Fire Technology

Manufactured in The United States
https://doi.org/10.1007/s10694-024-01567-z

A Simplified Method for Determining Fire Resistance of RC Columns Using Fire-Resistance-Column-Curves Approach

*Khaled Ahmed Mahmoud**, *Civil Engineering Department, Faculty of Engineering, Assiut University, Assiut 71518, Egypt*

Received: 7 October 2022/**Accepted:** 10 February 2024

Abstract. Eurocode-2 (EC2) empirical equation for fire resistance of RC columns is very sensitive to the value of column capacity at normal temperature conditions N_{Rd}. Techniques to determine N_{Rd} accurately for eccentric slender columns are difficult and computationally demanding; thus, adopting simplifications leads to unsatisfactory results in many column cases. Another shortcoming of EC2 equation is that it does not include an explicit term regarding the effect of load eccentricity on fire resistance. In this paper, a simplified method, as an attempt to overcome EC2 method defects, is developed to determine the fire resistance of RC columns using fire-resistance-column-curves. A rational numerical model is used to analyze various series of RC columns with different geometric, material, and loading properties at elevated temperatures. The results of the numerical study are utilized to construct different fire-resistance-column-curves from which simplified design equations are developed to predict the fire resistance of fixed- and pinned-end RC columns. The validity of the method is established with the aid of experimental data and it was found that in most cases, there is good agreement between assessed and test columns. It was also found that the proposed equations provide sufficiently safe predictions when appropriate material safety factors are adopted. The applicability of the proposed method to fire resistance design of RC columns is illustrated through numerical examples.

Keywords: Fire resistance, Column curves, Simplified method, RC column

List of Symbols

a	The distance between the center point of steel rebar and the nearest exposed surface [mm]
$b_1 \times b_2$	Cross-section dimensions [mm]
C	Concrete cover thickness [mm]
$N_{Ed,fi}$	Design axial load in the fire situation [kN]
$N^0_{Rd,\lambda^{\min}}$	Design resistance at normal temperature condition (at zero eccentricity and minimum slenderness ratio $\lambda^{\min}$) [kN]
$N_{Rd,\lambda^{\min}}$	Design resistance of the column at normal temperature condition (at an eccentricity e and minimum slenderness ratio) [kN]

* Correspondence should be addressed to: Khaled Ahmed Mahmoud, E-mail: kama_elsadek@yahoo.com

Published online: 06 May 2024

e	Load eccentricity [mm]
f'_c	Concrete compressive strength [MPa]
f_{cd}	Design compressive strength of concrete [MPa]
f_{ck}	Characteristic compressive strength of concrete [MPa]
f_{cm}	Mean compressive strength of concrete [MPa]
f_y	Steel yield strength [MPa]
f_{yd}	Design yield strength of steel [MPa]
f_{yk}	Characteristic yield strength of steel [MPa]
k_e	Load eccentricity coefficient
L	Column length [m]
M	Bending moment [kN.m]
P	Axial load at failure [kN]
R_a	Fire rating for concrete cover thickness
R_b	Fire rating for column dimension
R_f	Fire resistance, design fire resistance [min]
$\overline{R}_f$	Characteristic fire resistance [min]
$\overline{R}_f^0$	Characteristic fire resistance at zero eccentricity [min]
$R_{L\min}$	Fire rating for minimum effective length
R_n	Fire rating for reinforcing steel
$R_{\eta fi,\lambda^{\min}}$	Fire rating for load ratio at minimum slenderness ratio
r	Radius of gyration [mm

Greek Symbols

δ_0	Initial out-of-straightness [mm]
χ	Buckling coefficient, Buckling reduction factor
λ	Slenderness ratio
$\lambda_{\min}$	Minimum slenderness Ratio
λ_e:	Effective slenderness ratio ($\lambda_e = \lambda - 4.3$)
$\mu_{fi,\lambda^{\min}}$	Load ratio at $\lambda = 4.3$
ω	Mechanical reinforcement ratio at normal temperature conditions

1. Introduction

The provision for sufficient fire resistance for reinforced concrete columns is a fundamental subject in engineering design and is required by most building codes. This resistance to fire is determined primarily with the aid of performance of an isolated column subjected to a standard fire test. Although this fire test may not be representative of an actual fire, it is generally considered as being essential to provide a basis for comparison between different designs and to satisfy the need for reproducibility in test data. The considerable cost in conducting a standard fire test of even a simple column, however, led the researchers to develop thermo-mechanical models to predict analytically the behavior of reinforced concrete columns subjected to fire. Although these models are powerful tools for predicting accurately fire resistance of RC columns, they depend on computer programs, which in many cases are complex, required effort, and can not be implemented in design codes. In practice, designers require simpler methods, which are sufficiently accurate, to be applicable to the large variety of column problems.

When compared to other methods, simple calculation methods serve well in this subject. These simplified methods are based on theoretical and empirical equations, and consider the effects of various parameters on fire resistance. These equations are generally developed using data utilized from analytical and experimental analyses whereby the limited data are used to define empirical constants employed in the equations. These methods furnish a simple design basis not only for column problems in the available data range, but also for extrapolating, within reasonable limits, to situations that are not covered by the database.

Dotreppe et al. [1] proposed a theoretically equation-based method to calculate the ultimate capacity of RC columns at high temperatures. Their formula was developed later by Franssen and Dotreppe [2] to take into consideration the influences of smaller slenderness ratios λ and circular shape of the column on fire resistance. The basic equations of this method are expressed as follows:

$$N_u(t) = \gamma(t).\eta(\lambda)\,.\,P(t) \tag{1.a}$$

$$\eta(\lambda) = \frac{\chi(\lambda)}{\phi(\lambda)} \tag{1.b}$$

where $N_u(t)$ is the ultimate axial capacity at a fire duration t, $\gamma(t)$ and $\chi(\lambda)$ are spalling and buckling coefficients, and $\phi(\lambda)$ is a nonlinear amplification factor that accounts for load eccentricity. The fire resistance in this method can be obtained by performing an iterative process.

