Analysis of fire-damaged concrete-filled steel tube columns confined with FRP sheets

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Abstract. This paper presents an analysis of fire-damaged circular concrete-filled steel tube (CFST) stub columns confined with fiber-reinforced polymer (FRP) sheets under compression. Three main components in the analysis include (1) 2D heat transfer analysis to predict the temperature distributions in the CFST cross section under ISO-834 standard fire, (2) Post-fire mechanical properties of steel and concrete, and (3) Analytical model that incorporates the confinement effect to predict the load capacity of FRP-confined fire-damaged CFST columns. After validated with existing experimental results, the proposed analysis is employed to investigate the effects of heating period and number of FRP layers on the effectiveness of the FRP confinement method.

1. Introduction
Concrete-filled steel tube (CFST) columns offer several advantages due to composite action including reduced self-weight, fast construction, and high fire resistance [1]. With increasing adoption of CFST in engineering practice, the fire resistance and post-fire reparability of CFST columns are important for fire safety purpose [2]. Among several strengthening methods for CFST columns, the use of external wraps such as fiber-reinforced polymer (FRP) sheets is promising due to high strength-to-weight ratio, high corrosion resistance, and ease of installation [2]. So far, however, there have been few limited analytical studies on the fire-damaged CFST columns confined with FRP sheets [2, 3]. In this paper, the analysis of axial compression behavior of fire-damaged CFST columns confined with FRP sheets is presented. First, the 2D finite element heat transfer analysis is carried out to obtain the temperature profile (time-temperature relationship) of each discretized CFST cross-section layer in which temperature is assumed to be uniform. Next, the post-fire mechanical properties of steel and concrete proposed by Han and Huo [4] and Chang et al. [5] are adopted. Finally, by adopting the model of confined CFST columns [1] with post-fire material properties, the axial load capacities of FRP-confined fire-damaged CFST columns are calculated by the layer discretization method. The experimental results by Tao, Han [2] are used to verified the analysis. Based on the proposed analysis, a parametric study is performed to investigate the effects of number of FRP layers and heating period on the strength of FRP-confined fire-damaged CFST columns.
2. Analysis of FRP-confined fire-damaged CFST columns

2.1. Heat transfer analysis

2.1.1. Finite element model. A commercial finite element analysis package ANSYS is used to perform the heat transfer analysis to predict the temperature distributions within the CFST cross section during fire exposure (heating and cooling phases). The applied thermal boundary conditions and thermal parameters of concrete and steel are defined according to the recommendations from Eurocode 4 [6]. For the heating phase, the loading temperature refers to ISO 834 standard time-temperature curve:

\[ T = T_0 + 345 \log_{10}(8t + 1) \]  

where \( T_0 \) is the ambient temperature and \( T \) is the elevated temperature at time \( t \) (min).

2.1.2. Experimental results for model verification. To examine the validity of the 2D heat transfer analysis, an experimental program is conducted. Circular CFST tubular columns were heated for 120 min under ISO 834 standard fire inside the fire testing furnace, as shown in Figure 1a. Figure 1b shows a good agreement between predicted temperatures and experimental data. The maximum differences are 2.5% and 4.5% for peak steel tube and concrete temperatures, respectively.

![Figure 1](image_url)

(a) Experimental program: (a) Fire testing furnace and CFST specimens; (b) Comparison between experimental results and heat transfer analysis predictions.

2.2. Post-fire material properties

The post-fire mechanical properties of steel and concrete proposed by Han and Huo [4] and Chang et al. [5] are adopted for prediction of compression behavior of CFST columns. The post-fire properties of steel and concrete are assumed to depend on the peak temperature obtained from the heat transfer analysis. The accuracy of the material model has been validated in Rush et al. [7].

