Load-carrying capacity of circular concrete filled steel tubes under axial loading: Reliability analyses

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ABSTRACT

This paper presents the results of reliability analyses of load-carrying capacity of circular concrete filled steel tubes (CFST) using different codes. Four parameters that govern the load-carrying capacity of CFST were considered as variables. These variables include the yield strength of steel, the strength of concrete, the diameter of CFST, and the thickness of the steel tube. The Monte Carlo technique was used for the simulation. Simulations were conducted, and the obtained load-carrying capacities were analysed. The results indicated that the load-carrying capacity of circular CFST follows a normal distribution. Eurocode 4 provided the highest mean load-carrying capacity because the confinement effect was taken into consideration, whereas the mean load-carrying capacity obtained from the American Institute of Steel Construction (2016) and Architectural Institute of Japan (AIJ, 2008) codes were similar. All considered variables resulted in higher standard deviations and coefficients of variation, while the thickness of the steel tube resulted in the lowest standard deviation and coefficients of variation. Therefore, the reliability indices obtained from all considered variables are lowest while those obtained from the variable of thickness are highest.

1. Introduction

Concrete Filled Steel Tube (CFST) has been increasingly used in construction because of its advantages. The advantages of CFST can be listed as follows:

- Lightweight;
- Formwork is not needed;
- Steel tubes can support construction load during the concrete casting;
- Strength and ductility of concrete increase because of the confinement effect;
- Spalling of concrete is prevented by steel tube;
- Local buckling for steel tubes is prevented by concrete.

There are several studies devoted to various aspects of CFSTs, e.g., failure mode (Dundu, 2012; Xiao, Shan, Zheng, Chen, & Shen, 2009; Yang & Han, 2012), ductility and strength (Abed, AlHamaydeh, & Abdalla, 2013; Elremaily & Azizinamini, 2002; Han, He, & Liao, 2011; Han, Hou, Zhao, & Rasmussen, 2014; Nie, Wang, & Fan, 2012; Song, Han, & Yu, 2010; Yang & Han, 2012), load-deformation relationship (Chitawadagi & Narasimhan, 2009; Lee, Uy, Kim, Choi, &

Choi, 2011), absorbed energy (Elremaily & Azizinamini, 2002; Nie et al., 2012; Nie, Wang, & Fan, 2013). Different loads have been used to study the performance of CFST, e.g., static loading (Chitawadagi & Narasimhan, 2009; Dundu, 2012; Han et al., 2011; Lee et al., 2011; Song et al., 2010), cyclic loading (Abed et al., 2013; Elremaily & Azizinamini, 2002; Han et al., 2014; Nie et al., 2012; Nie et al., 2013; Xiao et al., 2009; Zhang, Wu, Wang, & Zhou, 2015), mechanical and thermal loading (Song et al., 2010; Yin, Zha, & Li, 2006).

The performance of circular CFST subjected to axial loading has attracted many researchers. Yang and Han (2006) investigated the performance of CFST, and Recycled Aggregate Concrete Filled Steel Tubes (RACFST) columns and found that the strength and ductility of RACFST columns were somewhat lower compared with those of CFST columns. Thayalan, Aly, and Patnaikuni (2009) investigated the effects of different parameters on the performance of CFST columns subjected to static and variable repeated loadings. The studied parameters included the length of columns, strength of concrete, and eccentricity of load. The results indicated that the strength of CFST columns subjected to variable repeated loading decreased by up to 16% compared with that under static loading. Skalomenos, Hayashi, Nishi, Inamasu, and Nakashima (2016) experimentally investigated the behavior of CFST columns using ultrahigh-strength steel. Seven square and circular CFST columns were tested. The result indicated that, compared with control columns made by conventional steel, the high-strength steel CFST columns exhibited larger strength, deformation capacity, and better local buckling. In addition, a simple analytical model was developed and validated by comparing it with the experimental results. Wang, Ma, Li, and Tang (2017) experimentally investigated the size effect on a load-carrying capacity of CFST with different diameter to thickness (*D/t*) ratios subjected to axial compressive load. The results showed that increase of the *D/t* ratio decreased the maximum nominal stress. When the *D/t* ratio increased, the hoop stress and the confinement effect decreased, whereas the vertical stress of the steel tube increased. Ouyang and Kwan (2018) developed a novel model to perform Finite Element (FE) analyses of square CFST columns under axial loading. The model takes into consideration of the lateral strain, behaviour of confined concrete, plastic behaviour of steel, and concrete-steel interaction. The results yielded by the model agree well with the experimental results. The results also indicated that the increase in corner radius yielded better confinement. Alrebeh and Ekmekyapar (2019) studied the behaviour of CFST columns with external and internal stiffening subjected to axial loading. Eighteen columns were tested, and the results showed that the combination of external and internal stiffened CFST columns significantly increased the ductility and load-carrying capacity compared to the control specimens. Cao, Le, and Nguyen (2019) experimentally investigated the behaviour of CFSTs under cyclic axial loading. Tests were conducted for 42 CFST specimens until failure. The results show that the cyclic loading slightly decreased the load-carrying capacity but significantly increased the strain at peak load. Cao et al. (2019) experimentally studied the performance of RACFST under axial loading. A total of 24 RACFST specimens were tested compared to those of 12 conventional CFST specimens. The results indicated that RACFST had slightly lower mechanical properties but lower degradation after peak stress.

