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POST-FIRE AXIAL CAPACITY OF RECYCLED AGGREGATE CONCRETE FILLED STEEL TUBE COLUMNS

Summary: The paper analyses the post-fire axial capacity of recycled aggregate concrete-filled steel tube (RACFST) columns. Since existing design codes lack guidelines for calculating this capacity, the modified method from the second-generation of Eurocode 4 is applied and its applicability is confirmed for RACFST columns. For method evaluation, the results from previous experimental campaigns are compiled. Additionally, to obtain a better understanding of the advantages of the RACFST solution compared to conventional RC columns regarding sustainability, the assessment of post-fire capacity for two chosen sections is conducted. A fair comparison is made to analyze the post-fire capacities of unprotected RACFST and RC section.

Keywords: post-fire capacity, recycled aggregate concrete, Eurocode 4, composite columns

POST-POŽARNA AKSIJALNA NOSIVOST SPREGNUTIH STUBOVA OD ČELIČNIH CEVI ISPUNJENIH BETONOM OD RECKLIRANOG AGREGATA

Rezime: U radu se analizira aksijalna nosivost spregnutih stubova od čeličnih cevi ispunjenih betonom sa recikliranim agregatom (RACFST) nakon dejstva požara. Budući da važeći propisi ne daju smernice za sračunavanje ove nosivosti, u radu je primenjena modifikovana metoda druge generacije Evrokoda 4 i potvrđena je njena primenljivost na RACFST stubove. Za evaluaciju ove metode, prikupljeni su rezultati ranijih eksperimentalnih istraživanja. Takođe, radi ilustracije prednosti RACFST rešenja u poređenju sa klasičnim armirano-betonskim stubovima, sprovedena je uporedna analiza procene kapaciteta nosivosti za dva odabrana preseka. Upoređeni su aksijalni kapaciteti nosivosti RACFST i AB preseka.

Ključne reči: nosivost nakon dejstva požara, beton od recikliranog agregata, Evrokod 4, spregnuti stubovi

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1. INTRODUCTION

Concrete-filled steel tube (CFST) columns efficiently merge the advantages of both steel and concrete, resulting in a structural element with many benefits. These consist of, but are not restricted to, enhanced load-bearing capacity, better ductility, and reduced construction time. Due to these factors, there is a growing trend in the global use of these members. In line with the overall trend of offering more sustainable options within the built environment and reducing natural resource consumption, there is an increasing focus on research and the utilization of concrete made with aggregates derived from crushed construction and demolition waste [1]. When this kind of concrete is incorporated in CFST columns, these elements are referred to as RACFST columns.

The previous investigations, although limited, have shown that recycled aggregate concrete (RAC) within steel tubes mostly overcomes the limitations of RAC when it is used in conventional reinforced concrete members, and that RACFST members have behaviour very similar to CFST members [1]. Consequently, there is substantial potential for practical application. However, a prerequisite for the wider use of RACFST columns in practice is further investigation on these members and the existence of reliable design code guidelines.

At present, Eurocode 4 serves as the European standard for the design of steel-concrete composite structures, with Part 1-1 [2] addressing their design and Part 1-2 [3] specifically the fire design. However, even the second generation of these standards [4, 5] provides only guidelines for CSFT columns, while the post-fire capacity is not covered. For these reasons, this paper presents the results of a preliminary study where the post-fire capacity of RACFST columns is determined by applying the method proposed by the second generation of Eurocode 4 for CFST columns at reference temperature [4], by introducing modifications to consider the effects of material degradation at higher temperatures.

More details about the study can be found in [6], while here will be presented only the major points with few additional conclusions.

2. CALCULATION OF POST-FIRE CAPACITY

To fully comprehend the behaviour and design of structures, it is crucial to understand a member's residual capacity after being subjected to fire for a specific period [7]. Currently, the design code Eurocode 4 lacks guidelines for determining the axial capacity of CFST after a fire [2]. Consequently, researchers primarily utilize formulas developed for the reference temperature and implement them with the remaining (post-fire) characteristics of materials [7]. Regarding the material properties after a fire, [5] provides formulas for assessing the residual strength of concrete based on the highest temperature it attained during the heating process. Nevertheless, there are no guidelines referring to the post-fire characteristics of steel.

