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FIRE AND POST-FIRE CAPACITY OF RECYCLED AGGREGATE CONCRETE FILLED STEEL TUBE COLUMNS USING THE SECOND GENERATION OF EUROCODE 4

POŽARNA I POST-POŽARNA NOSIVOST SPREGNUTIH STUBOVA OD ČELIČNIH CEVI ISPUNJENIH BETONOM SA RECIKLIRANIM AGREGATOM PREMA DRUGOJ GENERACIJI EVROKODA 4

Originalni naučni rad / Original scientific paper
Rad primljen / Paper received: 3.02.2026
https://doi.org/10.69644/ivk-2026-02-0223
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Keywords
- recycled aggregate
- composite columns
- fire analysis
- Eurocode 4
- nonlinear analysis

Abstract

The objective of this paper is to analyse the ultimate capacity of recycled aggregate concrete-filled steel tube (RACFST) columns exposed to elevated temperatures. As current design codes do not offer recommendations for their design, the study aims to evaluate the applicability of the simplified method of the second-generation Eurocode 4 for predicting the fire capacity of these columns. Additionally, the method for predicting their post-fire axial capacity is proposed and validated. This method is also based on the calculation of equivalent temperatures from the simplified method of Eurocode 4. The study analyses columns made of both carbon- and stainless steel tubes. To evaluate the methods, the results from previous experimental campaigns are compiled. The results show that the application of Eurocode 4's method and the proposed method for post-fire capacity calculation can be extended to RACFST columns. Furthermore, to gain deeper insight into the benefits of the RACFST solution over traditional RC columns from a sustainability perspective, the analysis of fire and post-fire capacity of two selected sections is performed. Through a fair comparison, the weak points of the unprotected concrete-filled steel tube solution are identified; however, these can be resolved by appropriate fire insulation measures.

Ključne reči
- reciklirani agregat
- spregnuti stubovi
- analiza na dejstvo požara
- Evrokod 4
- nelinearna analiza

Izvod

U radu je prikazan proračun granične nosivosti spregnutih stubova od čeličnih cevi ispunjenih betonom sa recikliranim agregatom (RACFST) pri visokim temperaturama. Budući da važeći propisi ne daju preporuke za njihov proračun, cilj studije je da ispita mogućnost primene pojednostavljene metode proračuna iz druge generacije Evrokoda 4 za određivanje nosivosti pri dejstvu požara. Takođe, metoda za predviđanje njihove post-požarne granične nosivosti je predložena i validirana. Ova metoda se zasniva na proračunu ekvivalentnih temperatura iz uprošćene metode Evrokoda 4. U radu su analizirani stubovi sa cevima od ugljeničnog i nerđajućeg čelika. Za validaciju metode, korišćeni su rezultati ranijih eksperimentalnih studija. Dobijeni rezultati su pokazali da se pojednostavljena metoda Evrokoda 4, kao i predložena metoda proračuna post-požarne nosivosti, mogu primeniti kod RACFST stubova. Pored toga, kako bi se stekao bolji uvid u prednosti RACFST stubova u odnosu na klasične AB stubove, sa stanovišta održive gradnje, izvršena je analiza nosivosti na dejstvo požara kao i post-požarne nosivosti dva izabrana poprečna preseka. Poređenjem dobijenih rezultata, identifikovane su slabosti nezaštićenih spregnutih stubova, koje se mogu prevazići korišćenjem odgovarajućih mera izolacije.

INTRODUCTION

Concrete-filled steel tube (CFST) columns effectively combine the strengths of steel and concrete, resulting in a robust structural component that is gaining popularity in various construction applications /1-3/. They offer numerous advantages such as increased load-bearing capacity, improved ductility, shorter construction time, increased fire resistance and enhanced stability. Traditionally, steel tubes used in concrete-filled steel tube columns are made from carbon steel. However, in the past decade, research has expanded to explore the use of stainless steel tubes in CFST columns /4-6/. Stainless steel offers several advantages, including enhanced durability, superior corrosion resistance, and improved fire resistance /5/. Despite these benefits, the higher cost associated with stainless steel remains a consideration.

Up to now, various concrete mixtures have been utilised within steel tubes /7-12/. Recently, as the construction industry is recognised as a major contributor to environmental impacts and consumption of natural resources, there has been a growing appreciation for more sustainable solutions, such as recycled aggregate concrete (RAC), i.e., concrete produced with aggregates obtained by crushing construction and demolition waste /2, 13-15/. Use of this concrete within steel tubes, because of the tubes' confining effects, increases the axial strength of RAC and its ductility, thus, allowing its application in structural members, /2/.

Consequently, interest in CFST columns filled with RAC referred to as RACFST columns has been increasing and further research is essential to optimise these members and promote their adoption in modern construction. It should be mentioned that the 2nd generation of Eurocode 2 Part 1-1, in informative Annex N /16/, allows the use of RAC with a maximum substitution ratio of natural aggregate (both fine and coarse) with recycled aggregate of 40 % in structural components (without need for experimental testing). In this context, the possibility of using RAC with higher or total substitution rate in RACFST members is highly appreciated.

In the past, there has been a limited number of studies examining the behaviour of RACFST columns at elevated temperatures /5, 6, 17-21/. These studies can be divided into two groups. The first group consists of studies where columns are firstly subjected to varying levels of constant axial loading and then exposed to heating until buckling occurs /17, 22/. All studied specimens include carbon steel tubes. The critical time t_c is defined as the moment when the column buckles. Yang et al. /17/ tested nine axially loaded square stub RACFST specimens. Investigated parameters included the coarse recycled aggregate replacement ratio r (0 %, 50 %, and 100 %), axial compressive load ratio (ranging from 0.2 to 0.5), and the thickness of the fire protective coating. The specimens were subjected to standard ISO 834 /23/ heating, and fire resistance was considered achieved when the prescribed axial displacement rate exceeded the specified limits. It was concluded that RACFST specimens exhibited ductile behaviour. The specimens with $r = 50$ % showed performance similar to specimens with natural aggregate concrete ($r = 0$ %), while specimen with $r = 100$ % (one such specimen) had a slightly lower measured critical time. Song et al. /22/ experimentally analysed six square and six circular specimens made with geopolymeric recycled aggregate concrete. The following parameters were investigated: axial compressive load ratio (0.3, 0.4, and 0.6) and two fire exposure scenarios (4-side and 2-side exposure), while the same concrete with $r = 50$ % was used in all specimens. A specified fire curve, different from ISO 834, was utilised. The failure mode for all specimens was local buckling of the steel tube, and columns exhibited behaviour similar to specimens with conventional concrete.

In the second group of studies are those that investigate the post-fire behaviour of axially loaded RACFST columns /5, 6, 18-21, 24, 25/. In these experimental campaigns, during the initial phase, the columns are subjected to heating for varying durations and heating protocols. Following this exposure, the columns are cooled down naturally to ambient temperature before being subjected to axial loading until failure occurs (at force N_R). Liu et al. /18/ tested the axial capacity of twelve circular specimens (six at reference temperature and six after being exposed to ISO 834 heating for 1 h and then cooled down). The investigated parameters include different thicknesses of the steel tube and three different concrete mixtures (one prepared as conventional concrete and two with recycled aggregate). The specimen failed due to buckling, and specimens with RAC exhibited a similar failure mode, regardless of whether they were exposed to fire or not. Yang et al. /25/ and Li et al. /24/ tested the post-fire axial capacity of specimens after being exposed for 3 h at selected temperatures: 300 °C, 600 °C, and 800 °C in /25/ and 200 °C, 500 °C, and 700 °C in /24/. Five different types of concrete with coarse and fine recycled aggregate (replacement ratios of 0, 50, and 100 %) are investigated in /25/. The study by Li et al. /24/ examines three different concrete mixtures made with coarse recycled aggregate with replacement ratios of 0, 50, and 100 %. The conclusion is that the failure patterns of specimens with different r are similar (local outward folding and buckling of the outer steel tube). The axial capacity of columns decreases with an increase in temperature. In comparison with specimens made of conventional concrete, RACFST specimens have shown slightly inferior post-fire behaviour.