The literature shows a tremendous number of studies on the behaviour and mechanical properties of CFST. However, the reliability of CFST seems to be less explored and needs to be further investigated. This study investigates the effects of different parameters on the load-carrying capacity of circular CFST. Monte Carlo simulation was used to simulate the load-carrying capacity based on the variation of random variables of parameters that govern the capacity of circular CFST under axial loading. Finally, the simulation results were analysed and conclusions were drawn.

2. Load-carrying capacity

There are several models to predict the load-carrying capacity of CFST under axial loading. Equation 1 shows the formula to estimate the axial load-carrying power of circular CFST adopted in Eurocode 4 (British Standards Institution, 2004). In this formula, D and t are the diameter and thickness of the steel tube, respectively; A_c and A_s are the cross-sectional areas of concrete and steel tube, respectively; f_y is the yield strength of steel tube; and $f_c^{'}$ is the compressive strength of concrete.

$$N = \eta_s A_s f_y + A_c f_c^{'} \left(1 + \eta_c \frac{t}{D} \frac{f_y}{f_c^{'}} \right) \tag{1}$$

When CFST is under axial loading, $\eta_s = \eta_{so}$ and $\eta_c = \eta_{co}$, which is defined in Equations 2 and 3, respectively:

$$\eta_{so} = 0.25\left(3 + 2\overline{\lambda}\right) \leq 1 \tag{2}$$

$$\eta_{co} = 4.9 - 18.5\overline{\lambda} + 17\overline{\lambda}^2 \geq 0 \tag{3}$$

Under axial loading, $\overline{\lambda}$=1. Thus, $\eta_s = \eta_{so} = 1$ and $\eta_c = \eta_{co} = 3.4$. Equation 1 can be rewritten as shown in Equation 4.

$$N = A_s f_y + A_c f_c^{'} \left(1 + 3.4 \frac{t}{D} \frac{f_y}{f_c^{'}} \right) \tag{4}$$

Equation 5 shows the axial load-carrying capacity of circular CFST adopted by American Institute of Steel Construction (2016), the parameters of this formula are similar to those of the formula adopted in Eurocode 4 (British Standards Institution, 2004).

$$N = A_s f_y + 0.95 A_c f_c^{'} \tag{5}$$

Japanese code AIJ-2008 (AIJ, 2008) used Equation 6 to compute the axial load-carrying capacity of circular CFST. In Equation 6, the compressive strength of concrete is determined from the tests of concrete cylinder samples with a diameter of 100mm and a height of 200mm. In order to use the compressive strength of standard cylinder samples, a factor of 0.97 can be used.

$$N = 1.27 A_s f_y + 0.85 A_c f_c^{'} \tag{6}$$

The cross-section areas of concrete and steel tube are calculated by Equations 7 and 8, respectively.

$$A_c = \frac{\pi}{4}\left(D - 2 \times t\right)^2 \tag{7}$$

$$A_s = \frac{\pi}{4}\left(D^2 - \left(D - 2 \times t\right)^2\right) \tag{8}$$

The above-mentioned formulas are selected to use for reliability analyses of the load-carrying capacity of circular CFST, which are presented in the following sections.