In a study presented with more details in [6], the post-fire axial capacity of RACFST columns is determined in the following way. The critical buckling force is determined according to Eurocode 4 guidelines for assessing the axial capacity of the CFST column at reference temperature, using modified material properties. As the specimens were allowed to cool naturally to room temperature, the properties of the concrete material are evaluated according to clause 5.3.2.2(6) of Eurocode 2. The strength of concrete heated to a maximum temperature θ_{max} and cooled down to 20°C is:

$$f_{c,\theta,20°C} = \phi f_c \tag{1}$$

where ϕ depends on $k_{c,\theta max}$:

$$\phi = k_{c,\theta_{max}} \text{ for } 20°\text{C} \leq \theta_{max} \leq 100°\text{C} \tag{2}$$

$$\phi = (-0.0005\theta_{max} + 1.05)k_{c,\theta_{max}} \quad \text{for} \quad 100°C \leq \theta_{max} \leq 300°C \tag{3}$$

$$\phi = 0.9k_{c,\theta_{max}} \quad \text{for} \quad \theta_{max} > 300°C \tag{4}$$

Temperature θ_{max} is determined for expressions from Eurocode 4.

For stainless steel tubes, the retention factors are adopted from the study by Molkens et al. [8], while for the carbon steel tube, these factors are taken from [9]. The retention factors depend on the maximum temperature to which the steel is exposed. This temperature is, again, calculated following the expressions from Eurocode 4. The axial capacity calculated this way is denoted as $N_{R,EC4}$ and, for method validation, the database consisting of 48 specimens of circular and square RACFST columns is compiled [6]. Figure 1 compares results of experimentally measured post-fire buckling force N_R and predictions obtained by the proposed method.

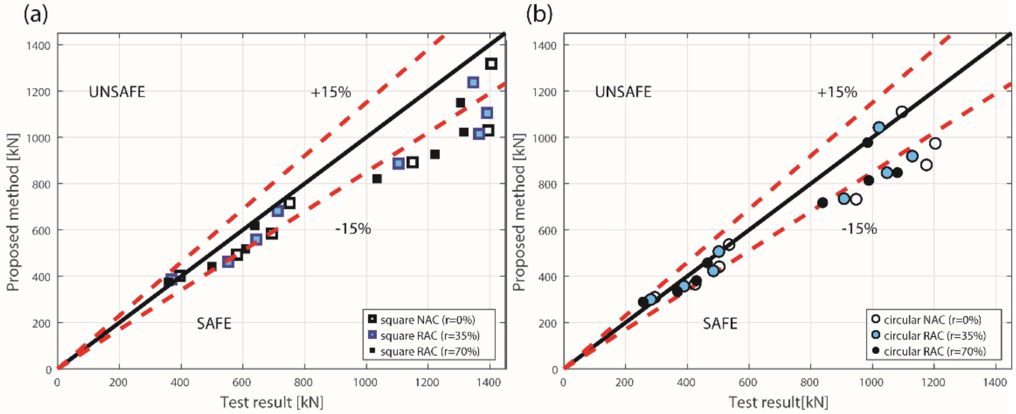

Figure 1: Comparison between experimentally obtained post-fire buckling force and prediction obtained by the proposed method: (a) square specimens and (b) circular specimens

Obviously, the predictions obtained by the proposed method are close to the experimental results. It is important to note that all three criteria adopted by the CEN/TC250/SC4 Horizontal Group Fire are fulfilled. These are: (1) the calculation result shall not be on the unsafe side of the reference result by more than 15%; (2) a maximum of 20% of the individual calculation results can be on the unsafe side and (3) the mean value of all percentage differences between calculation results and reference results shall be on the safe side.

The limitations of the study are as follows: the specimens in the validation database are exposed to fire durations of up to 45 minutes and exposure to the ISO 834 heating curve. Additionally, the analyzed specimens have small cross-sections with outer dimensions of the steel tube up to 130 mm. Therefore, the method also needs to be validated for larger cross-sections.

