850	40	0.312	0.786	250	13379.2	12963.1	0.969
C10	60.0	0.850	65	0.312	0.786	250	18866.4	18577.6	0.985
C11	60.0	0.850	80	0.312	0.786	250	22180.4	21946.2	0.989
C12	60.0	0.850	100	0.312	0.786	250	26613.2	26437.7	0.993
C13	70.0	0.850	80	0.478	0.763	270	29996.2	29872.5	0.996
Mean									0.993
Standard deviation (SD)									0.061
Coefficient of variation (COV)									0.061

Fig. 1. Cross-section of circular CFAT column.

Fig. 2. Comparison of stress-strain curves for aluminum and steel materials.

Fig. 3. Typical discretization of circular CFAT column section.

Fig. 4. Computer flowchart for computing the load-strain curve of circular CFAT short columns.

Fig. 5. Stress-strain curve for aluminum.

Fig. 6. Stress-strain curve for confined concrete.

Fig. 7. Comparison of lateral confining pressures predicted by the proposed concrete confinement model and obtained from experiments [10].

Fig. 8. Comparison of axial load-strain responses predicted by the developed computational model and obtained from experimental results [10].

Fig. 9. Axial load distributions in circular CFAT short columns with various D/t ratios.

Fig. 10. Effect of D/t ratio on contribution ratios.

Fig. 11. Axial load distributions in circular CFAT short columns with various aluminum proof strengths.

Fig. 12. Effect of aluminum proof stress on contribution ratios.

Fig. 13. Axial load distributions in circular CFAT short columns with various concrete strengths.

Fig. 14. Effect of concrete strength on contribution ratios.

Fig. 15. Influence of D/t ratio on axial load-strain curves.

Fig. 16. Influence of D/t ratio on strain ductility index PI_{sd} .

Fig. 17. Influence of aluminum proof stress $\sigma_{0.2}$ on axial load-strain responses.

Fig. 18. Effect of aluminum proof stress on strain ductility index.

Fig. 19. Influence of concrete compressive strength on axial load-strain responses.

Fig. 20. Influence of concrete compressive strength f'_c on strain ductility index PI_{sd} .

Fig. 21. Comparison of axial load-strain responses of circular CFST and CFAT columns.