3. Reliability analyses

There are four parameters in the formulas to determine the axial load-carrying capacity of circular CFST. These parameters include:

1) The yield strength f_y of steel.
2) The compressive strength f'_c of concrete.
3) The diameter D of CFST.
4) The thickness t of the steel tube.

These four parameters were used as variables for reliability analyses. The variables were assumed to follow normal distributions. The distribution parameters, e.g., the mean and Coefficient Of Variation (COV), are shown in Table 1.

Table 1

Parameters of variables

No	Parameter	Mean	COV	Reference
1	Yield strength f_y of steel	235MPa	0.05	Eamon and Jensen (2012)
2	Compressive strength f'_c of concrete	30MPa	0.12	Eamon and Jensen (2012)
3	Diameter D of CFST	300mm	0.04	Eamon and Jensen (2012)
4	Thickness t of steel tube	5mm	0.04	Eamon and Jensen (2012)

The Monte Carlo simulation was adopted in this study. The procedure of the simulation can be described as follows:

1. Random variables f_{yi}, f'_{ci}, t_i, and D_i were generated using the distribution and parameters mentioned above.

2. Load-carrying capacity N_i was calculated using Equations 4, 5, and 6.

3. Repeat step 2 to obtain n simulations.

4. Calculate the mean value using Equation 9, in which x_i is the load-carrying capacity obtained from simulation i:

$$\mu_X = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{9}$$

5. Calculate standard deviation using Equation 10.

$$\sigma_X = \sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \overline{x}\right)^2}{n-1}} = \sqrt{\frac{\left(\sum_{i=1}^{n} x_i^2\right) - n\left(\overline{x}\right)^2}{n-1}} \tag{10}$$

6. Calculate the coefficients of variation using Equation 11.

$$V_X = \frac{\sigma_X}{\mu_X} \tag{11}$$

7. Calculate the reliability index using Equation 12.

$$\beta = \frac{\mu_X}{\sigma_X} \tag{12}$$

Among the above steps, step 1 should be described in detail as follows. To generate values for random variables, values $u_1, u_2, \ldots, u_n$ of uniform random distribution is generated. These values are larger than or equal to 0 and less than or equal to 1. Then, corresponding to a value u_i, a value of the random variable is obtained by Equation 13, which Φ^{-1} is the inverse function of standard normal distribution. The generation of random values is illustrated in Figure 1.

$$z_i = \Phi^{-1}(u_i) \tag{13}$$

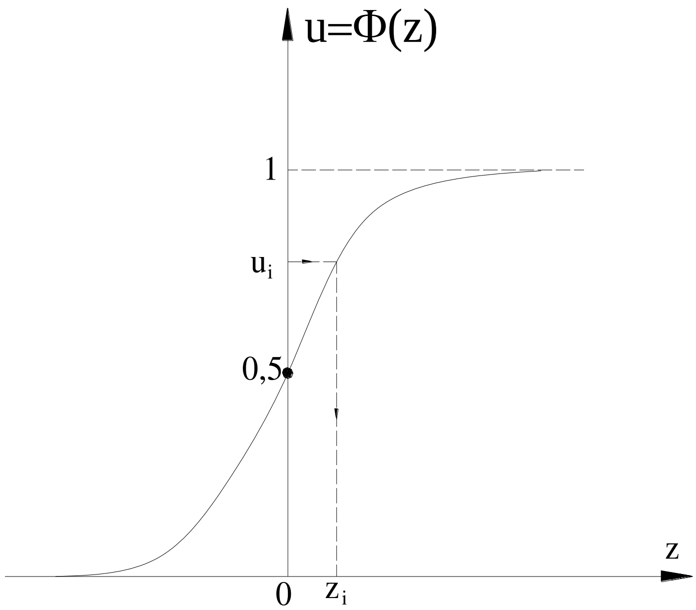
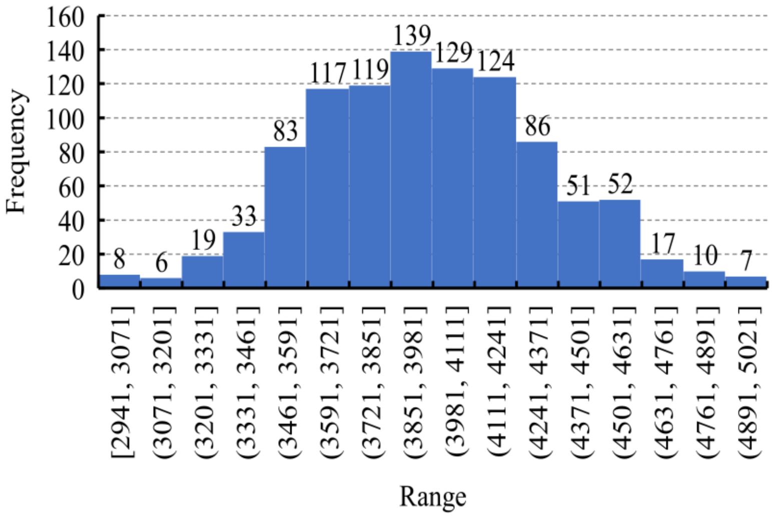


