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Equivalent temperature prediction for concrete-filled cold-formed steel (CF-CFS) built-up column sections (part A)

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ABSTRACT

This study aims to present an empirical formulation to predict equivalent temperature for steel and concrete components of the innovative concrete-filled cold-formed steel (CF-CFS) built-up column sections. This paper (part A) presents a 2-dimensional (2D) finite element modeling technique to predict temperature evolution through the CF-CFS built-up column sections. Heat transfer analysis was undertaken considering existing models/data for thermal properties (thermal conductivity and specific heat) of concrete and steel as a function of temperature. The resultant heat emissivity and the convective heat coefficient were defined to describe radiation and convection. The results of finite element modeling were calibrated against experimental data. The results showed a good agreement with experimental data for both steel and concrete temperature evolution. Therefore, the 2D finite element can accurately predict the temperature of the CF-CFS sections and can be used as a reliable tool for further parametric study.

1. Introduction

Due to its superior structural performance in various scenarios such as fire, concrete-filled steel tubes (CFST) are widely utilized in multi-story buildings. These structural components have high structural fire performance. Recently studies were carried out on applying cold-formed steel profiles and lightweight concrete instead of hot-rolled and normal concrete [1,2]. The cold-formed steel profiles have advantages over hot-rolled profiles, such as less difficulty in transportation, high strength-to-weight ratio, ease of fabrication, less construction time, ability to generate various cross-section shapes [3–6]. Understanding the behavior of these columns subjected to accidental fire action is necessary further to enhance the fire performance of such structural members. In the last few decades, a great deal of experimental, computational, and analytical work has been done to better understand the behavior of composite columns when subjected to fire [1-15]. Espinos et al. [8] numerically compared the fire resistance of concrete-filled steel tubular composite columns and concrete-filled steel tubular composite columns with a steel core. They calibrated their numerical modeling by comparing axial displacement history for experimental specimens and numerical simulations. Mao et al. [9] investigated the fire resistance of concrete-filled steel tubular composite columns. They showed an excellent agreement between finite element results and experimental data for the outer surface of the steel tube. However, remarkable differences were seen between experimental and numerical results for predicting the concrete core temperature. Zhou et al. [10] investigated the concrete-filled thin-walled circular steel tubular columns using experimental tests and numerical modeling. Their finite element modeling approach showed an acceptable prediction. Meng et al. [11] investigated the fire behavior of concrete-filled steel columns using experimental tests and numerical

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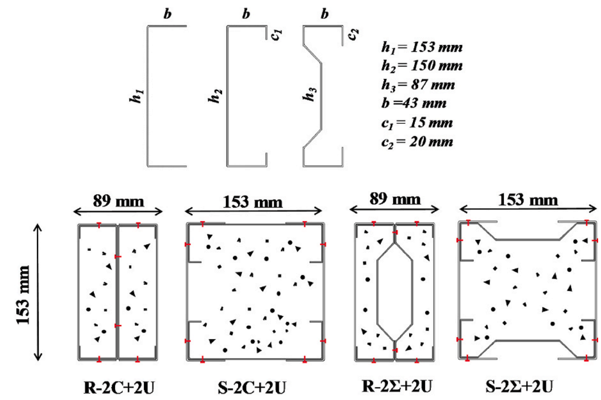

Fig. 1. Geometry details of the profiles and composite sections.