2.3. Confinement effect by FRP

By adopting the post-fire material properties for the external confinement effect model, the compression behavior of confined fire-damaged CFST columns can be determined. In this paper, steel and concrete refer to the post-fire condition unless specified. Lai and Ho [1] proposed the relationship between axial strain (\( \varepsilon_z \)) and hoop strain (\( \varepsilon_\theta \)) of the CFST column as follows:

\[ \varepsilon_z = LS \left( \frac{f'c}{30} \right)^m \left( \frac{\varepsilon_c}{\varepsilon_{co}} \right) \left[ 1 + 0.75 \left( \frac{-\varepsilon_\theta}{\varepsilon_{co}} \right)^{0.7} - \varepsilon_{co} \exp \left[ 7 \left( \frac{\varepsilon_\theta}{\varepsilon_{co}} \right) \right] + 0.07 \left( \frac{\varepsilon_\theta}{\varepsilon_{co}} \right)^{0.7} \right] + 0.07 \left( \frac{-\varepsilon_\theta}{\varepsilon_{co}} \right) \left( 1 + 26.8 \left( \frac{f_r}{f'c} \right) \right) \]  

where \( f'c \) is the cubic compressive strength of concrete, \( f_r \) is the radius of the CFST column, and \( L \) is the length of the column.
where \( \text{LS} \) is the parameter reflecting the effect of external confinement. For the FRP-confined column, \( \text{LS}=0.665 \); \( m \) is the parameter considering effect of concrete strength; \( \epsilon_{\text{co}} \) is the strain corresponding to unconfined concrete strength; \( f'_c \) is the compressive strength of unconfined concrete; \( f_r \) is the confining pressure from both steel tube \( (f_{rS}) \) and FRP confinement:

\[
f_r = f_{rS} + f_{rE}
\]

\[
f_{rS} = \frac{-2t}{D_0 - 2t} \sigma_{s\theta}
\]

\[
f_{rE} = \frac{-2t_{\text{FRP}}}{D_0 - 2t} \sigma_E
\]

where \( \sigma_{s\theta} \) is the hoop stress provided by the steel tube, which can be evaluated by Hooke’s Law, the yield surface is determined by Von Mises yield criterion, and Prantl-Reuss’s theory [1]; \( t \) and \( t_{\text{FRP}} \) are thicknesses of steel tube and FRP wrap, respectively; \( \sigma_E \) is the stress provided by external confinement (FRP):

\[
\sigma_E = \begin{cases} \epsilon_{\text{ssE}} E_{\text{ssE}} & E_{\text{ssE}} \leq \sigma_{\text{ssE}} \\ \epsilon_{\text{ssE}} \sigma_{\text{ssE}} & E_{\text{ssE}} > \sigma_{\text{ssE}} \end{cases}
\]

where \( \epsilon_{\text{ssE}}, E_{\text{ssE}}, \text{ and } \sigma_{\text{ssE}} \) are the average hoop strain, elastic modulus, and yield stress of FRP, respectively. Assume that \( \epsilon_{\text{ssE}} = \epsilon_{\theta} \).

For the confined core concrete, the stress-strain equation is:

\[
f_{\text{cc}} = \frac{A \left( \frac{\epsilon_z}{f'_c} \right) + B \left( \frac{\epsilon_z}{f'_c} \right)^2}{1 + (A - 2) \left( \frac{\epsilon_z}{f'_c} \right) + (B - 1) \left( \frac{\epsilon_z}{f'_c} \right)^2}
\]

\[
\epsilon_{cc} = \epsilon_{\text{co}} \left[ 1 + \left( \frac{17 - 0.06 f'_c}{f'_c} \right) \right]
\]

\[
\frac{f_{\text{ccp}}}{f'} = 1 + 4.1 \left( \frac{f_r}{f'_c} \right)
\]

where \( A \) and \( B \) are parameters that govern the shape of stress-strain curve [8]; \( f_{\text{cc}} \) is the confined concrete stress; \( f_{\text{ccp}} \) and \( \epsilon_{cc} \) are the peak confined concrete stress and corresponding axial strain.

**2.4. Compressive strength of FRP-confined fire-damaged CFST columns**

The composite cross section is divided into \( m \) layers. Each layer has its own peak exposed temperature and mechanical behavior. The steel tube is considered as one layer. The axial load capacity \( (F_t) \) is calculated as follows:

\[
F_t = F_c + F_s
\]

\[
F_t = \sum_{i=1}^{m} F_{ci} + F_s
\]

\[
F_t = \sum_{i=1}^{m} f_{cci} A_{cl} + \sigma_{sz} A_s
\]
where $A_s$ and $A_{ci}$ are areas of steel tube and confined concrete of layer $i$, respectively; $\sigma_{sz}$ is the axial stress of steel tube which can be evaluated by Hooke’s Law, and the aid of Prandtl-Reuss’s theory [1]; and $f_{cci}$ is the stress of confined concrete of layer $i$.