Figure 1. Illustration of generation of random values

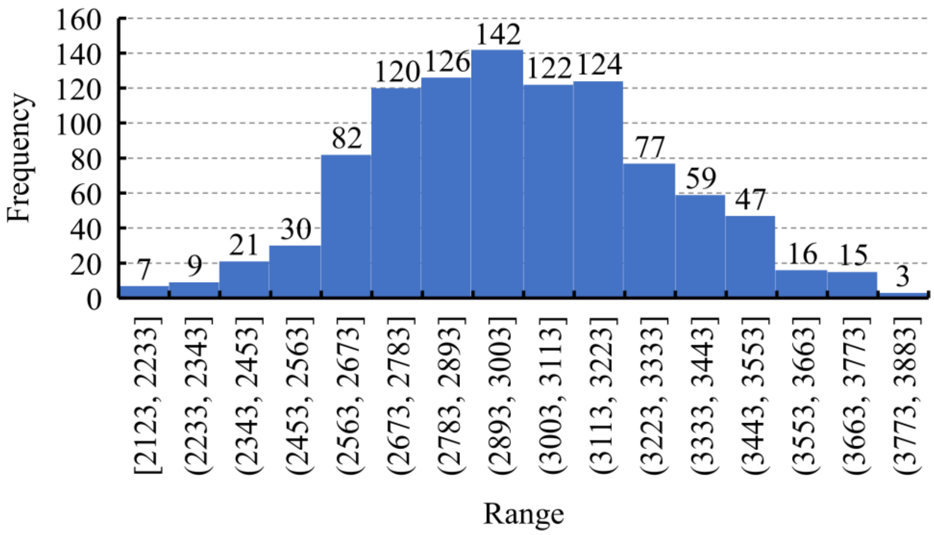
4. Results and discussion

In this study, the number of simulations n was selected as 1,000, which is large enough for analyses. The steel was the commonly used steel with f_y = 235MPa. Concrete with the compressive strength f'_c of 30MPa was used in the simulation. The diameter of the steel tube was 300mm, and the thickness of the steel was 5mm (*D/t* = 60, which is commonly used).

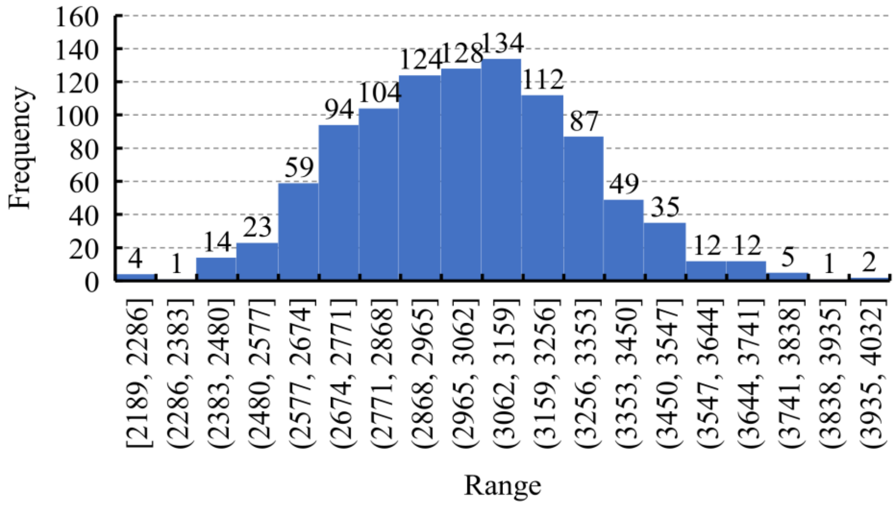
Figure 2 shows example histograms of load-carrying capacity when all variables are considered. This Figure shows that the data has the 'bell' shape, which is the form of normal distribution. This observation can be proven by plotting the data on probability paper. Figure 4 shows the variation of the data on the probability paper. The data can be approximated by straight lines. This shows that the data follows a normal distribution.