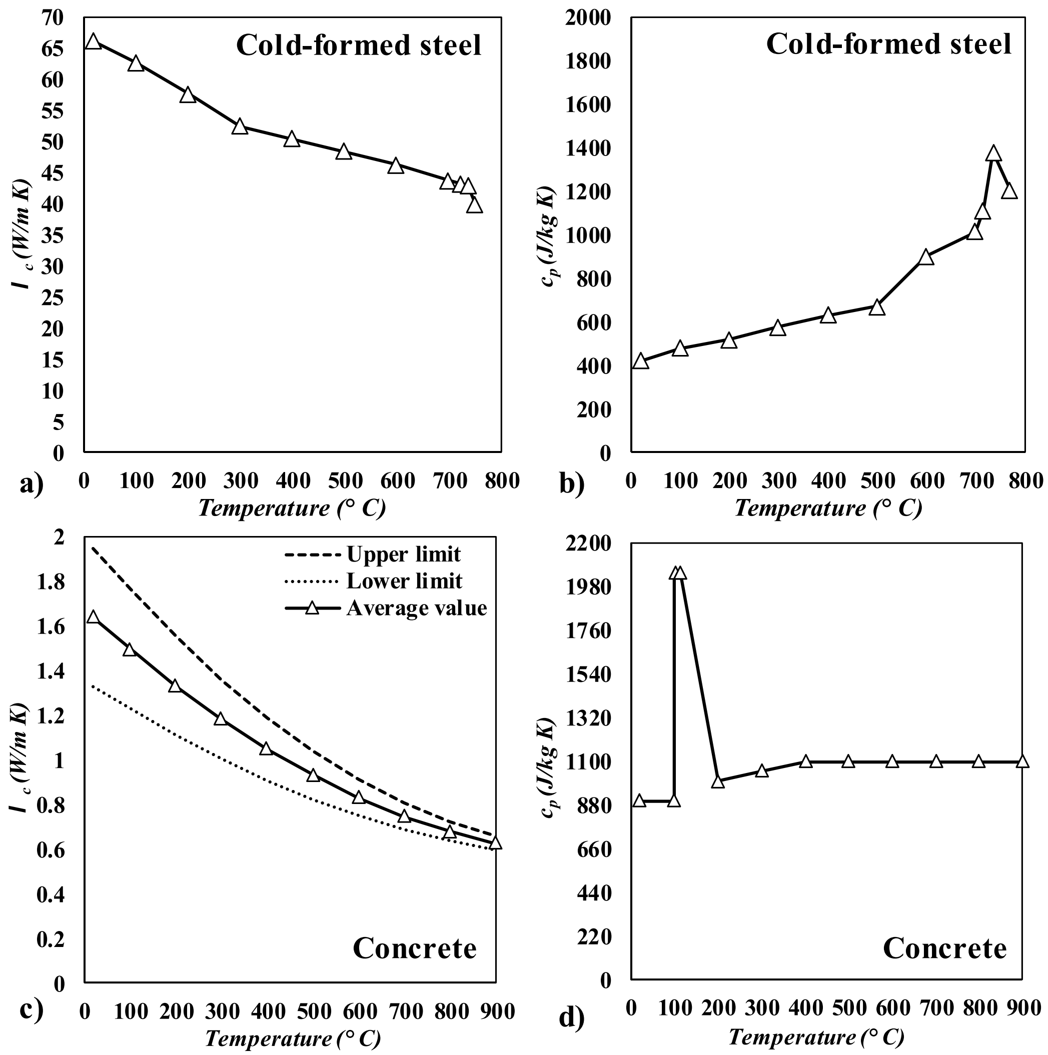

Fig. 2. a) steel thermal conductivity, b) steel specific heat [17,18]], c) concrete thermal conductivity, and d) concrete specific heat [19].

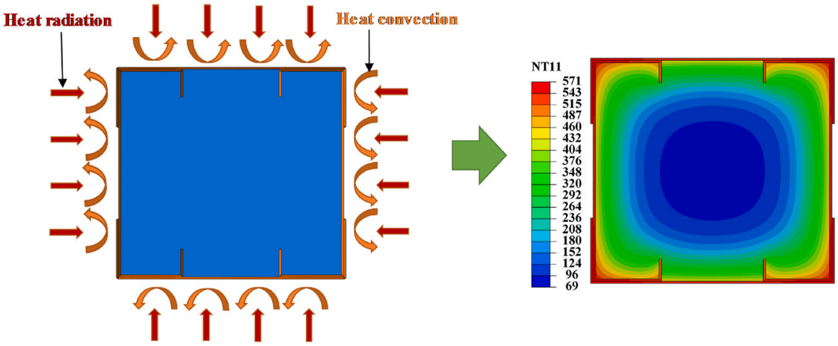

Fig. 3. Numerical modeling.

simulation. They compared the experimental results with the corresponding numerical model showing a remarkable disagreement in axial displacements and temperature evolution.

