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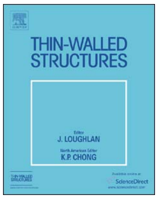

Full length article

# FE modelling of the flexural behaviour of square and rectangular steel tubes filled with normal and high strength concrete

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## ABSTRACT

In this research, numerical investigations were carried out to study the behaviour of concrete filled steel tubes having square or rectangular cross-sections. Separate models were used for both normal strength concrete and high strength concrete. More than 50 experimental results were used to verify the FE model and it was found that the FE model accurately predicts the load-deflection curve and ultimate moment capacity of the Concrete filled steel tube (CFST) beams. Thereafter, a parametric study was carried out to evaluate the effect of depth-to-thickness ratio (20 − 200), compressive strength of infilled concrete (2–100 MPa), shear span-to-depth ratio (1–8), depth-to-width ratio (0.6–2), and yield strength of steel tube (380–490 MPa) on the flexural behaviour of square and rectangular CFST members. It was found that the depth-to-thickness ratio, yield strength of steel and height-to-width ratio has significant effect on the ultimate capacity of CFST beams. The effect of shear span-to-depth ratio and strength of infilled concrete was found to be marginal. Finally, the results of parametric study and experimental data available in literature were used to check the accuracy of the existing design methods presented in EC4 (2004), CIDECT, AISC (2010) and GB50936 (2014). From comparison, it was found that GB50936 (2014) was more accurate but unsafe for low strength infilled concrete. For all cases, EC 4 (2004) was found to be safe and hence is recommended.

## 1. Introduction

Numerous problems arise while dealing with modelling of composite systems that combine two different materials i.e. ductile steel and brittle concrete. The modelling of such composite sections should capture the relative stiffness of each material properly. Concrete filled steel tube (CFST) is a composite material, which is composed of steel tube filled with concrete. Their use as columns and beams, in the construction of buildings, has increased exponentially in recent decades [1–3]. They have been used in several modern building projects [4,5]. Compared to conventional hollow steel/concrete members, this type of composite member has several advantages; such as high speed of construction work due to the omission of reinforcing bars and framework, low structure cost, conservation of environment, high ductility and strength capacity [6] and provides excellent resistant against seismic forces [7,8]. Furthermore, different types of concrete including recycled aggregates can be used as an infill in CFST, thus, providing safe disposal of solid waste [9–12].

Some of the prominent investigations carried out on CFST members are discussed here. Jiang et al. [13] tested 2 square and 2 rectangular specimens to study the bending behaviour of thin-walled CFST. An analytical model was developed for thin-walled CFST and verified using the results of the experiments. The increase in corner strength due to cold forming, welding residual stresses and confined concrete material properties were considered in the analytical model. It was concluded that the analytical model accurately predicts the load-strain curves of tested specimens. Hunaiti [14] performed 8 tests on lightweight CFST having square cross-section. 3 Unfilled similar samples were also tested for the purpose of comparison. It was observed that beams filled with lightweight aggregate showed good ductility as compared to hollow beams. The author concluded that lightweight aggregate can be utilized in composite construction to increase the flexural capacity of hollow steel sections. Yang and Ma [11] performed 14 experiments on square CFST beams. The infill concrete used was made with recycled aggregate having infilled concrete strength of more than 50 MPa. It was observed that recycled aggregate CFST members have similar failure pattern as

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that of normal CFST. Furthermore, the authors presented an analytical model to calculate the flexural capacity of recycled aggregate CFST. It was concluded that current design codes gave conservative values for the ultimate flexural capacity of CFST beams.

An experimental investigation on 12 square and rectangular steel beams for evaluating the effects of different D/t ratio and different shear span-to-depth ratio was carried out by Lu and Kennedy [15]. Depending on the relative proportions of concrete and steel, the authors reported that the flexural strength of the CFST increased by 10–30% over that of hollow steel sections. The flexural stiffness also increased due to concrete infill while the shear span-to-depth ratio had no significant effect on the ultimate strength of CFST. Finally, the formulae for the strength of square and rectangular CFST under flexure load were suggested. Gho and Liu [16] studied the flexural behaviour of rectangular CFST by using high strength steel and concrete. It was concluded that AISC, ACI, and EC4 substantially underestimated the flexural strengths of high-strength CFST. After conducting a series of experiments on square and rectangular CFST beams, Han [17] proposed a model to predict the structural behaviour of CFST. It was concluded that the moment capacities of CFST beam predicted by BS5400 (1979), LRFD-ASIC (1999), EC4 (1994) and AIJ (1997) were lower than the experimental values. However, the model is only valid for $D$ = 100–2000 mm; $f_{scy}$ = 200–500 MPa and $f_{ck}$ = 20–80 MPa and cannot be used for high strength and ultra-high strength concrete. Recently, Zhou et al. [18] studied the behaviour of square CFST under tensile loading. It was observed that the stiffness of hollow steel tube increased by 31.8% when concrete infill was added in the hollow steel tube.