Among the post-fire experiments on columns with carbon-steel tubes, the study of Zhao et al. /19/ should be mentioned. They investigate columns with an innovative, round-ended cross-section shape and analyse different section aspect ratios, as well as steel and recycled aggregate replacement ratios. According to the results, the residual bearing capacity and compressive stiffness decrease with increasing r. Additionally, as r increases, the concrete develops lower temperatures due to the lower thermal conductivity of RAC.

Recently, a group of authors investigated the post-fire axial capacity of RACFST columns with stainless steel tubes /5, 6, 20, 21/ after exposure to the ISO 834 standard fire for 15, 30, and 45 min. The studied columns included circular and square specimens with replacement ratios r of 0, 30, and 70 %. These studies include stub specimens /5, 6/, as well as longer columns to consider the overall buckling behaviour /20, 21/. It has been shown that for specimens with the same duration of exposure to elevated temperatures, the ultimate capacity decreases as r increases.

A prerequisite for the wider use of RACFST columns in practice is 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 1-2 /26/, specifically addressing structural fire design. In relation to the fire performance of concrete-filled steel tube columns, the new version of Eurocode 4 Part 1-2 /27/ offers clear design guidelines. Three approaches can be employed based on the specific problems at hand: the use of tabulated design data, simplified design methods, and advanced design methods. Among these, the simplified method is the most commonly utilised in design offices. While this method has been validated for CFST columns comprising natural aggregate concrete and carbon steel tubes /28/, it has yet to be assessed for RACFST columns /5, 19/. This is important since it is proven that thermal properties of RAC are slightly different from properties of concrete prepared with natural aggregate /2, 19/. Referring to the calculation of the column's post-fire capacity, there are no guidelines present in the new version of Eurocode 4 Part 1-2, /27/.

Therefore, this paper addresses the following identified gaps with the aim to facilitate wider use of RACFST columns in practice. Firstly, the study evaluates the applicability of the proposed simplified EC4 method for predicting the fire capacity of RACFST columns featuring carbon steel tubes. Secondly, the new procedure based on the recommendations from the 2nd generation of Eurocode 4 /27/ for calculating the post-fire axial capacity of RACFST columns is proposed and validated. Finally, in a study, a fair comparison and assessment of fire resistance and axial post-fire capacity between reinforced concrete and RACFST columns, taking into account sustainability and natural aggregate usage viewpoints is performed. The conducted numerical analyses offer greater insight into the fire performance of RACFST columns, including their advantages and drawbacks.

VALIDATION OF THE SIMPLIFIED METHOD FROM EUROCODE 4 ON RACFST COLUMNS

The second generation of the Eurocode 4 Part 1-2 /27/ introduces some additions to the simplified method for analysing CFST columns under fire conditions. These changes involve using equivalent temperatures for the different components of the composite section: the steel tube, concrete core, and reinforcement. As a result, engineers no longer need to conduct a thermal analysis first to determine the temperature distributions across the cross-section, which is a considerable relief.

According to this design code, the buckling force $N_{fi,Rd}$ of the composite column is calculated as follows. For brevity, the expressions are written here for the case considering circular and square CFST columns without additional reinforcement bars. Firstly, as previously mentioned, the equivalent temperatures are calculated for a given fire duration. It is assumed that a column is uniformly heated from all sides and that the heating follows the standard ISO 834 fire curve.

The equivalent temperature for the concrete core, $\theta_{c,eq}$ and steel tube $\theta_{a,eq}$ can be found from Eqs. (1) and (2):

$$\theta_{(c,eq)} = 81.8 - 5.05 t_{fi}^2 - 15.07 A_m/V + 0.3(A_m/V)^2 - \\ -0.88 t_{fi} A_m/V + 7.43 t_{fi}^{0.842} (A_m/V)^{0.714}, \quad (1)$$

$$\theta_{(a,eq)} = -824.67 - 5.58 t_{fi} + 0.007 t_{fi}^2 - 0.01 t_{fi} A_m/V + \\ +645.08 t_{fi}^{0.269} (A_m/V)^{0.017}. \quad (2)$$

Here, t_{fi} is the time of standard ISO 834 fire exposure and A_m/V is the cross-sectional factor equal to the ratio between the circumference exposed to fire and cross-sectional area.

The design value of the plastic resistance to axial compression $N_{fi,pl,Rd}$ in the fire can be calculated from Eq.(3):

$$N_{fi,pl,Rd} = \frac{A_a f_{y,\theta}(\theta_{a,eq})}{\gamma_{M,fi,a}} + \frac{A_c f_{c,\theta}(\theta_{c,eq})}{\gamma_{M,fi,c}}. \quad (3)$$

Here, A_a is the area of steel tube, A_c is the area of concrete, $f_{y,\theta}$ is design strength of steel at temperature $\theta_{a,eq}$, and $f_{c,\theta}$ is design strength of concrete at temperature $\theta_{c,eq}$. The design strength of steel and concrete can be found using the corresponding reduction factors k_θ given in /27/.

The partial factors of the materials in the fire situation $\gamma_{M,fi,a}$ and $\gamma_{M,fi,c}$ are assumed as unity, as advised by /27, 29/.

The effective flexural stiffness, $(EI)_{fi,eff}$, can be calculated from Eq.(4),

$$(EI)_{fi,eff} = \varphi_{a,\theta} E_{a,\theta}(\theta_{a,eq}) I_a + \varphi_{c,\theta} E_{c,\theta}(\theta_{c,eq}) I_c, \quad (4)$$

where: I_a and I_c are second moment of area of steel tube and concrete core; $\varphi_{a,\theta}$ and $\varphi_{c,\theta}$ are reduction coefficients for steel and concrete; and $E_{a,\theta}$ and $E_{c,\theta}$ are elasticity moduli of steel and concrete at temperatures $\theta_{a,eq}$ and $\theta_{c,eq}$. The reduction coefficient of concrete $\varphi_{c,\theta}$ is taken equal to 1.2. The reduction coefficient of steel $\varphi_{a,\theta}$ is calculated from Eqs.(5) and (6):

$$\varphi_{a,\theta} = 0.75 - 0.023\left(\frac{A_m}{V}\right) \text{ circular cross-section,} \quad (5)$$

$$\varphi_{a,\theta} = 0.15 - 0.001\left(\frac{A_m}{V}\right) \text{ square cross-section.} \quad (6)$$

The elastic critical force of a column with buckling length l_{fi} in the fire situation, $N_{fi,cr}$, can be calculated as in Eq.(7):

$$N_{fi,cr} = \frac{\pi^2 (EI)_{fi,eff}}{l_{fi}^2}. \quad (7)$$

Finally, the design value of axial resistance of a CFST column under compression, in the fire situation, can be found as, Eq. (8):

$$N_{fi,Rd} = \chi N_{fi,pl,Rd}, \quad (8)$$

where: χ is reduction coefficient for buckling curve '*a*' of Eurocode 3 /30/, and is a function of relative slenderness $\overline{\lambda_\theta}$, Eq.(9):

$$\overline{\lambda_\theta} = \sqrt{N_{fi,pl,Rd} / N_{fi,cr}}. \quad (9)$$

In order to validate this method for the calculation of RACFST column axial fire capacity, the experimental results from previous campaigns are collected. Since the simplified Eurocode 4 method refers to heating according to standard ISO 834 temperature curve, tests by Yang et al. /17/ serve as the dataset.

The specimen properties are given in Table 1. Here, B denotes the outer size of the steel tube, t is tube thickness, f_y is yield stress of steel, $f_{c,28}$ is compression strength of concrete at 28 days after casting, and N_E is applied axial force. All columns have a length of 3810 mm.