Prior work by the authors [1,2] demonstrated the compression behavior of the CF-CFS column at both room temperature and increased temperatures. Even though extensive experimental and numerical investigations into the fire resistance of composite columns have been carried out, advanced tools such as finite element analysis are still required to determine the temperature distribution in the cross-section and, therefore, to determine the fire resistance composite columns. Moreover, the design procedure for composite columns following EN 1994-1-2 [16] is incorporated with advanced heat transfer analysis. Moreover, the difficulty of EN 1994-1-2 [16] methodologies (general method and simplified method (Annex H)) is to obtain accurate temperature distribution in steel components and layers of the concrete section. This paper presents a 2D modeling approach as a verification tool for future studies (part B of this study).

2. Finite element modeling

2.1. Geometry details of the CF-CFS built-up sections

Cold-formed steel profiles with cross-sections in the shapes of C, U, and Σ were used in this work as the numerical models for this investigation. All of the profiles have a plate thickness of 1.5 mm. The CF-CFS composite cross-sections are presented in Fig. 1. The tested CF-CFS composite sections were fully described in [2].

2.2. Thermal properties

2.2.1. Steel

All profiles were made of S280GD + Z structural steel (nominal yield strength of 280 MPa and ultimate tensile strength of 360 MPa). The thermal parameters of this material (thermal conductivity (λ_c) and specific heat (c_p)) were taken from the experimental study performed by Craveiro et al. [17,18], where the Transient Plane Source technique was used. The obtained experimental results are displayed in Fig. 2a and b.

2.2.2. Concrete

The thermal conductivity (λ_c) for the concrete was defined according to the expression presented by the EN1992-1-2 [19]; it includes lower and upper limits determined by Eq. (2). In this study, an average between lower and upper limits was considered for the numerical models. Fig. 2c depicts the upper and lower limits and their average thermal conductivity as a function of temperature. The specific heat (c_p) was also defined as a function of temperature according to the EN1992-1-2 [19] as shown in Fig. 2d. Note that the moisture content of 3% was assumed for the concrete.

$$\begin{cases} \lambda_c = 2 - 0.2451(\theta/100) + 0.0107(\theta/100)^2 \; 20\,^\circ C \leq \theta \leq 1200\,^\circ C \; (lower\ limit) \\ \lambda_c = 1.36 - 0.136(\theta/100) + 0.0057(\theta/100)^2 \; 20\,^\circ C \leq \theta \leq 1200\,^\circ C \; (upper\ limit) \end{cases} \tag{2}$$

2.3. Numerical modeling

2D transient heat transfer analyses were conducted using Abaqus [20] to obtain the thermal gradient within the composite steel-concrete cross-section.

The radiation and convection were defined to simulate the transferring temperature from the fire to the external surface of the sections (Fig. 3), hence determining the boundary conditions of the heat transfer analysis. The fire's temperature was defined according to the furnace air temperature based on an experimental study performed by Rahnavard et al. [2]. The resultant heat emissivity of 0.23 was used to represent radiation. A value of 20 (W/m^2 K) was also used for the convective heat coefficient [2]. The heat resistance at the interface can be described using the heat contact conductance parameter. The 200 (W/m^2 K) heat contact conductances were defined for steel to concrete contact. Steel to steel contact conductances was defined as 2000 (W/m^2 K). The initial ambient temperature was defined as 20 °C.