Regarding empirically equation-based methods, Franssen [3] suggested a simple equation, which has been later incorporated in Eurocode (EC2-1-2-2004) [4]. This method considers the fire resistance of columns R_f in terms of fire ratings as

$$R_f = 120.\left(\frac{R_{\eta fi} + R_a + R_L + R_b + R_n}{120}\right)^{1.8} \tag{2}$$

in which $R_{\eta fi}$, R_a, R_L, R_b, and R_n are the fire ratings values, which account for load ratio, concrete cover thickness, column length, cross-section size, and longitudinal reinforcement, respectively.

Another simple method, in the form of an empirical equation, was developed by Kodur and Raut [5] to evaluate fire resistance of RC columns. According to this method, the fire resistance R_f is expected as

$$R_f = C_t\left[8 \times k_{cp} \times k_{ec} \times (30 - (S_R + 5) \times (L_R - 0.2))\right]^{0.94} \tag{3}$$

where C_t is a constant that accounts for aggregate type,k_{cp} is a parameter that depends on the cover thickness and the percentage steel, k_{ec} is a factor that accounts for load eccentricity, load ratio L_R, and slenderness ratio S_R.

Although the authors [1–5] argued that these methods yield safe predictions, these equations still have some drawbacks. Buch and Sharma [6] observed that equations proposed by Refs. [4] and [5] give unsafe results for larger eccentricity values. In addition, fire resistances below 100 min predicted using EC2 equation are mostly unsafe. Moreover, Raut and Kodur equation [5] results in inaccurate predictions in the case of varying reinforcement configurations. In an investigation carried out by Mahmoud [7], similar observations have been indicated. He observed that the abovementioned three methods provide unsatisfactory predictions at certain column cases. In addition, predictions obtained from Ref. [1] are generally conservative. Moreover, equations proposed by Refs. [3] and [4] lead to unsafe results at higher eccentricities and higher load ratios. Furthermore, EC2 equation may provide unsafe predictions at medium and high slenderness ratios. In general, these methods proposed one equation that used at all end conditions in which the influence of end conditions is considered by multiplying the column length by the effective length factor at ambient temperature. However, a study conducted by Mahmoud [8] revealed that the value of effective length factor at high temperature is different from its value at ambient temperature. In addition, effective length factor depends on the slenderness ratio and load eccentricity.

The main contribution of this paper is that it proposes an alternative simple calculation method, which considers appropriate measures as an attempt to overcome the previous simplified methods limitations, to predict fire resistance of RC columns subjected to fire. Whereas previous studies on column fire resistance have focused on developing one empirically- or theoretically-based equation for pin-ended column in which the column length parameter is modified by multiplying by the effective length factor to account for fixed-end conditions; this paper pays attention to consider the effects of end conditions individually and, therefore, presents two different equations for pin-ended and fixed-end columns, which adds to the literature. Another important contribution is that this study is the first to use the concept of fire-resistance-column-curves in which all the influential parameters are related to the slenderness ratio to attain more logical predictions. The equations proposed in this paper are simple and can be safely used for every day design practice. Parametric studies are conducted using a rational numerical model; then, the obtained results are utilized to construct column curves for various parameters; consequently, two different equations are derived using curve-fitting technique. To improve the accuracy of the method, the column curve equation of pinned columns is modified by considering the experimental data. The validity of the method is established with the aid of experimental data obtained from literature. Finally, illustrative examples are presented to explain the applicability of the proposed method.

2. Fire Resistance Column Curves Method

The controversy about the existed simplified methods has always been rooted in the question of the proper representation of fire resistance of all column cases. One of the basic issues of these methods lies in the assumption that the utilized experimental and numerical data in deriving the simplified equations, which mostly based on results of medium length columns, is enough to provide accurate predictions for all column lengths.

In this context, column curves technique furnishes a rational tool to obtain reasonable predictions because these curves are constructed based on a wide range of column lengths. For simplicity, Fire Resistance Column Curves method used in the current study will be denoted FRCC method.

2.1. Concept of Fire Resistance Column Curves

For any RC column of specific geometric, material, and loading properties, and of specific end conditions, a unique fire-resistance-column-curve exists. This curve describes the relationship between fire resistance R_f and slenderness ratio λ; its shape is dependent on all parameters that affect fire resistance. Figure 1 shows two column curves for a RC column with pin-ended and fixed-end conditions. It can be noticed that as slenderness ratio decreases, fire resistance increases and the influence of end condition on fire resistance decreases until a certain value of λ is reached at which the effect of end condition diminishes. For RC columns, this value of λ was found about 4.3 [8]. This value of λ can be treated as the minimum slenderness ratio that affects fire resistance of RC columns and will be denoted by $\lambda^{\min}$. At $\lambda^{\min}$, fire resistance is maximum. It is a characteristic for a specific column since it is independent on the column end conditions. This characteristic fir resistance will be denoted by $\overline{R}_f$.

Experimental-related simplified approaches to determine fire resistance of RC columns have been shown to provide an unsatisfactorily and a much too simple column curves, which are generally described by first-order polynomial curves [7]. However, it would generally not be economical to test a sufficiently large number of columns to construct experimentally fire-resistance-column-curves for a spectrum of possible designs. The theoretically based methods thus provide more practicable means of studying the variation of fire resistance and of constructing the column curves.