2.5. Generation of the axial load-strain curves

Fig 2 shows an iterative process to generate the axial load-strain curves of the FRP-confined fire-damaged CFST column.

Fig 2. Iterative process: (a) Confinement effect by FRP (iterative process 1); (b) Generation of axial load-strain curve of FRP-confined fire-damaged CFST column (adapted from [1])

3. Verification

Table 1 shows a comparison between the experimental results by Tao et al. [2] and analysis results. Ratios of predicted-to-experimental load capacity range from 0.967 to 0.998. The close agreement implies that the proposed analysis can be used for predicting the compressive strength of FRP-confined fire-damaged CFST columns.

Table 1. Experimental results by Tao et al. [3] vs. analysis predictions

| Specimen | D × t₀ (mm × mm) | $f'_{y}$ (N/mm²) | $f_{cu}$ (N/mm²) | Fire damage | Number of layers | Predicted load capacity (kN) | Experimental results (kN) | $N_{pre}/N_{Exp}$ |
|----------|------------------|------------------|------------------|-------------|-----------------|-----------------------------|--------------------------|---------------------|
| CSC      | 150 x 3.0        | 356              | 75               | No          | 0               | 1911                        | 1915                     | 0.998               |
| CSCF-0   | 150 x 3.0        | 356              | 75               | ISO-3 h     | 0               | 910                         | 915                      | 0.994               |
| CSCF-1   | 150 x 3.0        | 356              | 75               | ISO-3 h     | 1               | 1003                        | 1020                     | 0.983               |
| CSCF-2   | 150 x 3.0        | 356              | 75               | ISO-3 h     | 2               | 1508                        | 1560                     | 0.967               |

Table 2. Material properties of CFRP and epoxy

| Material | Elastic Modulus (kN/mm²) | Tensile Strength (N/mm²) | Ultimate Strain (%) | Thickness (mm) |
|----------|--------------------------|--------------------------|---------------------|----------------|
| CFRP     | 247                      | 3950                     | 1.60                | 0.170          |
| Epoxy    | 2.7                      | 42.8                     | 1.85                | -              |

4. Effects of parameters on compressive strength of FRP-confined fire-damaged CFST columns

Based on the proposed analysis, a parametric study is performed to investigate the effects of number of FRP layers and heating time on the compressive strength of CFST columns. In the study, specimen properties are taken from experiments by Tao et al. (Table 1 and 2). Fig 3 shows that the compressive strength of unconfined CFST columns decreases by 21%, 35% and 52% for 1-h, 2-h and 3-h ISO 834 standard fire exposures, respectively. Also, the two-layer FRP is more effective than one-layer FRP. For the two-layer FRP, the strength increases by 33%, 46%, 52%, and 66% for 0-h (no fire exposure),
1-h, 2-h, and 3-h ISO 834 standard fire exposures, respectively. For the one-layer FRP, the strength increases by 12%, 12%, 11%, and 10% for 0-hour (no fire exposure), 1-h, 2-h, and 3-h ISO-834 standard fire exposures, respectively. The confinement effectiveness of the two-layer FRP is higher for fire damaged CFST columns than undamaged ones, while the use of one-layer FRP provides similar confinement effectiveness.

**Figure 3.** Effects of number of FRP layers and heating time parameters

5. **Conclusions**

In this paper, an analysis procedure for predicting the axial compression behavior of FRP-confined fire-damaged circular CFST columns is described. The 2D finite element model is used to perform the heat transfer analysis. The proposed analysis can accurately predict the temperature distribution within the CFST cross section during fire exposure and load carrying capacity of both unconfined and FRP-confined fire-damaged CFST columns. The parametric study shows that the confinement effectiveness depends on heating time (level of fire damage) and number of FRP layers.

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