For calculation of critical time according to Eurocode 4 the procedure depicted in Fig. 1 is performed. For each column specimen, the axial resistance of a RACFST column $N_{fi,Rd}$ is calculated from Eqs.(1)-(9) through iterations, by increasing the fire exposure time. The time when resistance $N_{fi,Rd}$ becomes equal to the applied axial force is saved as t_{EC4}. These results, for specimens from the first group, are given in the last column of Table 1.

Table 1. Properties of RACFST column tests with square carbon steel tubes, /17/.

No	Shape	Specimen	B (mm)	t (mm)	r (%)	t_c (min)	f_y (MPa)	$f_{c,28}$ (MPa)	N_E (kN)	t_{EC4} (min)	t_c / t_{EC4}
1	square	NC-0.34-0	300	5.9	0	36	345	30.6*	528.9	33	1.09
2	square	RAC1-0.35-0	300	5.9	50	40	345	29.7*	540.0	32	1.25
3	square	RAC2-0.37-0	300	5.9	100	29	345	29.0*	568.0	31	0.94
4	square	RAC1-0.24-0	300	5.9	50	80	345	29.7*	246.9	51	1.57
5	square	RAC1-0.47-0	300	5.9	50	23	345	29.7*	966.9	23	1.00
6	square	RAC1-0.59-0	300	5.9	50	16	345	29.7*	1517.2	17	0.94

Note: * Converted from cube strength to cylinder strength by factor 0.8.

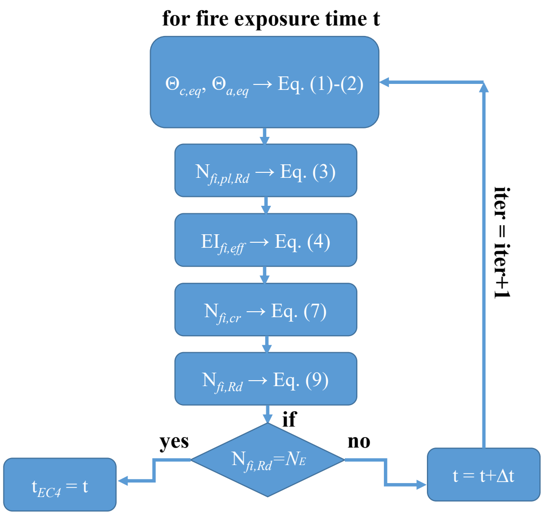


Figure 1. Flowchart of procedure for calculating the column's critical time.

Figure 2 shows the comparison between experimental results and time predicted by Eurocode 4, t_{EC4}.

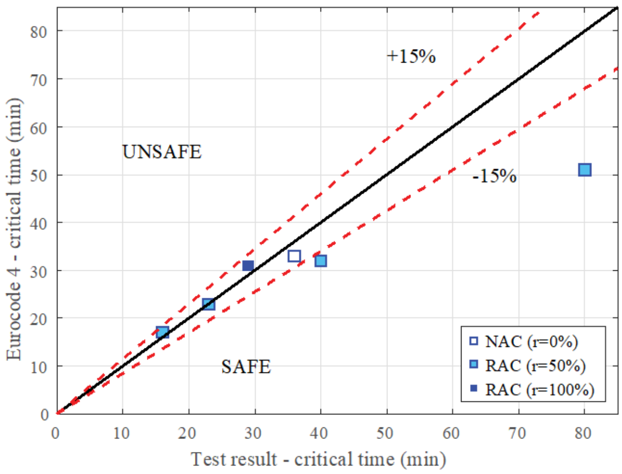


Figure 2. Comparison between experimentally obtained critical time and prediction of Eurocode 4.

It can be seen that Eurocode 4 predictions are very accurate, and, generally, on the safe side. All three criteria adopted by the CEN/TC250/SC4 Horizontal Group Fire for considering the safe method /28/, are fulfilled. These are: (1) calculation result shall not be on the unsafe side of the reference result by more than 15 %; (2) a maximum of 20 % of individual calculation results can be on the unsafe side and (3) the mean value of all percentage differences between calculation and reference results shall be on the safe side. Additionally, this research highlights the need for more experimental studies on the fire behaviour of RACFST columns to expand the dataset and support this conclusion.

CALCULATION OF POST-FIRE AXIAL CAPACITY OF RACFST COLUMNS

For a full understanding of the behaviour and design of structures, being able to predict the post-fire capacity of members, i.e., a member's residual capacity after being exposed to a fire for a certain duration, is equally important as predicting their fire capacity. The design code Eurocode 4 /26/ and its new version /27/ do not include recommendations for calculating the CFST's post-fire axial capacity. So far, researchers mostly use expressions derived for reference temperature and apply them with the residual (post-fire) properties of materials /31/. Referring to post-fire material properties, /27/ gives expressions on how to determine the residual strength of concrete depending on the maximal temperature it reaches during heating. However, there are no clear guidelines regarding the post-fire properties of steel.

In this study, for calculating the post-fire axial capacity of RACFST columns, the following method, similar to the one proposed by /31/ but with different residual properties of steel and concrete, is employed.

The critical buckling force is calculated following Eurocode 4 rules for determining CFST column's axial capacity at reference temperature, but with modified material properties. Since specimens were cooled naturally to ambient temperature, the concrete material properties are determined following the clause 5.3.2.2(6) of /27/. According to this, the strength of concrete heated to a maximal temperature $\theta_{c,\max}$ and cooled down to 20 °C is found as in Eqs.(10)-(13):

$$f_{c,20°C} = \phi f_c \,, \tag{10}$$

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

$$\phi = k_{c,\theta\max} \quad 20\ °C \le \theta_{\max} < 100\ °C \,, \tag{11}$$

$$\phi = (-0.0005\,\theta_{\max} + 1.05)k_{c,\theta\max} \quad 100\ °C \le \theta_{\max} < 300\ °C, \tag{12}$$

$$\phi = 0.9 k_{c,\theta\max} \quad \theta_{\max} \ge 300\ °C \,. \tag{13}$$

Maximum temperature $\theta_{\max}$ is taken equal to $\theta_{c,eq}$ and is calculated from Eq.(1).

Table 2. Properties of post-fire RACFST column tests with square stainless steel tubes /5, 20/.

No	Specimen	B (mm)	t (mm)	L (mm)	r (%)	time (min)	f_y (MPa)	$f_{c,28}$ (MPa)	N_R (kN)	$N_{R,EC4}$ (kN)	$N_R/N_{R,EC4}$
1	S120-R0-T0	120.27	4.80	361	0	0	313.1	50.9	1405.1	1317.6	1.07
2	S120-R0-T15	120.49	4.82	359	0	15	313.1	50.9	1471.3	1169.3	1.26
3	S120-R0-T30	120.31	4.81	358	0	30	313.1	50.9	1394.9	1029.4	1.36
4	S120-R0-T45	120.72	4.84	360	0	45	313.1	50.9	1149.9	892.1	1.29
5	S120-R35-T0	120.21	4.81	360	35	0	313.1	44.3	1346.3	1237.0	1.09
6	S120-R35-T15	120.75	4.78	358	35	15	313.1	44.3	1391.7	1104.9	1.26
7	S120-R35-T30	120.48	5.05	359	35	30	313.1	44.3	1365.6	1014.9	1.35
8	S120-R35-T45	120.77	5.06	359	35	45	313.1	44.3	1104.3	887.2	1.24
9	S120-R70-T0	120.60	4.81	359	70	0	313.1	36.7	1305.1	1149.5	1.14
10	S120-R70-T15	120.58	4.73	360	70	15	313.1	36.7	1315.7	1022.5	1.29
11	S120-R70-T30	120.13	4.80	358	70	30	313.1	36.7	1222.2	926.2	1.32
12	S120-R70-T45	120.84	4.81	360	70	45	313.1	36.7	1034.9	821.1	1.26
13	S100-R0-T0	100.04	2.79	1199	0	0	314.2	50.9	751.4	716.2	1.05