2.2. Construction of Column Curves

Numerical analyses are carried out herein to construct fire-resistance-column-curves for different series of RC columns. The influential parameters that are taken into considerations are slenderness ratio, load eccentricity, initial imperfections, load ratio, column size, reinforcement ratio, and concrete cover thickness. Geometric, material, and loading properties of the analyzed column are listed in Table 1, 2, 3, 4, and 5. A two-dimensional heat and mass transfer model [9] was used to predict temperatures inside the columns at different fire exposure times. All columns were analyzed by exposing entire perimeter to ASTM-E119 [10] or ISO 834 [11] standard fire exposure. Concrete thermal conductivities proposed by ASCE manual [12] were used in the analysis. Other temperature dependent properties were considered based on the relationships presented in Eurocode 2 [4]. A rational numerical model [7, 13] was developed by the author and utilized to perform structural analysis. The main feature of the structural model is that it incorporates the nonlinear behavior of RC sections at high temperatures. In addition, the model adopts an iterative technique to obtain the strain distributions on the heated concrete section using Newton–Raphson method. Moreover, the model includes a simple and reliable methodology to determine the lateral deflection of

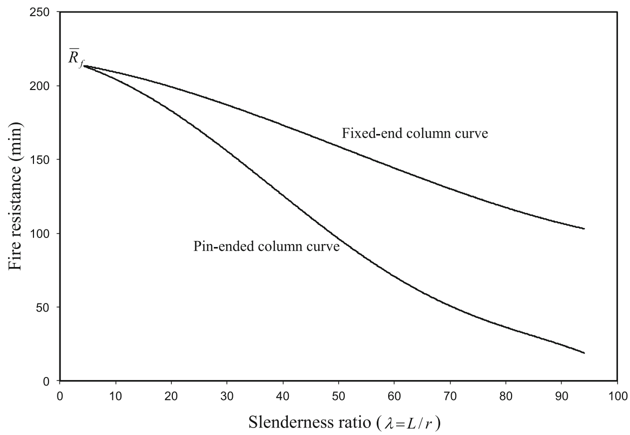

Figure 1. Schematic of two fire resistance column curves for fixed-end and pin-ended column.

RC columns with different rotational end restraint levels. Furthermore, the model considers material degradations due to elevated temperatures and takes into consideration different time-dependent effects, strain components, and the nonlinear responses of slender columns. Model output includes axial and lateral deformation, bending moment, slope, curvature, and stiffness distributions at different sections through the column length. In structural analysis, the column was divided into 20 segments through its length and each cross-section was further subdivided into 60 60 square elements.

The resulted fire resistances for various column series are listed in Table 1, 2, 3, 4, and 5. For comparison purposes, each column curve is plotted in terms of the nondimensional quantities $\frac{R_f}{\overline{R}_f}$ where $\overline{R}_f$ is the characteristic fire resistance corresponding to that curve. Figures 2 and 3, respectively, show the band of column curves that has been developed for the fixed-end and pin-ended columns. The width of the band is largest for the intermediate slenderness ratios, and tapers off towards the ends. For low slenderness ratios, the variation of the maximum fire resistance is influenced more by yielding and crushing than any other factor.

It should be noted that the best solution is that one whereby every column could be represented by its own fire resistance curve. However, this would complicate the method in that the practical advantages might be lost. The suitable number of column curves therefore should be such that an optimum of rationale and practicality can be achieved.

It can be observed from Figures 2 and 3 that the number and the density of the curves between the upper and lower limits prevent a meaningful illustration of each separate curve. In addition, the resulted curves in some cases overlaid and in other cases overlap each other and thus, the band width of all columns in each figure is relatively small. Therefore, the curves for each end condition case may be represented by one individual column curve.

Table 1
Properties and Results for RC Columns Used in the Parametric Study at Different Initial Imperfection, Eccentricity, Load Ratio, and Concrete Cover Conditions: Series 1–5

			Series 1		Series 2		Series 3		Series 4		Series 5	
			$e_0 = 5$		$e_0 = 15$		$e_0 = 25$		$e_0 = 15$		$e_0 = 15$	
			$\delta_0 = 10$		$\delta_0 = 10$		$\delta_0 = 10$		$\delta_0 = 0$		$\delta_0 = 0$	
			(mm)		(mm)		(mm)		(mm)		(mm)	
			R_f(min)		R_f(min)		R_f(min)		R_f(min)		R_f(min)	
Column	L m (in.)	λ $\left(\frac{L}{r}\right)$	F	H	F	H	F	H	F	H	F	H
1	0.380 (15)	4.3	**224**	**224**	**214**	**214**	**199**	**199**	**188**	**188**	**190**	**190**
2	0.635 (25)	7.2	222	221	211	208	197	196	186	185	188	185
3	1.270 (50)	14.5	218	214	205	195	189	178	182	178	185	178
4	1.910 (75)	21.7	212	204	198	180	178	157	175	170	177	165
5	2.54 (100)	28.9	202	190	188	159	167	138	167	158	170	138
6	3.18 (125)	36.2	192	169	178	136	158	117	160	138	160	120
7	3.81 (150)	43.4	183	148	168	115	148	98	147	90	150	102
8	4.45 (175)	50.6	173	128	158	96	138	79	141	78	138	87
9	5.08 (200)	57.9	163	105	148	75	125	59	133	64	132	68
10	5.72 (225)	65.1	152	86	138	60	117	47	125	50	118	55
11	6.35 (250)	72.3	140	68	127	47	107	37	109	35	112	41
12	6.99 (275)	79.6	129	53	117	37	99	28	102	25	107	33
13	7.62 (300)	86.8	119	40	109	28	89	19	95	18	102	29
14	8.26 (325)	94.0	111	27	104	19	83	11	88	9	95	22
Load (kN)			1200	1200	1200	1200	1200	1200	1710	1710	1200	1200
Load ratio			35	35	35	35	35	35	50	50	35	35
Cover to main bars (mm)			48	48	48	48	48	48	48	48	25	25

Dimensions: 305 305 mm, R_f: Fire resistance, Reinforcement: 4No 25 mm, f_y: 444 MPa, Aggregate: Siliceous, f'_c: 40 MPa, L: Column length, F: Fixed ends, H: Hinged ends, e: Initial end eccentricity, δ_0: Initial mid-length deflection.
All columns are subjected to ASTM- E119 fire loading unless otherwise specified
Bold values represent the characteristic fire resistance in each case

The concept of using two individual column curves for pinned- and fixed-end conditions therefore lies in the fact that no one column curve can represent the fire resistance of all columns rationally and adequately. It is to be noted that the use of an appropriate single column curve for each end condition case would not significantly over- or underestimate the fire resistance of many columns. In addition, the difference between the actual and the assessed fire resistance will not be completely eliminated, but rather reduced to an acceptable level. The most important information in Figures 2 and 3 is given by the arithmetic mean curves, which show the gradual shifting of the means; from being located in the vicinity of the upper envelope curve at low λ-values, to being closer to the median at high λ-values in the case of fixed-end columns; and from being closer to the upper envelope curve at low λ-values, to being closer to the lower envelope curve at intermediate and high λ-values in the case of pin-ended columns.