a) Eurocode 4

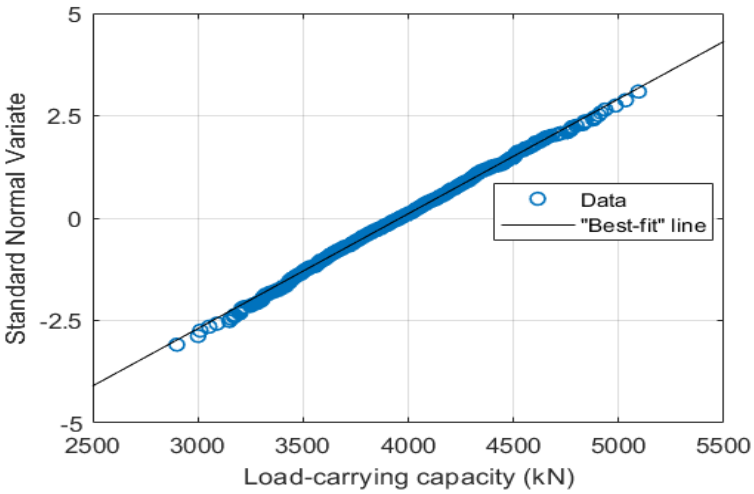


b) AISC 360-16

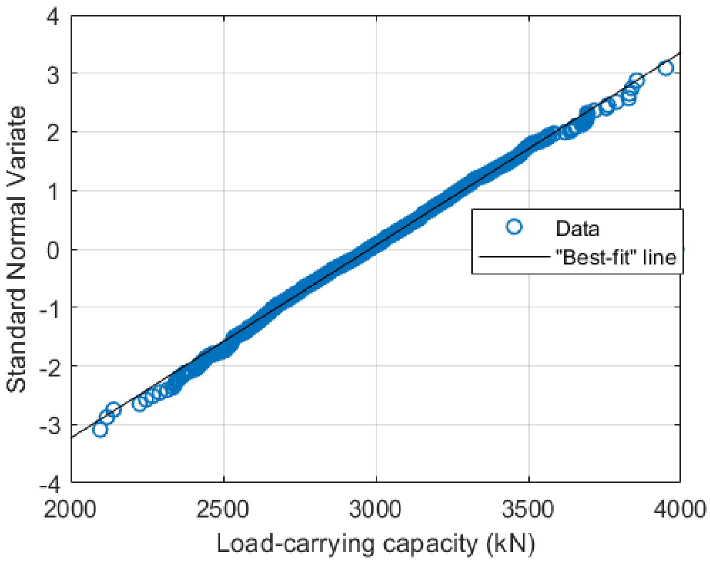


c) Japanese code AIJ 2008 (AIJ, 2008)