14	S100-R0-T15	100.28	2.80	1200	0	15	314.2	50.9	694.6	584.7	1.19
15	S100-R0-T30	100.23	2.86	1200	0	30	314.2	50.9	581.1	493.2	1.18
16	S100-R0-T45	100.02	2.81	1201	0	45	314.2	50.9	395.1	402.1	0.98
17	S100-R35-T0	100.79	2.85	1200	35	0	314.2	44.3	712.8	681.9	1.05
18	S100-R35-T15	100.21	2.88	1200	35	15	314.2	44.3	643.9	558.7	1.15
19	S100-R35-T30	100.12	2.78	1200	35	30	314.2	44.3	552.6	462.0	1.20
20	S100-R35-T45	100.03	2.78	1201	35	45	314.2	44.3	369.2	386.0	0.96
21	S100-R70-T0	100.40	2.84	1200	70	0	314.2	36.7	638.3	618.5	1.03
22	S100-R70-T15	100.54	2.83	1200	70	15	314.2	36.7	608.4	517.9	1.17
23	S100-R70-T30	100.35	2.81	1200	70	30	314.2	36.7	499.8	441.8	1.13
24	S100-R70-T45	100.49	2.79	1199	70	45	314.2	36.7	358.7	375.2	0.96

Table 3. Properties of post-fire RACFST column tests with circular stainless steel tubes /6, 21/.

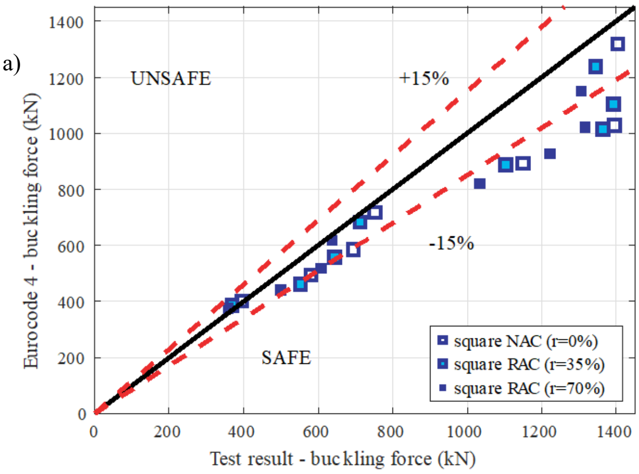
No	Specimen	D (mm)	t (mm)	L (mm)	r (%)	time (min)	f_y (MPa)	$f_{c,28}$ (MPa)	N_R (kN)	$N_{R,\text{EC4}}$ (kN)	$N_R/N_{R,\text{EC4}}$
1	D127-R0-T0	127.58	2.90	380.8	0	0	298.1	48.2	1095.1	1110.4	0.99
2	D127-R0-T15	127.64	2.84	381.2	0	15	298.1	48.2	1203.3	973.9	1.24
3	D127-R0-T30	127.50	2.98	383.0	0	30	298.1	48.2	1174.6	880.7	1.33
4	D127-R0-T45	127.64	2.80	381.3	0	45	298.1	48.2	946.8	732.6	1.29
5	D127-R35-T0	127.07	2.92	380.7	35	0	298.1	42.5	1020.8	1042.7	0.98
6	D127-R35-T15	127.50	2.83	382.4	35	15	298.1	42.5	1128.7	918.6	1.23
7	D127-R35-T30	127.54	3.00	381.6	35	30	298.1	42.5	1046.8	847.2	1.24
8	D127-R35-T45	127.44	2.99	382.2	35	45	298.1	42.5	907.7	735.0	1.23
9	D127-R70-T0	127.75	3.00	380.9	70	0	298.1	34.7	984.2	977.5	1.01
10	D127-R70-T15	127.41	2.83	383.3	70	15	298.1	34.7	1080.5	847.4	1.28
11	D127-R70-T30	127.45	3.11	380.5	70	30	298.1	34.7	987.7	813.7	1.21
12	D127-R70-T45	127.48	3.10	381.7	70	45	298.1	34.7	838.4	717.8	1.17
13	D101-R0-T0	100.81	2.78	1200	0	0	315.3	48.2	535.3	536.5	1.00
14	D101-R0-T15	100.93	2.75	1200	0	15	315.3	48.2	503.2	440.9	1.14
15	D101-R0-T30	100.78	2.77	1199	0	30	315.3	48.2	425.2	365.6	1.16
16	D101-R0-T45	100.81	2.81	1202	0	45	315.3	48.2	425.2	309.0	0.95
17	D101-R35-T0	100.81	2.84	1200	35	0	315.3	42.5	502.0	506.5	0.99
18	D101-R35-T15	101.06	2.83	1199	35	15	315.3	42.5	484.6	422.9	1.15
19	D101-R35-T30	100.80	2.84	1200	35	30	315.3	42.5	388.7	357.2	1.09
20	D101-R35-T45	100.77	2.80	1201	35	45	315.3	42.5	281.6	299.2	0.94
21	D101-R70-T0	100.97	2.76	1199	70	0	315.3	34.7	465.1	457.3	1.02
22	D101-R70-T15	100.84	2.75	1204	70	15	315.3	34.7	429.4	381.2	1.13
23	D101-R70-T30	100.90	2.78	1200	70	30	315.3	34.7	368.3	333.3	1.10
24	D101-R70-T45	100.94	2.81	1200	70	45	315.3	34.7	256.8	289.0	0.89

In the past, there were several studies that investigated residual properties of steel /32-35/. According to these studies, steel mostly fully recovers (after cool-down) if being exposed to temperatures below 400 °C or 500 °C, depending on the model. For higher temperatures, material properties reduce. In this study, for stainless steel tube samples, the adopted retention factors follow the study by Molkens et al. /35/, while for carbon steel tube (section 4), these factors are taken from /34/. As for concrete, in this section, the maximal temperature that steel is being exposed to, $\theta_{a,eq}$, is calculated following Eq.(2). This way calculated axial capacity is denoted as $N_{R,\text{EC4}}$.

The dataset used for validation of the proposed method consists of a total of 48 stainless steel tube samples from studies /5, 6, 20, 21/. Here, the measured post-fire axial capacity is denoted as N_R. Details about columns with square cross section and circular cross section are provided in Tables 2 and 3, respectively. The calculated axial capacity is shown in the last columns of Tables 2 and 3.

Figure 3 shows the comparison between experimental results and results obtained by Eurocode 4 for the post-fire axial capacity. It is clear that the predictions of Eurocode 4 are very close to experimental results, and again, all three criteria adopted by the CEN/TC250/SC4 Horizontal Group Fire are fulfilled. The mean value of the ratio $N_R/N_{R,\text{EC4}}$ for square specimens is 1.16 with standard deviation 0.12, while these values for circular specimens are 1.11 (mean) and 0.12 (standard deviation). For the whole group of 48 specimens, the mean value is 1.14 (standard deviation 0.12).

a)



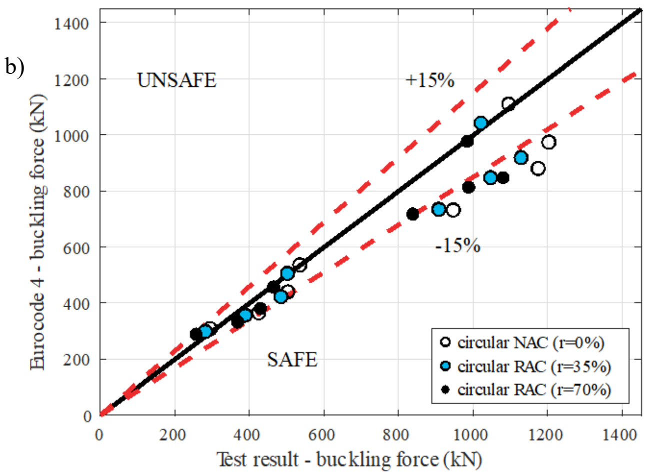


Figure 3. Comparison between experimentally obtained post-fire buckling force and prediction of EC4: a) square specimens; and b) circular specimens.