3. COMPARISON OF POST-FIRE CAPACITY OF RACFST AND RC SECTIONS

The aim of this section is to compare RACFST columns with conventional RC columns from a sustainability perspective and the post-fire axial capacity of these columns. It is assumed that the same design procedures of CFST sections are applicable to RACFST sections, which is in agreement with previous studies [1]. For this purpose, two square cross sections depicted in Figure 2 are chosen. Two sections are selected to have comparable section capacities at reference temperature. The first section is a square RACFST section with the geometrical properties given in Figure 2(a). The concrete with f_{ck}=40MPa and steel tube with f_y=355MPa are selected. The second section is a square RC section (Figure 2(b)) with the same concrete material properties (f_{ck}=40MPa), reinforced with $8\phi 28$ reinforcement bars with f_y=500MPa. For these two sections Figure 3 compares their ultimate axial force-bending moment interaction curves N-M, at reference temperature. These curves are constructed using the fiber section analysis and material models from Eurocode 4 [4] and Eurocode 2 [10]. The axial capacity of the RC section is 9.3% higher than that of the RACFST section, while the bending capacity of the RC section is 10.2% lower than the value of the RACFST section. Therefore, the sections can be considered comparable.

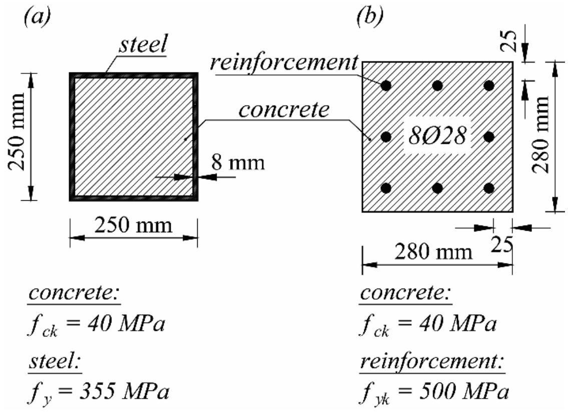

Figure 2: Two analysed cross sections: (a) RACFST and (b) RC section

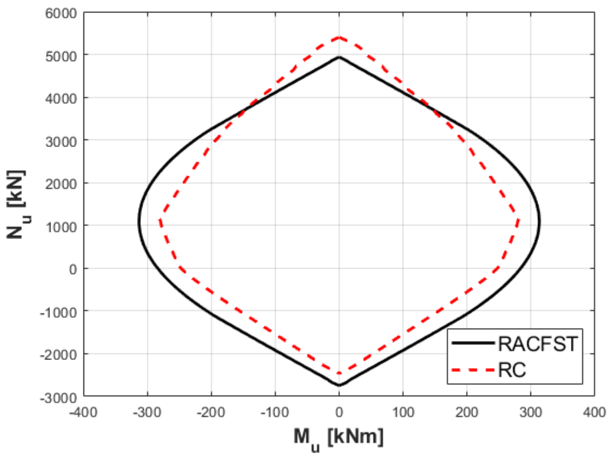

Figure 3: Axial force - bending moment interaction curves for compared RACFST and RC sections

Comparing the amount of used concrete within these two sections we can conclude that area of concrete in RC section is 43% larger than area of concrete in RACFST section. Therefore, in terms of natural aggregate use, this indicates considerable savings. Besides, it is important to note that the second generation of Eurocode 2 Part 1-1, in informative Annex N [10], permits the use of RAC with a maximum substitution ratio of natural aggregate (fine and coarse) with recycled aggregate of 40% in structural elements (without requiring experimental testing). In this regard, the potential for employing RAC with an elevated or complete substitution rate in RACFST members is greatly valued.