Table 2
Properties and Results for RC Columns Used in the Parametric Study at Different Eccentricity, and Loading Ratio Conditions: Series 6, 7, and 8

Column	L m (in.)	λ $\left(\frac{L}{r}\right)$	Series 6 $e_0 = 15$ $\delta_0 = 0$ (mm) R_f(min) F	H	Series 7 $e_0 = 25$ $\delta_0 = 0$ (mm) R_f(min) F	H	Series 8 $e_0 = 50$ $\delta_0 = 0$ (mm) R_f(min) F	H
1	0.380 (15)	4.3	**222**	**222**	**222**	**222**	**170**	**170**
2	0.635 (25)	7.2	221	218	220	218	167	167
3	1.270 (50)	14.5	217	211	215	205	160	152
4	1.910 (75)	21.7	209	194	207	190	152	133
5	2.54 (100)	28.9	200	162	199	168	141	117
6	3.18 (125)	36.2	189	141	179	145	133	98
7	3.81 (150)	43.4	178	125	177	124	124	81
8	4.45 (175)	50.6	162	106	169	105	115	64
9	5.08 (200)	57.9	148	92	159	85	105	48
10	5.72 (225)	65.1	138	73	149	69	97	38
11	6.35 (250)	72.3	130	57	138	57	89	29
12	6.99 (275)	79.6	125	46	127	46	81	21
13	7.62 (300)	86.8	121	39	119	37	73	14
14	8.26 (325)	94.0	118	35	115	28	67	6
Load (kN)			1200	1200	1000	1000	1200	1200
Load ratio %			35	35	30	30	35	35

Dimensions: 305 305 mm, Cover to main bras: 48 mm, Reinforcement: 4No 25 mm, $f_y = 444$ MPa, Aggregate: Siliceous, $f'_c = 40$ MPa

Series 7 is subjected to ISO 834 fire loading

All columns are subjected to ASTM- E119 fire loading unless otherwise specified

Bold values represent the characteristic fire resistance in each case

The bands of column curves shown in Figures 2 and 3 were analyzed statistically throughout the range of slenderness ratios between 4.3 and 94; the results of the statistical computations are show in Figure 4. The mathematical expressions representing the arithmetic mean curves, illustrated in Figure 4, provide a simplified and practical solution that can be easily used. These curves were obtained by originating at the point where $R_f/\overline{R}_f = 1.0$ and $\lambda = \lambda^{\min} = 4.3$. The obtained relationship for fixed-ended columns can be written as follows

$$k_\lambda^F = \frac{R_f}{\overline{R}_f} = -8.43 \times 10^{-10}\lambda_e^4 + 7.788 \times 10^{-7}\lambda_e^3 - 1.105 \times 10^{-4}\lambda_e^2 - 1.176 \times 10^{-3}\lambda_e + 1.0 \tag{4}$$

Table 3
Properties and Results for RC Columns Used in the Parametric Study at Different Initial Imperfection, Eccentricity, and Reinforcement Conditions: Series 9 and 10

			Series 9		Series 10	
			$e_0 = 5$		$e_0 = 15$	
			$\delta_0 = 10$		$\delta_0 = 10$	
			(mm)		(mm)	
	L	λ	R_f(min)		R_f(min)	
Column	m (in.)	$(\frac{L}{r})$	F	H	F	H
1	0.380 (15)	4.3	**228**	**228**	**220**	**220**
2	0.635 (25)	7.2	225	225	217	216
3	1.270 (50)	14.5	221	218	211	205
4	1.910 (75)	21.7	216	209	205	191
5	2.54 (100)	28.9	210	197	198	170
6	3.18 (125)	36.2	204	177	190	147
7	3.81 (150)	43.4	196	158	179	125
8	4.45 (175)	50.6	187	138	170	105
9	5.08 (200)	57.9	176	116	160	85
10	5.72 (225)	65.1	166	98	152	70
11	6.35 (250)	72.3	157	78	141	57
12	6.99 (275)	79.6	147	62	132	48
13	7.62 (300)	86.8	136	48	123	38
14	8.26 (325)	94.0	128	36	115	28

Dimensions: 305 305 mm, Cover to main bras: 48 mm, Reinforcement: 8 No, 25 mm, $f_y = 444$ MPa, Aggregate: Siliceous, $f'_c = 40$ MPa, Load = 1450 kN

All columns are subjected to ASTM- E119 fire loading unless otherwise specified

Bold values represent the characteristic fire resistance in each case

For pin-ended column, the relationship can be expressed as

$$k_\lambda^P = \frac{R_f}{\overline{R}_f} = -2.305 \times 10^{-8}\lambda_e^4 + 6.008 \times 10^{-6}\lambda_e^3 - 4.797 \times 10^{-4}\lambda_e^2 + 1.671 \times 10^{-3}\lambda_e + 1.0 \tag{5}$$

where $\lambda_e = \lambda - 4.3$

Equations (4) and (5) may now be used to find the fire resistance R_f of a column, provided that the characteristic fire resistance $\overline{R}_f$ and the slenderness ratio λ are given.