To summarise, the prediction of post-fire axial capacity of RACFST columns under fire conditions determined following the presented method are of acceptable accuracy and on the safe side. Therefore, under the limitations of fire duration of up to 45 min and exposure to ISO 834 heating curve, it is safe to conclude that the application of this method can be recommended to RACFST columns, in the absence of other specific design guidelines.

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

Development of RACFST columns is motivated by the aim of reducing the use of natural aggregates and increasing the recycling of construction waste. In this section, the evaluation of this solution compared to traditional RC columns from a sustainability perspective, particularly concerning fire, is performed. Following the conclusions from previous analysis and other studies /2/, we adopt that the same design procedures of CFST sections are applicable to RACFST sections. Firstly, the fire resistance of RC and RACFST sections is compared, followed by a comparison of their post-fire axial capacity.

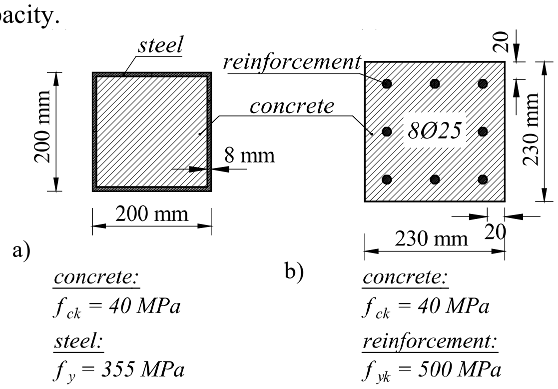


Figure 4. Geometrical and material properties of selected sections: a) RACFST section; and b) RC section.

One of the reasons for the increasing use of CFST columns in high-rise buildings is their high capacity. In these members, the steel tube positioned at the perimeter of the section enhances the column's load-carrying capacity and reduces the size of the required cross-section, providing savings in space and material. To illustrate this, two cross-sections from Fig. 4 are compared.

The first section is a square RACFST section with geometrical properties given in Fig. 4a. Concrete with f_{ck} = 40 MPa and steel tube with f_y = 355 MPa are selected. For this section, the ultimate axial force-bending moment interaction curve N-M, at reference temperature, is shown in Fig. 5 (compression is shown as positive). The curve is constructed using the material models from EC4, /36/.

For the equivalent square RC section with the same concrete material properties (f_{ck} = 40 MPa) and similar section capacity, the section from Fig. 4b is selected. This section is reinforced with 8 ϕ25 reinforcement bars with f_y = 355 MPa. For this section, the corresponding N-M interaction curve at reference temperature is also shown in Fig. 5 (constructed using material properties defined by EC2 /37/). Obviously, the capacities of the two sections are not completely equal: the axial capacity of RC section is about 11 % higher than that of the RACFST section. On the other hand, the maximal bending capacity of RACFST section is about 10 % higher than the corresponding capacity of the selected RC section. However, despite these differences, the two sections are considered to have comparable overall capacity. Here, the area of concrete part of RACFST section, $A_{c,\text{RACFST}}$ and the area of RC section, $A_{c,\text{RC}}$ are given by Eqs.(14) and (15):

$$A_{c,\text{RACFST}} = (20 - 2\cdot 0.8)^2 = 338.56 \text{ cm}^2 , \quad (14)$$

$$A_{c,\text{RC}} = 23^2 = 529 \text{ cm}^2 . \quad (15)$$

Therefore, the RC section has a 56 % larger concrete area compared to concrete core area in the RACFST section. Thus, from the perspective of natural aggregate consumption, this represents significant savings.

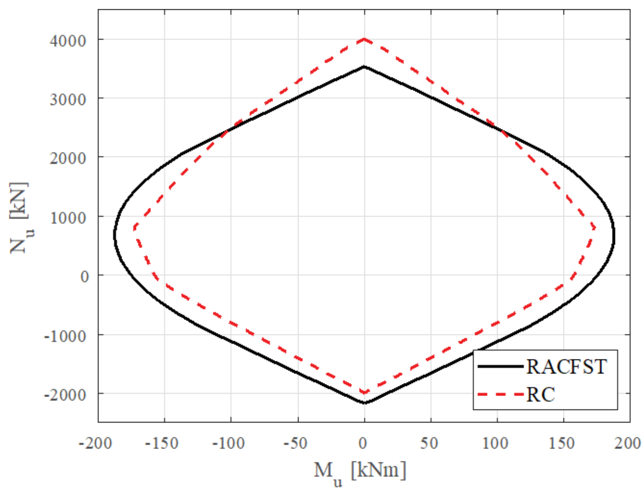


Figure 5. Axial force-bending moment interaction curves for RACFST and RC sections from Fig. 4, at reference temperature.

To evaluate the capacity of these sections under fire conditions, the N-M interaction curves for different durations of heating, according to the ISO 834 heating curve, are constructed. These interaction curves are constructed following a similar numerical procedure for both sections. In the first step, the thermal analysis for the specified fire duration is performed according to the 2nd generation Eurocode 2 and Eurocode 4, Part 1-2 fire design guides /27, 38/. As a result, the temperature distribution over the cross-section is obtained. In the next step, the fibre section analysis is performed. The section is discretised into fibres, and temperature-dependent material properties of corresponding material are assigned to each fibre. These temperature-dependent material properties are adopted from /27, 38/. Finally, following the procedure denoted as 'exact' in Fib bulletin 46, chapter 3 /39/, the section N-M interaction curve for the specified fire duration is calculated.

For verification of the performed analysis on the RC section, a different cross section from Fig. 6 is analysed. It is a square 300 mm × 300 mm section, with 4 ϕ16 reinforcement bars, with the distance from the centroid of the bar to the closest surface equal to 38 mm (net concrete cover is 30 mm). This section is previously analysed in /39/. Concrete compressive strength is f_{ck} = 30 MPa, and yield stress of the reinforcement is f_{yk} = 500 MPa.

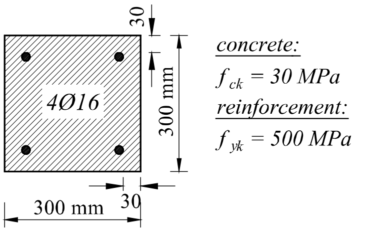


Figure 6. RC section /39/ for validation of numerical procedure.

For this section, Fig. 6, Fig. 7 shows the comparison of temperature distributions obtained by heat transfer analysis from this study and distributions from the Annex of Eurocode 2 /40/ for heating durations of 30 and 60 min. Figure 8 shows the comparison between N-M interaction curves obtained in this study and curves from /39/. It can be seen that both temperature distributions and interaction diagrams agree very well. For RACFST sections, the numerical procedure for determining the temperature-dependent yield curves is verified in /41/.

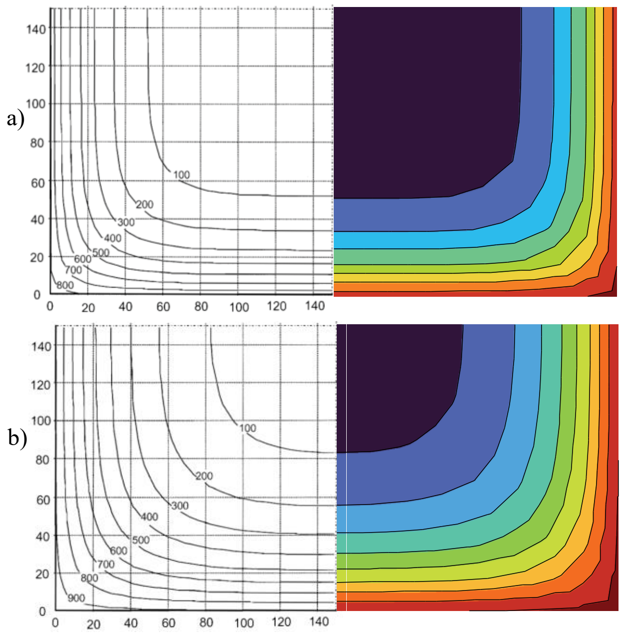


Figure 7. Comparison of temperature distributions from this study with EC2 for square 300 mm × 300 mm section subjected to ISO 834 heating for: a) 30 min; and b) 60 min.