From the above literature, it can be seen that numerical studies focusing on the flexural behaviour of square and rectangular CFST members is scarce. The only study found on this topic was done recently by Wang et al. [19]. In this research, the authors developed FE model for the flexural analysis of rectangular CFST and validated with the previous experimental results available in literature. The authors studied the failure pattern of rectangular CFST members and concluded that the load transfer mechanism of rectangular CFST is similar to circular CFST members. We would also like to mention here that the use of high strength concrete has increased in CFST beams and columns. However, its behaviour in CFST is different from normal concrete [20,21] and needs further investigation. Hence, in this research, the flexural behaviour of square and rectangular CFST beams have been numerically investigated by using commercial FEA package ANSYS [22]. Parametric study was carried out to investigate the influence of compressive strength of concrete, D/t ratio and yield strength of steel on the performance of CFST beams under flexure load. The flexural behaviour, interaction of concrete and steel and load-deflection curves of different grades of steel and concrete for square and rectangular CFST's under pure bending were analysed. This study is limited to the steel tubes having yield strength up to 400 MPa and concrete having compressive strength up to 150 MPa.

## 2. Model description

The structural behaviour of a square and rectangular CFST beams filled with normal strength concrete and high strength concrete was investigated using nonlinear FE models in ANSYS software. In nonlinear analysis, the convergence is more easily achieved by using displacement controlled load. Hence, for all cases, displacement controlled load was applied. The displacement was slowly increased until the ultimate capacity of the beam was reached.

### 2.1. Material constitutive models

#### 2.1.1. Steel

A model for structural steel as suggested by Han et al. [23] was used for uni-axial stress-strain relation of steel. In this model, the effect of strain hardening of steel was considered. The deformation of steel included elastic, elastic-plastic, plastic, hardening and fracture as shown in Fig. 1. Where, $f_p$, $f_y$, and $f_u$ represents the proportional limit, yield, and ultimate strength of steel, at their respective strains while $\varepsilon_e = 0.8\,\varepsilon_y$, $f_y/E_s$, $\varepsilon_y = 1.5\,\varepsilon_e$, $\varepsilon_{uy} = 10\,\varepsilon_y$, $\varepsilon_u = 100\,\varepsilon_y$.

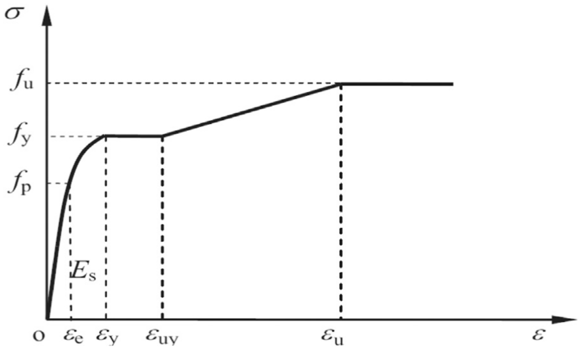

**Fig. 1.** Schematic sketch of uniaxial stress–strain relation for steel.

The Von-Mises yield function with associated plastic flow was used in multi axial stress states. The structural steel was assumed to have isotropic hardening behaviour, so that yield stresses increase or decrease in all stress directions when plastic straining occurs. Moreover, when Mises stress reaches the yield stress of the steel, the stress can still increase when subjected to further plastic straining. The modulus of elasticity and the Poisson's ratio for the steel were taken as 2 × $10^5$ MPa and 0.3, respectively.

#### 2.1.2. Concrete

For this research, concrete having compressive strength less than 50 MPa was termed as Normal strength concrete while concrete having compressive strength more than 50 MPa was termed as High-strength concrete. As the structural behaviour, effect of confinement and mode of failure of normal and high strength concrete are completely different from each other, therefore both were modelled separately [24–28]. The effect of confinement on normal and high strength concrete is shown in Fig. 2.

Although the confinement effect of different CFST cross-sections is different [29,30], yet a same average model for different cross-sections can be used [31–33]. For normal strength concrete, the equations given by Elchalakani [34] for circular CFST members were used. The model is known as concrete damaged plasticity model and uses the combination of different equations. The combination includes equations for an unconfined compressive behaviour of concrete as given by [35] in Eq. (1) and the effect of confinement of concrete presented by [36] in Eqs. (2) and (3).

$$\frac{f}{f_c} = \frac{r\left(\frac{\varepsilon}{\varepsilon_c}\right)}{1 + (r-1)\left(\frac{\varepsilon}{\varepsilon_c}\right)^{\beta}} \tag{1}$$

$$f_{cc} = f_c + 4.1\sigma_{lat} \tag{2}$$

$$\varepsilon_{cc} = 5\varepsilon_c\left[\frac{f_{cc}}{f_c} - 0.8\right] \tag{3}$$

The modulus of elasticity was calculated by using the following equation.

$$E_c = 0.043\rho_c^{1.5} f_c^{0.5} \tag{4}$$

In the above equations, f and ε is the strength and deformation of concrete, $f_{cc}$ and $\varepsilon_{cc}$ is the maximum compressive strength and strain of confined concrete, $r$ is material parameter, $\beta$ is $r/(r-1)$, $\rho_c$ and $f_c$ is the average density and compressive cylinder strength of concrete at 28 days.

For high strength concrete, the model used by HAN [37] for CFST square columns was used. It takes into account the effect of