The principal shortcoming of EC2 equation lies in the fact that techniques to determine the exact value of N_{Rd}, the design resistance (capacity) of the column at normal temperature conditions, for eccentric slender columns are very complex and subject to high overheads. A major defect associated with this shortcoming is

Table 4
Properties and Results for RC Columns Used in the Parametric Study at Different Initial Imperfection, Eccentricity, and Size Conditions: Series 11 and 12

			Series 11		Series 12	
			$e_0 = 5$		$e_0 = 15$	
			$\delta_0 = 10$		$\delta_0 = 10$	
			(mm)		(mm)	
	L	λ	R_f(min)		R_f(min)	
Column	m (in.)	($\frac{L}{r}$)	F	H	F	H
1	0.380 (15)	3.3	**252**	**252**	**248**	**248**
2	0.635 (25)	5.4	251	250	247	247
3	1.270 (50)	10.9	249	246	245	240
4	1.910 (75)	16.3	246	239	241	227
5	2.54 (100)	21.7	242	231	236	215
6	3.18 (125)	27.1	236	220	227	201
7	3.81 (150)	32.6	229	207	220	176
8	4.45 (175)	38.0	221	188	210	162
9	5.08 (200)	43.4	214	171	202	141
10	5.72 (225)	48.8	206	155	193	124
11	6.35 (250)	54.3	196	135	183	105
12	6.99 (275)	59.7	189	115	175	86
13	7.62 (300)	65.1	179	100	166	74
14	8.26 (325)	70.5	169	85	156	62
15	8.89 (350)	76.0	158	69	145	50
16	10.16 (400)	86.8	143	51	133	37
17	11.43 (450)	97.7	132	31	124	23

Dimensions: 406406 mm, Cover to main bras: 48 mm, Reinforcement: 4 No, 25 mm, $f_y = 444$ MPa, Aggregate: Siliceous, $f'_c = 40$ MPa, Load = 2015 kN

All columns are subjected to ASTM- E119 fire loading unless otherwise specified

Bold values represent the characteristic fire resistance in each case

that EC2 equation does not provide reasonable predictions for all column lengths when simplifications are adopted to calculate N_{Rd}. Determination of capacity of slender columns not only exhibit difficulty due to the presence of non-linear stresses resulted from external applied loads, but also due to the presence of initial imperfections. Finding capacity of slender columns considering the combined effect of non-linear stresses, initial imperfections, and second order deflection is rather complicated. The simplified approaches, which is valid only for stocky columns, can not be used here. Instead, other approaches, such as model-column approach or load–deflection approach must be utilized and thus recourse to numerical and iterative methods is inevitable. This shortcoming can be alleviated by modifying EC2 equation by adopting the column curve technique, which essentially means that N_{Rd} is calculated for very short columns and therefore the term

Table 5
Properties and Results for RC Columns Used in the Parametric Study at Different Initial Imperfection, Eccentricity, and Reinforcement Conditions: Series 13 and 14

			Series 13 $e_0 = 30$ $\delta_0 = 0$ (mm) R_f(min)		Series 14 $e_0 = 50$ $\delta_0 = 0$ (mm) R_f(min)	
Column	L m (in.)	λ $(\frac{L}{r})$	F	H	F	H
1	0.760 (30)	4.3	**320**	**320**	**308**	**308**
2	1.270 (50)	7.2	318	314	304	301
3	2.54 (100)	14.5	312	304	296	283
4	3.81 (150)	21.7	300	281	286	261
5	5.08 (200)	28.9	288	235	272	230
6	6.35 (250)	36.2	272	206	257	197
7	7.62 (300)	43.4	249	171	242	168
8	8.86 (350)	50.6	232	155	229	141
9	10.16 (400)	57.9	214	135	214	110
10	11.43 (450)	65.1	199	108	200	88
11	12.70 (500)	72.3	188	85	184	69
12	13.97 (550)	79.6	182	67	169	54
13	15.24 (600)	86.8	176	57	158	40
14	16.51 (650)	94.0	172	50	152	26

Dimensions: 610 610 mm, Cover to main bras: 48 mm, Reinforcement: 8 No 25 mm, $f_y = 444$ MPa, Aggregate: Siliceous, $f'_c = 40$ MPa, Load = 3000 kN

All columns are subjected to ASTM- E119 fire loading unless otherwise specified

Bold values represent the characteristic fire resistance in each case

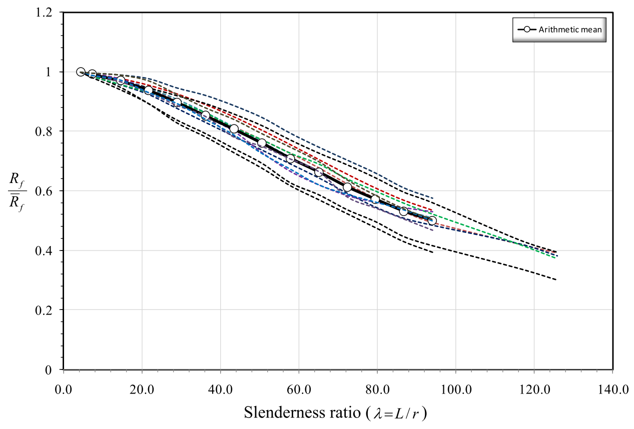

Figure 2. Fire-resistance-column-curves band and arithmetic mean for fixed-end column case.

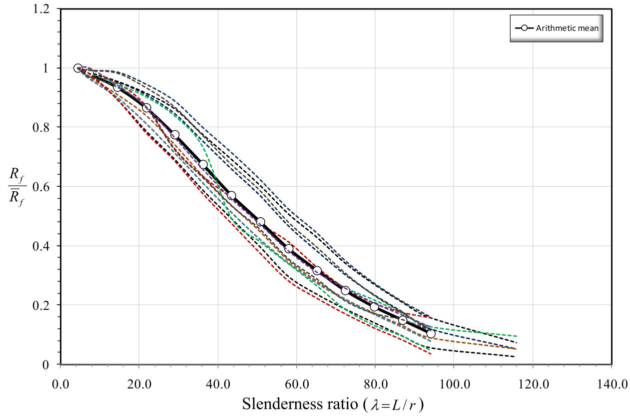

Figure 3. Fire-resistance-column-curves band and arithmetic mean for pin-ended column case.

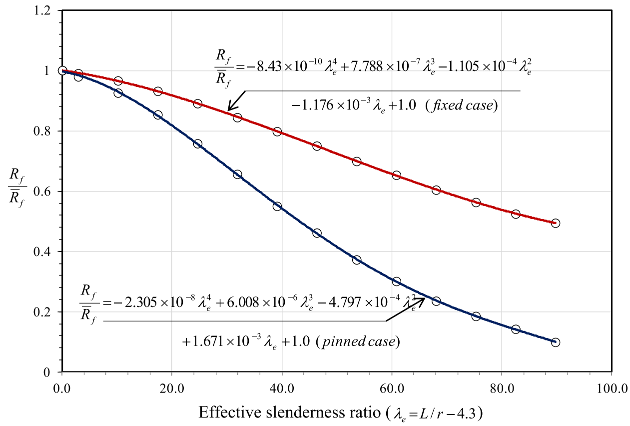

Figure 4. Proposed column curves for fixed-end and pin-ended column cases.

including the column length in the equation will be adjusted using Equations (4) and (5).