Moreover, physical constants such as absolute zero temperature and the Stefan-Boltzmann constant were considered −273.15 °C

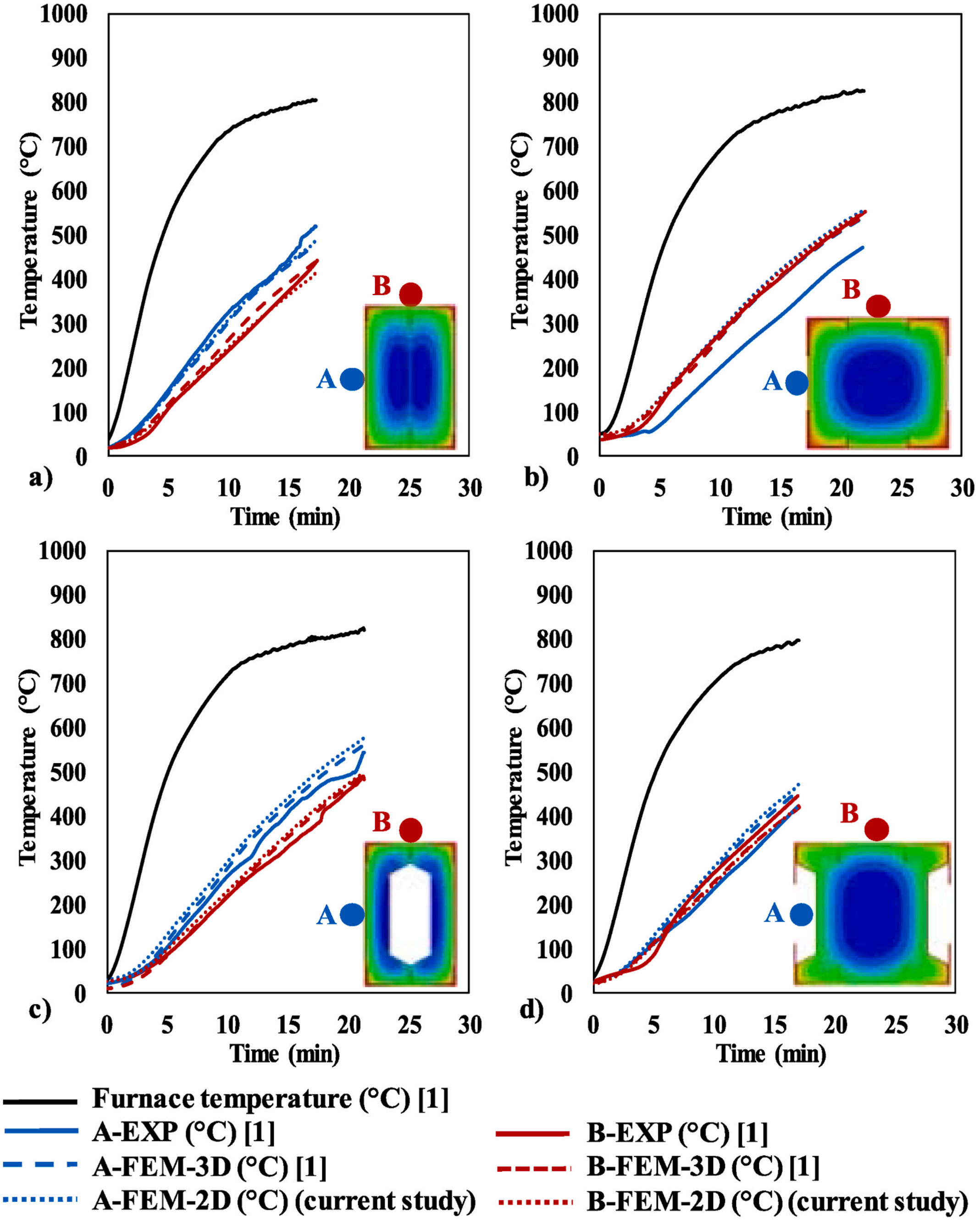

Fig. 4. Comparison of experimental and finite element results for temperature history on steel surface; a) R–2C+2U, b) S–2C+2U, c) R-2Σ+2U, d) S-2Σ+2U.

and 5.67×10^{-8} W/(m [2]·k [4]), respectively. More information regarding the interaction definition is presented in [2]. For the meshing, DC2D4, a 4-node linear heat transfer quadrilateral from Abaqus [20] library, was selected for both steel and concrete components. Note that the mesh size for concrete and steel was considered as 0.5 mm.