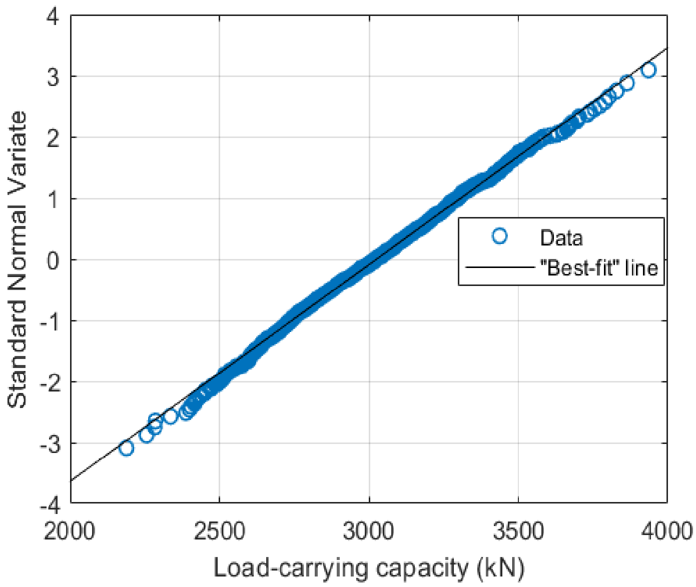
Figure 2. Examples of frequency of load-carrying capacity



a) Eurocode 4



b) AISC 360-16



c) Japanese code AIJ 2008 (AIJ, 2008)

Figure 3. Data plotted on probability paper

Based on the obtained data, the mean, standard deviation, COV, and reliability index were computed. Figure 4 shows the mean values of axial load-carrying capacity when all variables and individual variables were considered. Overall, the mean value seems to be similar in different cases of considered variables. However, the mean values obtained from the equation adopted by Eurocode 4 are always larger than those obtained from AISC 360-16 (American Institute of Steel Construction, 2016) and AIJ 2008 (AIJ, 2008). This can be explained as follows. Eurocode 4 takes into account the effects of confinement, while the other two codes do not account for this effect.

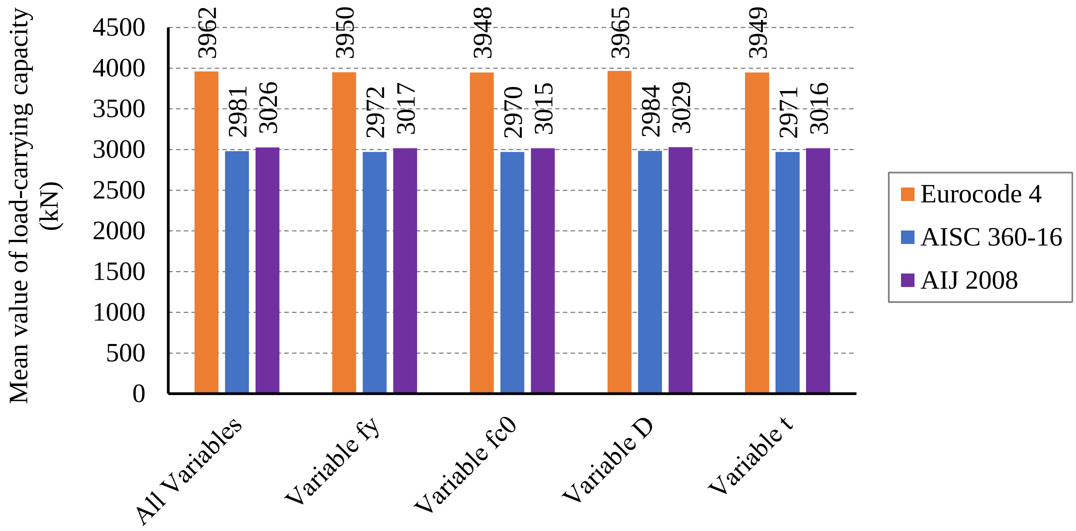


Figure 4. Mean values of load-carrying capacity

Figure 5 shows the variation of standard deviations of load-carrying capacity when different variables were considered. The standard deviations of load-carrying capacity resulting from all variables are 352kN, 300kN, and 279kN based on Eurocode 4, AISC 360-16 (American Institute of Steel Construction, 2016) and AIJ 2008 (AIJ, 2008) codes, respectively. These standard deviations are the largest compared with those resulted from individual variables. The concrete strength and the diameter of CFST resulted in similar standard deviations. The thickness of the steel tube resulted in lowest standard deviations.