It has to be noted that the key solution for the proposed FRCC method is the characteristic fire resistance $\overline{R}_f$ because it includes almost all the properties of the assessed column. However, there are no experimental fire tests in literature for very small slenderness ratios, particularly at $\lambda^{min} = 4.3$, regarding fire resistance of RC columns. Therefore, $\overline{R}_f$ should be theoretically determined.

Following the recognition that other simplified methods provide unsatisfactory prediction even for short columns [7], the simple characteristic of EC2 equation may form the bases of calculating $\overline{R}_f$ since it provides safe predictions for small slenderness ratios.

To establish the applicability of EC2 equation in determining $\overline{R}_f$, a comparative study was performed. The analyzed columns were of 305 305 mm cross-section and 4.3 slenderness ratio. The concrete and steel were of 40 MPa and 420 MPa compressive and yield strengths, respectively. The investigated parameters were load ratio, cover thickness, steel percentage, and column size. The characteristic fire resistance $\overline{R}_f$ was calculated using EC2 equation and the results compared with those obtained using the numerical model as shown in Figures 5, 6, 7 and 8. It is clear that there is good agreement between predictions obtained using Eurocode equation and model results, which indicates that this equation could be safely used to calculate $\overline{R}_f$.

Another shortcoming of Eurocode equation is that it does not account for load eccentricity even though it is stated that the equation is applicable for eccentricity ratio e/b(the ratio of the load eccentricity to the cross-section size) up to 0.40. In fact, EC2 equation implicitly account for load eccentricity by taking its impact on N_{Rd} in the case of slender columns. To determine appropriately the characteristic fire resistance at slenderness ratio $\lambda = 4.3$, EC2 equation should be modified by adding a parameter to account for load eccentricity.

Indeed, the effects of load eccentricity, load ratio, and slenderness ratio on fire resistance are interrelated. Previous studies on intermediate slender columns revealed that fire resistance decreases by about 10% to 24% for every 10% increase in eccentricity ratio e/b. In a study performed by Raut and Kodur [14], it was found that at 50% load ratio, fire resistance decreases by about 24% for every 10% increase in eccentricity ratio e/b. Mahmoud [13] observed that up to an eccentricity ratio of 0.17, the drop in fire resistance in the case of column bent in double curvature is about 10%, whereas it reaches 20% in the case of column bent in single curvature, for each 10% increase in eccentricity ratio. To establish the influence of load eccentricity on the characteristic fire resistance $\overline{R}_f$, an investigation was carried out with the aid of the numerical model. The properties of the analyzed columns and the obtained results are shown in Table 6. To eliminate the effect of column size, the load eccentricity is included in terms of the eccentricity ratio e/b. The effect of slenderness ratio is already eliminated because the results in Table 6 are for columns of $\lambda = 4.3$. The variation of characteristic fire resistance with respect to load eccentricity individually (load ratio up to 50%) was obtained and the non-dimensional characteristic fire resistance was plotted against the eccentricity ratio as shown in Figure 9. It can be seen that at this range of load ratio, eccentricity ratio less than 0.05 has no effect on $\overline{R}_f$. For eccentricity ratio more than 0.05, however, $\overline{R}_f$ decreases by about 14% for each 0.1 increase in eccentricity ratio. From the above, the effect of eccentricity on characteristic fire resistance can be expressed as

$$\begin{aligned} \overline{R}_f &= k_e.\overline{R}_f^0 \\ k_e &= 1.0 \qquad e/b \leq 0.05 \\ k_e &= 1 - 1.43\left(\frac{e}{b} - 0.05\right) \qquad 0.05 < e/b \leq 0.17 \end{aligned} \tag{6}$$

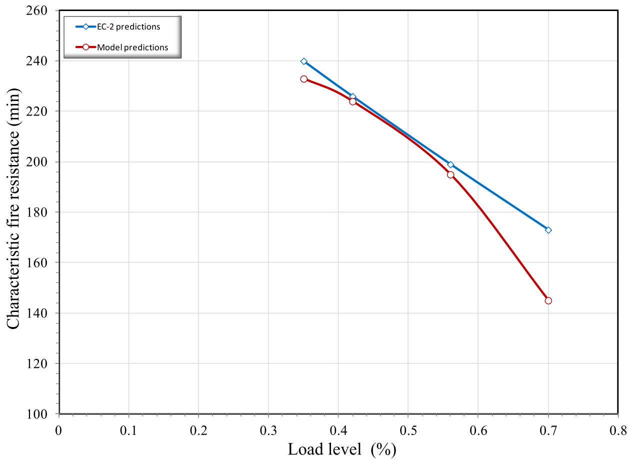

Figure 5. Effect of load level on characteristic fire resistance.

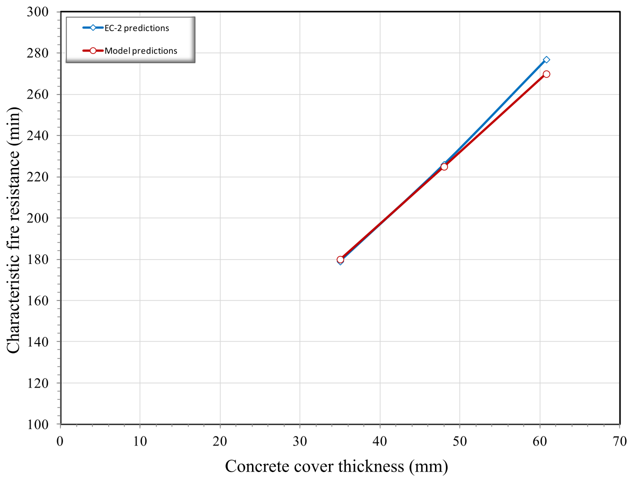

Figure 6. Effect of concrete cover thickness on characteristic fire resistance.

where $\overline{R}_f^0$ is the characteristic fire resistance at zero eccentricity, k_e is the load eccentricity coefficient, and b is the dimension of column in direction of e.