3. Verification of temperature evolution

In this section, the 2D modeling approach is verified against experimental results in [2]. The temperature vs. time of specific positions on steel surface for 2D finite element (current study) and both 3D finite element modeling [2] and experimental tests [2] are plotted in Fig. 4. Note that the temperature evolution of the mid-height level of the column from the experimental study [2] was adopted for comparison purposes. The numerical results obtained using the 2D heat transfer analysis are in very good agreement with the experimental results. The current study's 2D heat transfer analysis results were consistent with those from previous 3D heat

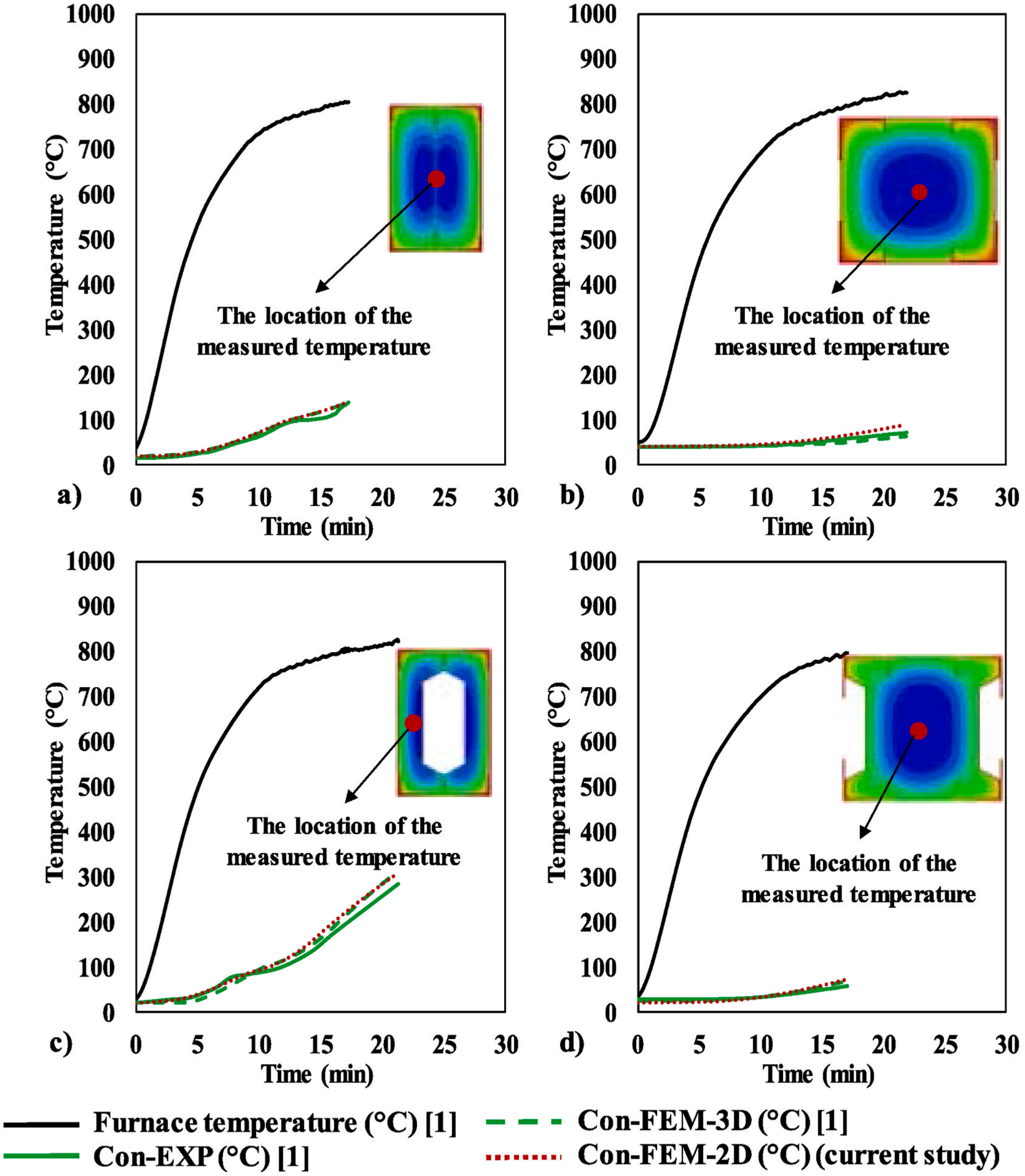

Fig. 5. Comparison of experimental and finite element results for temperature history in the concrete core; a) R–2C+2U, b) S–2C+2U, c) R-2Σ+2U, d) S-2Σ+2U.

transfer investigations [2]. As shown in Fig. 4a–c, the temperature on the steel surface for R–2C+2U and R-2Σ+2U cross-sections had lower temperatures on point B (U-channel flanges) than their webs (point A). This variation is because point B is located in the web, which is thinner (no overlapping steel plates).

Fig. 4b shows the results for the square section S–2C+2U. The actual temperatures varied, while it was assumed that all surfaces in Fig. 4b would have the same temperature due to the section's square shape and equal thickness in points A and B. This difference in the experimental results is because the furnace chamber is divided into two sections. There are no electrical resistances in the area where the two chambers link [2], which means that the two sides of the column were somewhat less exposed to heat radiation. Fig. 4d shows a close agreement between experimental results and the 2D heat transfer analysis for S-2+2U.