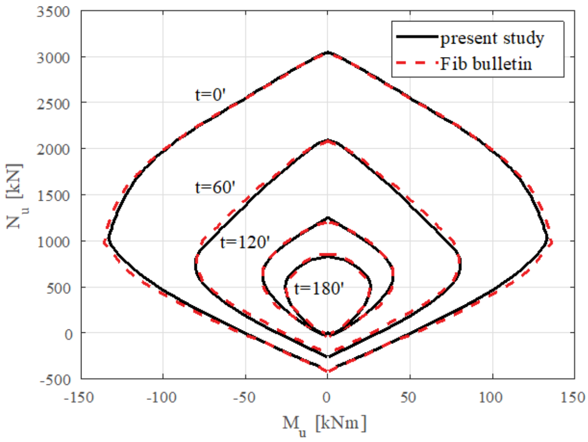


Figure 8. Comparison between N-M interaction curves from this study with results from /39/ for square 300 mm × 300 mm section subjected to ISO 834 heating curve for 0, 60, 120, and 180 min.

Therefore, applying the previously verified procedure, the sections from Fig. 4 are analysed. Figure 9 shows the N-M interaction curves for these two selected sections and different durations of 4-side exposure to ISO 834 heating. Obviously, under these conditions, the position of the steel tube in the RACFST section with direct exposure to heating results in a rapid reduction of section capacity.

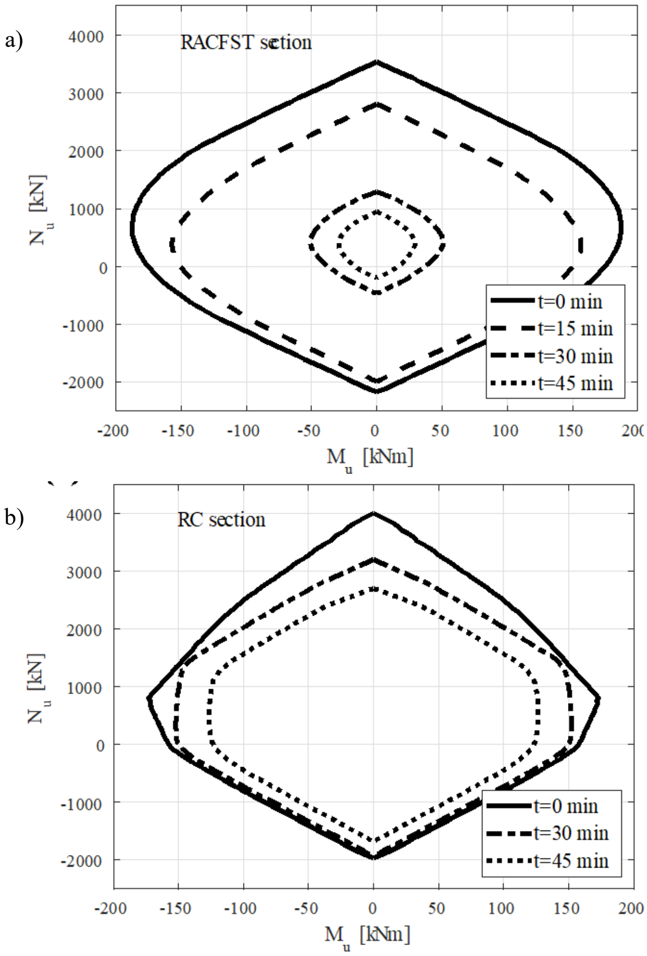


Figure 9. Axial force-bending moment interaction curves for different durations of ISO 834 heating: a) RACFST 200×200×8 section; and b) RC 230×230 section.

Consequently, after only 15 min. of fire duration, the capacity is reduced by approximately 20 %, while after 30 min. of fire duration, its capacity represents only 40 % of the capacity at reference temperature. On the other hand, the protection of reinforcement bars by concrete cover and their position within the concrete part of the RC section results in a more gradual reduction of section capacity in this case. Consequently, the capacity of the RC section after 30 min. reduces by approximately 20 % and is similar to the capacity of the RACFST section after 15 min.

Furthermore, after 45 min. of heating, the capacity of the RC section reduces to approximately 70 % of capacity at reference temperatures. Therefore, unprotected RACFST sections are more vulnerable to fire conditions than RC sections. However, previous experimental and numerical investigations have proven that the fire resistance of CFST columns significantly improves by applying appropriate fire protection measures /42, 43/. It has been shown that these can extend fire resistance from 1 h to 3 h, depending on the thickness and properties of the fire protection. With this in mind, we can conclude that RACFST columns represent a sustainable alternative to traditional RC columns with significant savings in the consumption of natural aggregates, especially considering that steel tubes can be reused from dismantled existing structures.

It should be noted that the savings offered by RACFST column solutions extend beyond merely reducing the amount of concrete required through decreased cross-section sizes and improved bearing capacity /44/. Additionally, the smaller dimensions of RACFST columns create larger usable interior spaces and free up building area, providing significant architectural, economic, and societal benefits.

Furthermore, RACFST columns enhance construction efficiency by accelerating the building process, as they eliminate the need for traditional formwork. During construction, steel tubes alone can withstand loads if cast in situ prior to concrete reaching its full strength, increasing workflow and reducing labour and material costs.

Connections of RACFST columns with other structural elements, as beams and footings, are designed similarly to steel structures. This approach allows for easily mountable and demountable connections, increasing their reusability and supporting sustainable construction practices.

Finally, the last part of this study investigates the post-fire axial capacity of two selected cross sections from Fig. 4. The sections are considered to be exposed to 4-sided heating in accordance with ISO 834 heating curve for different durations (15, 30, 45, and 60 min) and then cooled down to reference temperature. For the RACFST section, this capacity is determined following the method from section 3 for a stub column when all second-order effects are neglected. Since the steel tube is now considered to be made of carbon steel, the steel retention factors are taken from /34/. Here, two methods are applied. In the first method, the residual capacity is determined using the temperature distribution over the cross-section from the previously described thermal analysis. Next, the cross-section is discretised into fibres, and the post-fire strength of the corresponding material (steel or concrete) is assigned to each fibre. Finally, the residual axial capacity is determined from the fibre section analysis. In the second case, the procedure is simplified excluding the thermal analysis and using equivalent temperatures from Eqs.(1)-(2) as maximal temperatures in concrete and steel parts of the section, respectively. Then, the residual axial capacity is calculated applying the material retention factors according to these temperatures.

For the RC section, there is still no consensus regarding the calculation of residual section capacity /45-47/. Here, we follow the method proposed by Kodur et al. /45/, based on application of the 500 °C isotherm method. It is assumed that only concrete within the isotherm of 500 °C has post-fire strength, while concrete outside of this isotherm is neglected. Residual strength of concrete is calculated from Eqs.(10)-(13), while residual strength of reinforcement is assumed to follow /48/. The isotherm at 500 °C is determined from the previously described thermal analysis. In the next step, again, the fibre section analysis is performed to obtain the residual post-fire section axial capacity.

Table 4. Post-fire axial capacity for 2 analysed sections from Fig. 4.