To account for the modifications in EC2 equation regarding the influence of slenderness ratio in the characteristic fire resistance, Equation (2) can be rewritten as follows

$$\overline{R}_f^0 = 120.\left(\frac{R_{\eta fi,\lambda^{\min}} + R_a + R_{L^{\min}} + R_b + R_n}{120}\right)^{1.8} \tag{7}$$

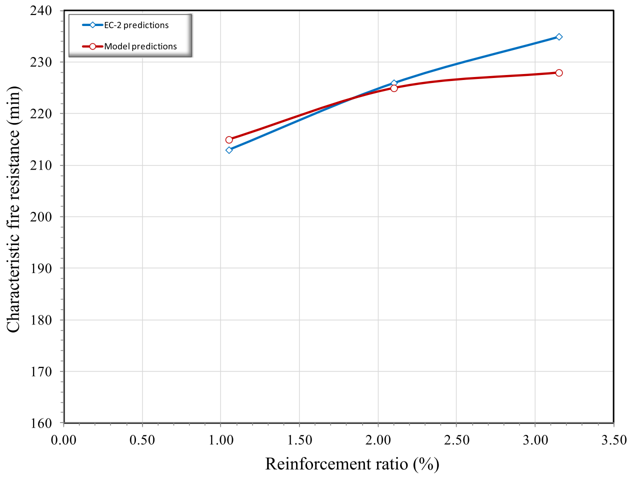

Figure 7. Effect of reinforcement ratio on characteristic fire resistance.

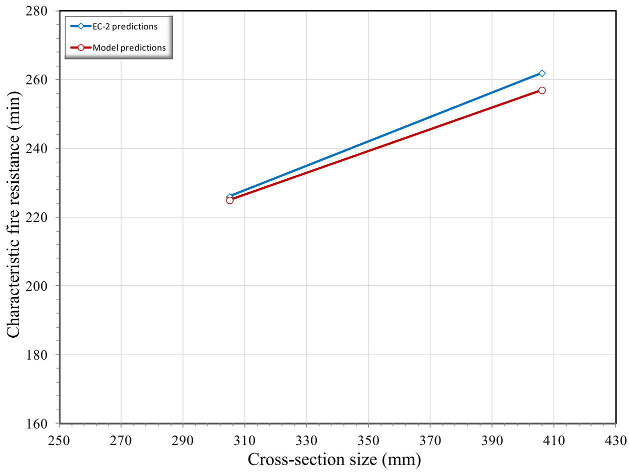

Figure 8. Effect of cross-section size on characteristic fire resistance.

The parameters $R_{\eta fi,\lambda^{\min}}$, R_a, $R_{L^{\min}}$, R_b, and R_n can be calculated as follows

$$R_{\eta fi,\lambda^{\min}} = 83\left(1.0 - \mu_{fi,\lambda^{\min}}\frac{(1+\omega)}{(0.85/\alpha_{cc})+\omega}\right) \tag{8}$$

in which $\mu_{fi,\lambda^{\min}} = \frac{N_{Ed,fi}}{N_{Rd,\lambda^{\min}}}$. The term $N_{Ed,fi}$ represents the design axial load (or failure load) in the fire situation, and $N_{Rd,\lambda^{\min}}$ is the design resistance (or ultimate capacity) of the column at normal temperature condition and minimum slender-

Table 6
Properties and Results for RC Columns Used to Determine the Influence of Load Eccentricity on Fire Resistance

Column	Load (kN)	Load Level (%)	L (m) (in.)	λ $(\frac{L}{r})$	e (mm)	R_f (min)
CE1	1200	0.29	0.38 (15)	4.3	0	224
CE2	1200	0.43	0.38 (15)	4.3	15	224
CE3	1200	0.37	0.38 (15)	4.3	25	215
CE4	1200	0.41	0.38 (15)	4.3	35	199
CE5	1200	0.48	0.38 (15)	4.3	50	170

Dimensions: 305 305 mm, Cover to main bras: 48 mm, Reinforcement: 4 No 25 mm, $f_y = 444$ MPa, Aggregate: Siliceous: $f_c' = 40$ MPa

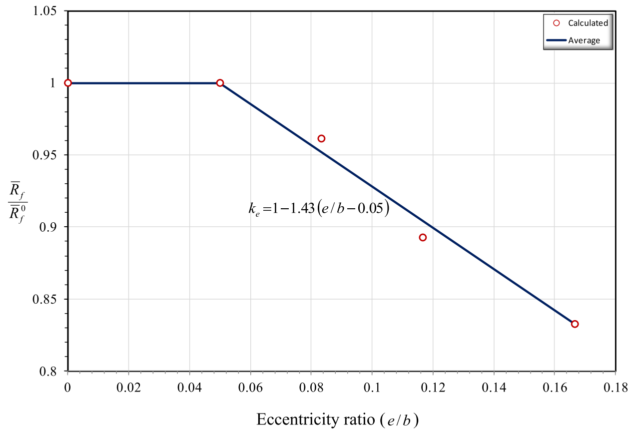

Figure 9. Variation of characteristic fire resistance with respect to eccentricity.

ness ratio. The term ω can be determined from $\omega = A_s \cdot f_{yd} / A_c \cdot f_{cd}$ where f_{yd} and f_{cd} are the design yield and compressive strength for steel and concrete, respectively.

For very short columns acted on by concentric load (slenderness ratio 4.3), the design resistance at zero eccentricity $N^0_{Rd,\lambda^{\min}}$ can be simply calculated as

$$N^0_{Rd,\lambda^{\min}} = A_s \frac{f_{yk}}{\gamma_s} + A_c \frac{0.85 f_{ck}}{\gamma_c} \tag{9}$$

The ultimate capacity at zero eccentricity can be obtained by replacing f_{ck} by f_{cm}.