To compare the post-fire axial capacity of these two selected cross sections, the following methods are applied. The capacity of the RACFST section is determined according to the method explained in Section 2 for a stub column when all second-order effects are neglected. The steel tube is considered to be made of carbon steel, and the steel retention factors are taken from [9]. In the RC section, there remains a lack of agreement on how to calculate the residual section capacity. In this study the method proposed by Kodur et al. is applied [11]. This method is based on the application of the 500°C isotherm method and assumes that only concrete within the isotherm of 500°C has post-fire strength, while concrete outside of this isotherm is neglected. The residual strength of concrete is calculated from Eqs. (1)-(4), while the residual strength of reinforcement is assumed to follow [9]. The isotherm at 500°C is obtained from the section thermal analysis. Finally, the residual post-fire section axial capacity is determined from the fiber section analysis. Both sections (RACFST and RC) are considered to be exposed to 4- sided heating in accordance with the ISO 834 heating curve for different durations (15, 30, 45, and 60 min) and then cooled down to the reference temperature. Table 1 presents the numerical results for the post-fire axial strength of these sections, and Figure 4 illustrates these results visually.

Table 1: Post-fire axial capacity for analysed RACFST and RC sections

Fire duration [min]	RACFST [kN]	RC [kN]
0	4939.4	5400.8
15	4815.8	4861.5
30	3999.8	4428.8
45	3535.8	4237.8
60	3225.9	4006.0

For shorter fire durations (15 min), the reduction in the post-fire axial capacity of RACFST columns is smaller than that of the RC section. This can be explained by the steel's ability to largely recover its strength after cooling when exposed to relatively moderate peak temperatures (up to 600 °C). For longer fire durations, the steel tube temperature can reach 700 °C or higher, leading to a more significant reduction in capacity. Therefore, the reduction in post-fire axial capacity of the RACFST section becomes equal to or slightly higher than, but still comparable to, the reduction of the RC section. The application of adequate insulation measures would be beneficial for both sections and would reduce the decrease in post-fire axial capacity.

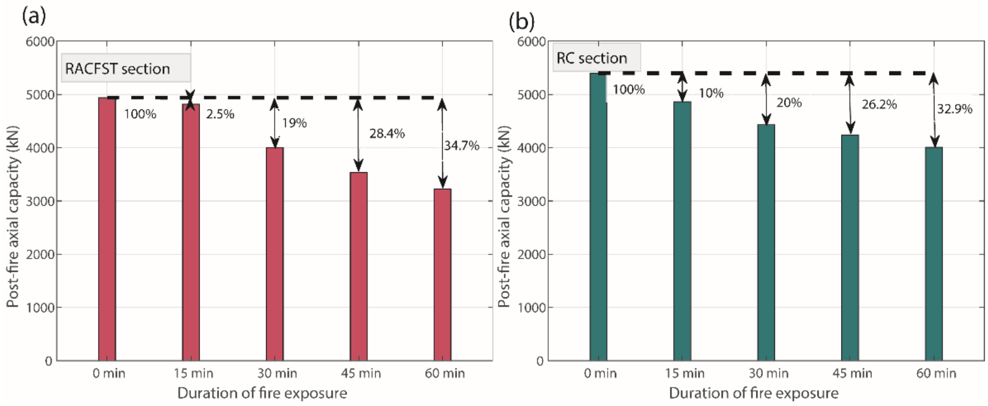

Figure 4: Change of post-fire axial capacity with fire exposure time: (a) RACFST section and (b) RC section

4. CONCLUSIONS

The study analysed the post-fire axial capacity of RACFST columns. At present, there are no established design guidelines for these columns. For that reason, the study investigated the possibility of applying the method for CFST columns at reference temperature but with modifications in order to predict the post-fire axial capacity of RACFST columns. The method is validated on a set of experimental test results available in the literature and has shown to provide results of acceptable accuracy and being on the safe side. To further support this conclusion, validation with a larger set of experimental results is required.

Comparing the post-fire axial capacity of the RACFST section with the RC section has shown that, for shorter fire durations (up to 60 min), the two sections are comparable, with RC sections performing slightly better for longer exposures.

Finally, considering that RACFST columns: (a) require significantly smaller cross-sections than traditional RC sections, thus providing larger usable interior spaces; (b) increase construction efficiency by accelerating the building process, as they eliminate the need for traditional formwork; and (c) achieve similar structural performances as CFST columns, even when a higher substitution ratio of natural aggregate with recycled aggregate is used, the sustainability potential of RACFST columns is very promising.

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