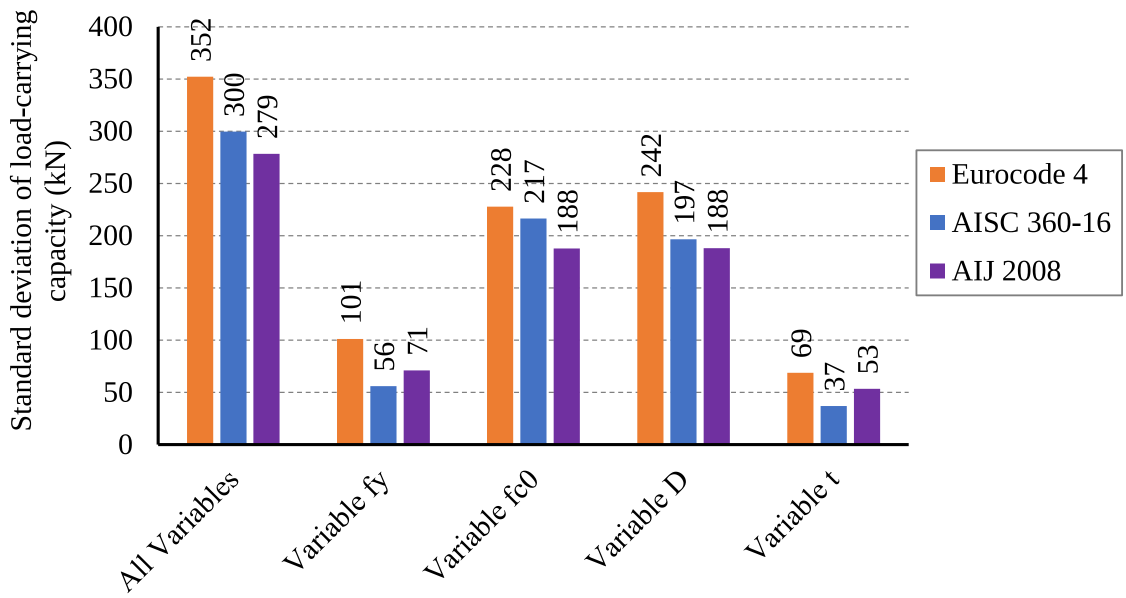


Figure 5. Standard deviations of load-carrying capacity

COVs were computed and plotted in Figure 6. All variables resulted in the COVs of 0.089, 0.100, and 0.092 based on Eurocode 4, AISC 360-16 (American Institute of Steel Construction, 2016), and AIJ 2008 codes (AIJ, 2008), respectively. The variables of concrete strength and diameter of CFST produced similar variation coefficients of load-carrying capacity, which vary between 0.058 and 0.073. The lowest COVs result from the variable of steel thickness, which vary from 0.012 to 0.018.