Fire duration (min)	Post-fire axial capacity (kN)		
	CFST section		RC section
	Method 1	Method 2	
0	3535.4	3535.4	3921.5
15	3424.3	3431.5	3460.7
30	2824.7	2805.3	3213.6
45	2404.1	2446.7	3002.3
60	2167.5	2216.3	2706.2

NOTE: Method 1 - using thermal analysis
Method 2 - using equivalent temperatures

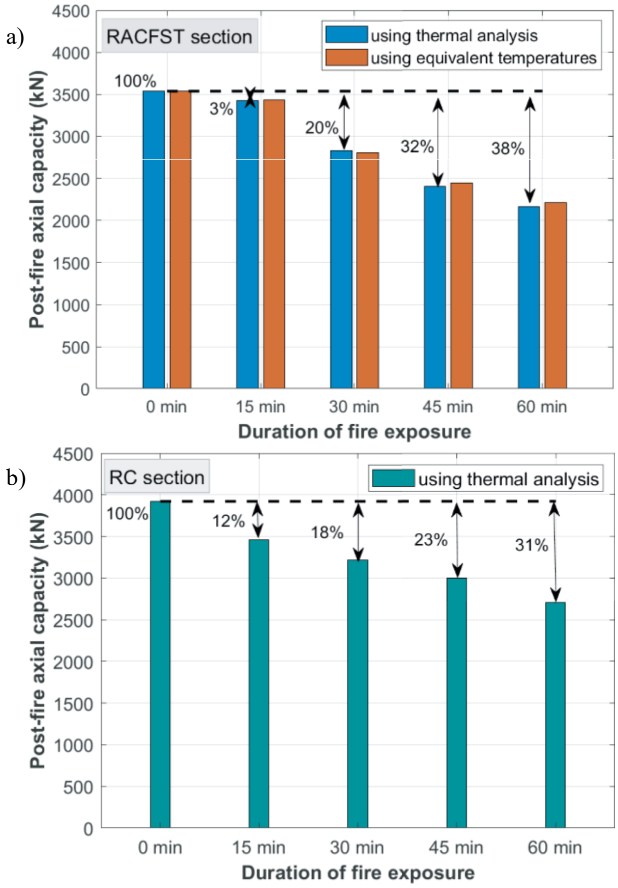


Figure 10. Post-fire axial capacity: a) RACFST; and b) RC section.

Table 4 shows numerical results obtained for residual post-fire axial capacity, while Fig. 10 depicts them graphically. The difference between the two methods for calculating RACFST residual capacity is very small (below 2.5 %), which implies that the simplified procedure with equivalent temperatures can be used. Due to the capability of steel to fully recover strength after cooling when exposed to lower maximal temperatures (up to 600 °C), the reduction of post-fire axial capacity of the RACFST section is smaller than that of the RC section for a fire duration of 15 min. For a fire duration of 30 min., the steel tube reaches temperatures of up to 700 °C, resulting in a higher capacity reduction that becomes almost equal to the reduction of the RC section. For longer fire durations (45 and 60 min), the reduction of the post-fire axial capacity of the RACFST section becomes larger than that of the equivalent RC section but remains comparable. However, as noted regarding the fire capacity of RACFST columns, applying adequate insulation on the RACFST member reduces the maximum temperature in the steel tube and concrete, leading to a decrease in axial capacity reduction.

CONCLUSIONS

The study analyses the behaviour of RACFST columns under fire conditions, focusing on both their fire and post-fire resistance. Currently, no specific design guidelines exist for calculating the fire capacity of RACFST columns. Therefore, this research evaluates the applicability of the simplified analysis method proposed by 2nd generation of Eurocode 4 for these calculations. Additionally, the procedure that follows this design code for calculating the columns' post-fire capacity is also presented and validated using experimental test results available in literature. Key findings are:

- The simplified analysis method from 2nd generation of Eurocode 4 and the proposed method for calculating the post-fire capacity provide accurate and conservative predictions for fire and post-fire capacities of RACFST columns.
- Validation is currently limited to standard fire exposure (ISO 834) and fire durations up to 45 min, indicating the need for further research under prolonged fire scenarios.
- Compared to traditional reinforced concrete columns of similar ambient capacity, RACFST columns require significantly smaller cross-sections, highlighting their material efficiency and environmental benefits. When additional known advantages such as increased load-bearing capacity, enhanced construction efficiency, larger usable interior spaces, and compatibility with demountable connections are considered, the sustainability potential of RACFST columns is substantial.
- In fire conditions, RACFST columns are more vulnerable than RC columns due to the exposed steel tube, leading to faster strength degradation; however, this can be mitigated with appropriate insulation measures.
- Post-fire behaviour is comparable between RACFST and RC columns, with RACFST showing slight advantages for fire durations up to 30 min. and RC performing slightly better for longer exposures.

In summary, it can be concluded that RACFST columns represent a promising sustainable alternative to conventional RC column solutions. To enhance their fire performance, implementing effective insulation measures is essential.

ACKNOWLEDGEMENTS

The first and the third author thank the Ministry of Science, Technological Development and Innovation, Republic of Serbia, for support through the project number 200092. The second author thanks the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for financial support via a Ph.D. student stipend.

REFERENCES

1. Nikolić, J., Kostić, S., M., Stošić, S. (2023), *Numerical modelling of concrete-filled steel tubular short columns under axial compression*, Build. Mater. Struct. 66(2): 93-106. doi: 10.5937/GRMK2300004N
2. Nikolić, J., Tošić, N., Murcia-Delso, J., Kostić, S.M. (2024), *Comprehensive review of the structural behaviour and numerical modelling of recycled aggregate concrete-filled steel tubes*, Eng. Struct. 303: 117514. doi: 10.1016/j.engstruct.2024.117514
3. Shintani, Y., Nishimura, T., Okazaki, T., et al. (2021), *Experimental study on the fire resistance of unprotected concrete-filled steel tubular columns under multi-loading*, Fire Safety J, 120: 103174. doi: 10.1016/j.firesaf.2020.103174
4. Han, L.-H., Xu, C.-Y., Tao, Z. (2019), *Performance of concrete filled stainless steel tubular (CFSST) columns and joints: Summary of recent research*, J Constr. Steel Res. 152: 117-131. doi: 10.1016/j.jcsr.2018.02.038
5. Wang, Z., Zhong, Y., Jiang, K., et al. (2024), *Post-fire behaviour and resistances of square recycled aggregate concrete-filled stainless steel tube stub columns*, Thin-Walled Struct. 197: 111564. doi: 10.1016/j.tws.2024.111564
6. Wang, Z., Zhong, Y., Zhao, O. (2024), *Circular recycled aggregate concrete-filled stainless steel tube stub columns after exposure to fire: Experiments, simulations, and design*, Eng. Struct. 302: 117418. doi: 10.1016/j.engstruct.2023.117418
7. Jia, Q., Xiao, L., Liu, H., et al. (2025), *Post-fire compressive performance of basalt fiber recycled aggregate concrete filled steel tube*, J Constr. Steel Res. 224(Part A): 109164. doi: 10.1016/j.jcsr.2024.109164
8. Liu, Y., Liu, J., Liu, X., Zhang, C. (2025), *Axial compressive behavior of stone encased concrete-filled square steel tube stub columns*, J Constr. Steel Res. 224: 109134. doi: 10.1016/j.jcsr.2024.109134
9. Wang, J., Duan, Y., Lyu, X., et al. (2024), *Axial compression behavior of coal gangue coarse aggregate concrete-filled steel tube stub columns*, J Constr. Steel Res. 215: 108534. doi: 10.1016/j.jcsr.2024.108534
10. Mujdeci, A., Guo, Y.T., Bompa, D.V., Elghazouli, A.Y. (2022), *Axial and bending behaviour of steel tubes infilled with rubberised concrete*, Thin-Walled Struct. 181: 110125. doi: 10.1016/j.tws.2022.110125
11. Shah, S.M.I., Ganesh, G.M. (2023), *Micro-steel fiber-reinforced self-compacting concrete-filled steel-tube columns subjected to axial compression*, Int. J Steel Struct. 23(4): 1031-1045. doi: 10.1007/s13296-023-00747-x
12. Liu, B., Zhang, L., Feng, M., et al. (2023), *Experimental study of rubber-concrete-filled CST composite column under axial compression*, Int. J Steel Struct. 23(1): 247-262. doi: 10.1007/s13296-022-00692-1
13. Tošić, N., Torrenti, J.M., Sedran, T., Ignjatović, I. (2021), *Toward a codified design of recycled aggregate concrete structures: Background for the new fib Model Code 2020 and Eurocode 2*, Struct. Concr. 22(5): 2916-2938. doi: 10.1002/suco.202000512