The concrete core temperature history curves were compared to the temperature curves of the 2D heat transfer analysis, which are depicted in Fig. 5. Overall, all configurations were found in good agreement, resulting in finite element modeling that is both accurate and reliable. The maximum concrete core temperatures difference obtained from experimental and numerical 2D models is 6%, 9%, 1%, and 8% for R-2+2U, S-2+2U, R-2Σ+2U, and S-2Σ+2U. The modest differences in the temperature between the finite element models and the experimental specimens may be due to variations in thermal property values. Note that the moisture content of the concrete infill was assumed uniform throughout the finite element. In contrast, the concrete infill in the cross-center section of the experimental specimens may be higher than the moisture content of the concrete infill in the area adjacent to the steel tube.

In sum, the 2D modeling techniques could precisely predict the steel temperature and the generated thermal gradient in the concrete infill.

4. Conclusions and future work

A 2D numerical modeling of heat transfer analysis was developed to investigate the temperature evolution of composite sections. The composite sections were made of cold-formed steel built-up sections and filled with concrete. The results of the 2D modeling approach showed a high accuracy against experimental and 3D finite element results in [2]. The 2D modeling approach had the advantage of being less complex than the 3D approach presented by authors [2]. Therefore, the adopted simulation techniques will be used in future parametric studies as a reliable verification tool for the development of empirical formulations (part B of this study) capable of estimating the temperature evolution of steel and concrete parts of the composite section for future application with existing structural design methodologies presented in the EN 1994-1-2 [19].

CRediT authorship contribution statement

Rohola Rahnavard: Numerical modeling. Formulation. Formal analysis and interpretation of the results. Writing the original draft. Hélder D. Craveiro: Funding acquisition. Supervision. Formal analysis and interpretation of the results. Writing – review, and editing. Rui A. Simões: Supervision. Writing – review, and editing. Aldina Santiago: Writing – review, and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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