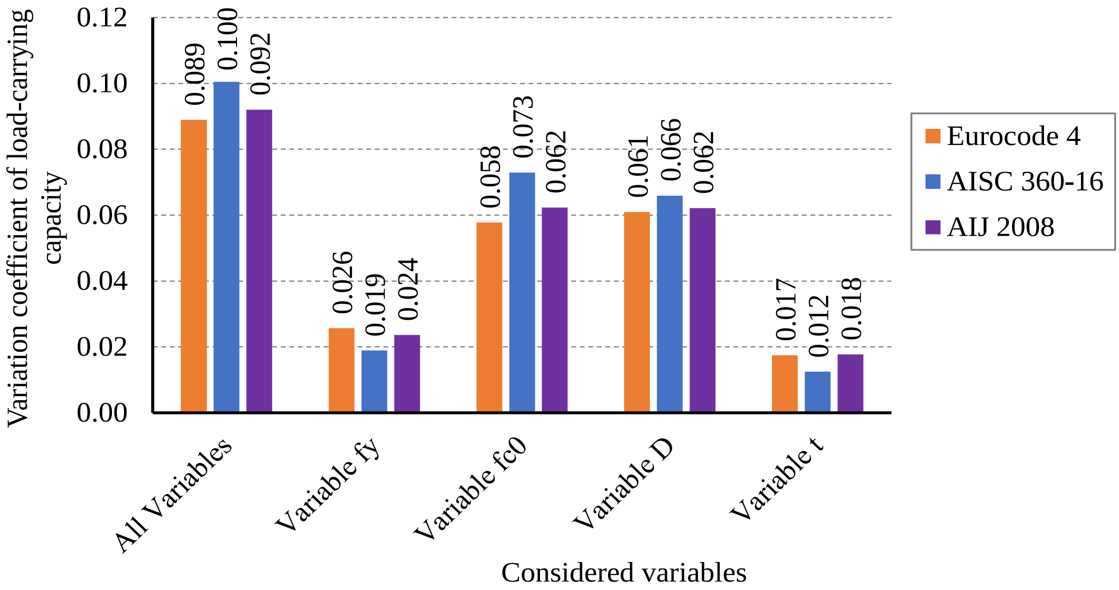


Figure 6. COVs of load-carrying capacity

Figure 7 shows the reliability indices obtained from different cases of considered variables. The thickness of the steel tube produced highest reliability indices, followed by the yield strength of the steel tube. The lowest reliability indices resulted from the variations of all considered variables.

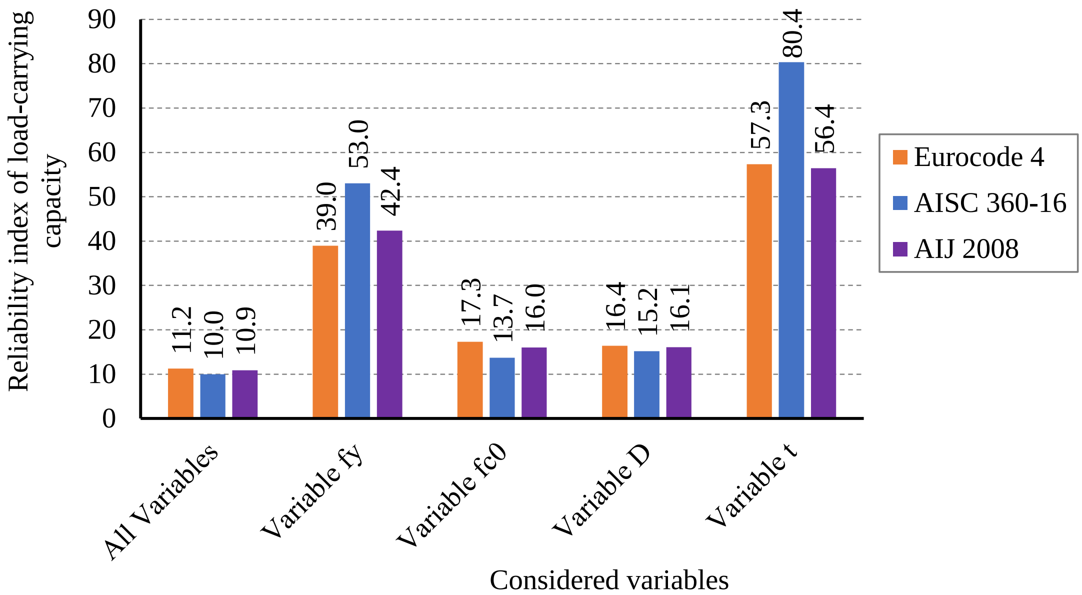


Figure 7. Reliability indices of load-carrying capacity

5. Conclusions

This paper presents the reliability analyses of the load-carrying capacity of circular CFST using different codes. The considered variables include the yield strength f_y of steel, the compressive strength f'_c of concrete, the diameter D of CFST, and the thickness t of steel tube. All simulations were conducted for four variables, and the corresponding load-carrying capacities were calculated using different formulas. The mean, standard deviation, COV, and reliability index were computed and compared. The results lead to the following conclusions:

- Under the combinations of considered variables, the load-carrying capacity of circular CFST follows a normal distribution.

- The mean load-carrying capacity obtained from Eurocode 4 is the highest while the mean load-carrying capacities obtained from ASIJ 360-16 (American Institute of Steel Construction, 2016) and AIJ 2008 (AIJ, 2008) codes are similar.

- The standard deviations resulting from all considered variables are much higher than those resulting from each variable. The thickness of the steel tube resulted in the lowest standard deviation.

- COVs resulted from all considered variables are the highest whereas the thickness of steel tubes resulted in the lowest coefficients of variation.

- The reliability indices obtained from all considered variables are the lowest while those obtained from the variable of thickness are the highest. The diameter of the steel tube and the compressive strength of the concrete are variables that produced similar reliability indices.

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