14. Savić, A.R.. Terzić, A., Broćeta, G., et al. (2025), *Rheological and mechanical behaviour of self-compacting concrete with modified recycled concrete aggregate*, Struct. Integr. Life 25(2): 169-180. doi: 10.69644/ivk-2025-02-0169
15. Terrones, J.G.S., Martínez, J.A.A. (2025), *Study on the influence of applied biochar on the properties of concrete*, Struct. Integr. Life, 25(2): 301-309. doi: 10.69644/ivk-2025-02-0301
16. European Committee for Standardization, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, bridges and civil engineering structures, 2021.
17. Yang, Y.-F., Zhang, L., Dai, X. (2017), *Performance of recycled aggregate concrete-filled square steel tubular columns exposed to fire*, Adv. Struct. Eng. 20(9): 1340-1356. doi: 10.1177/1369433216677603
18. Liu, W., Cao, W., Zhang, J., et al. (2017), *Mechanical behavior of recycled aggregate concrete-filled steel tubular columns before and after fire*, Mater. 10(3): 274. doi: 10.3390/ma10030274
19. Zhao, H., Wang, Z., Zhang, W., et al. (2024), *Performance of round-ended recycled aggregate CFST stub columns after fire exposure*, J Constr. Steel Res. 212: 108311. doi: 10.1016/j.jcsr.2023.108311
20. Wang, Z., Zhong, Y., Su, A., et al. (2024), *Post-fire flexural buckling and resistances of square recycled aggregate concrete-filled stainless steel tube (RACFSST) columns*, Thin-Walled Struct. 205(Part A): 112490. doi: 10.1016/j.tws.2024.112490
21. Wang, Z., Zhong, Y., Liang, Y., Zhao, O. (2025), *Global buckling and residual capacities of circular recycled aggregate concrete-filled stainless steel tube (RACFSST) columns after exposure to fire*, Eng. Struct. 322(Part B): 119166. doi: 10.1016/j.engstruct.2024.119166
22. Song, T.-Y., Qu, X.-Y., Pan, Z., et al. (2022), *Fire resistance tests on concrete-filled steel tubular columns with geopolymeric recycled aggregate*. Fire Technol. 58(5): 2727-2754. doi: 10.1007/s10694-022-01271-w
23. ISO 834-1:2025 Fire-resistance tests - Elements of building construction. Part 1: General requirements
24. Li, W., Zhiyu, Luo, Z., Tao, Z., et al. (2017), *Mechanical behavior of recycled aggregate concrete-filled steel tube stub columns after exposure to elevated temperatures*, Constr. Build. Mater. 146: 571-581. doi: 10.1016/j.conbuildmat.2017.04.118
25. Yang, Y.F., Hou, R. (2012), *Experimental behaviour of RACFST stub columns after exposed to high temperatures*, Thin-Walled Struct. 59: 1-10. doi: 10.1016/j.tws.2012.04.017
26. European Committee for Standardization, Eurocode 4: Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design, 2008.
27. European Committee for Standardization, Eurocode 4: Design of composite steel and concrete structures - Part 1-2: General rules - Structural fire design, 2021.
28. Albero, V., Espinos, A., Romero, M.L., et al. (2016), *Proposal of a new method in EN1994-1-2 for the fire design of concrete-filled steel tubular columns*, Eng. Struct. 128: 237-255. doi: 10.1016/j.engstruct.2016.09.037
29. Tkalenko, I., Tretyakov, A., Wald, F. (2023), *Analytical model for steel fibre-reinforced concrete-filled tubular columns exposed to fire*, Eur. J Eng. Technol. Res. 8(1): 66-74. doi: 10.24018/ejeng.2023.8.1.2966
30. European Committee for Standardization, Eurocode 3: Design of steel structures - Part 1-1: General rules and rules for buildings, 1992.
31. Medall, D., Ibáñez, C., Albero, V., et al. (2023), *Experimental residual capacity of steel-reinforced concrete-filled steel tubular stub columns after fire exposure*, Thin-Walled Struct. 189: 110900. doi: 10.1016/j.tws.2023.110900
32. Tao, Z., Wang, X.-Q., Uy, B. (2013), *Stress-strain curves of structural and reinforcing steels after exposure to elevated temperatures*, J Mater. Civ. Eng. 25(9): 1306-1316. doi: 10.1061/(ASCE)MT.1943-5533.0000676
33. Gao, X., Zhang, X., Liu, H., et al. (2018), *Residual mechanical properties of stainless steels S30408 and S31608 after fire exposure*, Constr. Build. Mater. 165: 82-92. doi: 10.1016/j.conbuildmat.2018.01.020
34. Molkens, T., Cashell, KA., Rossi, B. (2021), *Post-fire mechanical properties of carbon steel and safety factors for the reinstatement of steel structures*, Eng. Struct. 234: 111975. doi: 10.1016/j.engstruct.2021.111975
35. Molkens, T., Cashell, K.A., Malaska, M., et al. (2021), *Performance of structural stainless steel following a fire*, Eng. Struct. 235: 112001. doi: 10.1016/j.engstruct.2021.112001
36. European Committee for Standardization, Eurocode 4: Design of composite steel and concrete structures - Part 1.1: General rules and rules for buildings, 2004.
37. European Committee for Standardization, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings, 2004.
38. European Committee for Standardization, Eurocode 2 - Design of concrete structures - Part 1-2: Structural fire design, 2023.
39. fib Bulletin No.46, Fire design of concrete structures - structural behaviour and assessment. State-of-the-art report. International Federation for Structural Concrete, 2008.
40. European Committee for Standardization, Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design, 2004.
41. Bursać, M., Kostić, S.M. (2025), *Nonlinear analysis of elliptical CFST columns at ambient and elevated temperatures*, J Constr. Steel Res. 229: 109491. doi: 10.1016/j.jcsr.2025.109491
42. Han, L.-H., Yamg, Y.-F., Xu, L (2003), *An experimental study and calculation on the fire resistance of concrete-filled SHS and RHS columns*, J Constr. Steel Res. 59(4): 427-452. doi: 10.1016/S0143-974X(02)00041-X
43. Wang, J.H., He, J., Xiao, Y. (2019), *Fire behavior and performance of concrete-filled steel tubular columns: Review and discussion*, J Constr. Steel Res. 157: 19-31. doi: 10.1016/j.jcsr.2019.02.012
44. Thai, S., Thai, H.-T., Uy, B., Ngo, T. (2019), *Concrete-filled steel tubular columns: Test database, design and calibration*, J Constr. Steel Res. 157: 161-181. doi: 10.1016/j.jcsr.2019.02.024
45. Kodur, V.K.R., Raut, N.K., Mao, X.Y., Khaliq, W. (2013), *Simplified approach for evaluating residual strength of fire-exposed reinforced concrete columns*, Mater. Struct. 46(12): 2059-2075. doi: 10.1617/s11527-013-0036-2
46. Peña, D.L., Albero, V., Ibáñez, C., Hospitaler, A. (2021), *Sectional model for the fire evaluation of reinforced concrete columns subjected to biaxial bending*, Eng. Struct. 247: 113094. doi: 10.1016/j.engstruct.2021.113094
47. Jovanović, B., Caspeele, R., Reynders, E., et al. (2024), *Bayesian updating methodology for the post-fire evaluation of the maximum temperature profile inside concrete elements*, Fire Technol. 60(3): 2155-2175. doi: 10.1007/s10694-024-01564-2
48. Neves, I.C., Rodrigues, J.P.C., de Pádua Loureiro, A. (1996), *Mechanical properties of reinforcing and prestressing steels after heating*, J Mater. Civ. Eng. 8(4): 189-194. doi: 10.1061/(ASCE)0899-1561(1996)8:4(189)