When the load is eccentrically applied, the problem would be much complex; thus, a specific calculation is required to obtain $N_{Rd,\lambda^{\min}}$. Therefore, an investigation was carried out to find a simple expression regarding the impact of load eccentricity on the design resistance (ultimate capacity) at $\lambda^{\min}$. Parameters that are considered include steel ratio, column size, and concrete compressive strength. Properties of the analyzed column and results are shown in Table 7. The ratio $\frac{N_{Rd,\lambda^{\min}}}{N^0_{Rd,\lambda^{\min}}}$ was calculated and plotted against e/b as shown in Figure 10. It can be noticed that up to an eccentricity ratio e/b of 0.33, the obtained relationships are very close to each other. Consequently, the results were curve-fitted and the obtained arithmetic mean can be described by

$$k_R = \frac{N_{Rd,\lambda^{\min}}}{N^0_{Rd,\lambda^{\min}}} = -8.49\left(\frac{e}{b}\right)^3 + 6.91\left(\frac{e}{b}\right)^2 - 3.049\frac{e}{b} + 1.0 \tag{10}$$

Equation (10) furnishes a method of estimating $N_{Rd,\lambda^{\min}}$, the capacity of very short columns subjected to an eccentric load, given the capacity at zero eccentricity and the load eccentricity.

The value of R_a is calculated as

$$R_a = 1.6(a - 30) \tag{11}$$

where a is the distance between the center point of steel rebar and the nearest exposed surface in mm.

The term $R_{L^{\min}}$ is obtained by

$$R_{L^{\min}} = 9.6\left(5 - L^{\min}\right) \tag{12}$$

where $L^{\min}$ is the shortest effective length of the column that corresponds to $\lambda^{\min} = 4.3$. It can be determined as $L^{\min} = 4.3.r$ where r is the radius of gyration.

The fire rating for cross-section size is

$$R_b = 0.09b' \tag{13}$$

in which b' is determined by $b' = 4A/p$ with A and p are the area and perimeter of cross-section.

Finally, the term R_n will be

$$\begin{aligned} R_n &= 0 \qquad for\, n \geq 4 \\ R_n &= 12 \qquad for\, n < 4 \end{aligned} \tag{14}$$

The design fire resistance R_f can be determined as

$$R_f = k_\lambda . k_e . \overline{R}_f^0 \tag{15}$$

Table 7
Properties and Results for RC Columns Used to Determine the Influence of Load Eccentricity on Ultimate Capacity of Very Short Columns at Zero Temperature

C1 (305 305)	e (mm)	0.0	5.0	10.0	20.0	25.0	50.0	100.0
	e/b	0.0	0.01639	0.03278	0.06557	0.08196	0.16393	0.32786
	$\frac{N_{Rd,\lambda\min}}{N^0_{Rd,\lambda\min}}$	1.0	0.949	0.902	0.823	0.789	0.641	0.424
	Notes	$b = 305$ mm, $A_s = 4$No25, $f'_c = 40$ MPa, $f_y = 444$ MPa, $\lambda = 4.3$						
C2 (610 610)	e (mm)	0.0	10.0	20.0	40.0	50.0	100.0	200.0
	e/b	0.0	0.01639	0.03278	0.06557	0.08196	0.16393	0.32786
	$\frac{N_{Rd,\lambda\min}}{N^0_{Rd,\lambda\min}}$	1.0	0.955	0.911	0.835	0.800	0.657	0.437
	Notes	$b = 610$ mm, $A_s = 8$No25, $f'_c = 40$ MPa, $f_y = 444$ MPa, $\lambda = 4.3$						
C3 (305 305)	e (mm)	0.0	5.0	10.0	20.0	25.0	50.0	100.0
	e/b	0	0.01639	0.03278	0.06557	0.08196	0.16393	0.32786
	$\frac{N_{Rd,\lambda\min}}{N^0_{Rd,\lambda\min}}$	1.0	0.951	0.904	0.824	0.788	0.645	0.445
	Notes	$b = 305$ mm, $A_s = 8$No25, $f'_c = 40$ MPa, $f_y = 444$ MPa, $\lambda = 4.3$						
C4 (305 305)	e (mm)	0.0	5.0	10.0	20.0	25.0	50.0	100.0
	e/b	0.0	0.01639	0.03278	0.06557	0.08196	0.16393	0.32786
	$\frac{N_{Rd,\lambda\min}}{N^0_{Rd,\lambda\min}}$	1.0	0.950	0.903	0.825	0.791	0.641	0.417
	Notes	$b = 305$ mm, $A_s = 4$No25, $f'_c = 50$ MPa, $f_y = 444$ MPa, $\lambda = 4.3$						
(Average)	$\frac{N_{Rd,\lambda\min}}{N^0_{Rd,\lambda\min}}$	1.0	0.951	0.905	0.827	0.792	0.646	0.431

3. Evaluation

3.1. Evaluation of the Proposed Method by Comparison with Experimental Data

The evaluation of the proposed method is established by comparing its predictions with experimental data found in literature [3, 15, 16]. This comparison demonstrates good examples of different columns behaviors because it was performed over a broad range of section properties and loading conditions. The geometric, material, loading properties, as well as the results of the tested columns are shown in Table 8, 9, and 10. For all columns, the values of λ, λ_e, $L^{\min}$, and k_e were calculated and then, $\overline{R}_f^0$ and $\overline{R}_f$ were determined using Equations (6) and (7). Consequently, the developed column curves (Equations (4) and (5)) and $\frac{R_{f,test}}{\overline{R}_f} - \lambda$ relationships in the cases of fixed- and pinned-end conditions were plotted as illustrated in Figures 11 and 12, respectively. It shall be mentioned that the test columns have a broader range of eccentricity ratio ($0.0 \leq e/b \leq 0.5$) than that used to construct the column curves ($e/b \leq 0.17$), which might help to demonstrate the usefulness of FRCC method to assess columns with higher eccentricity.

It can be seen that in both cases, the distribution of the experimental results tends to follow a similar trend to that of the developed column curve. In addition, the developed column curve for fixed-end columns represents approximately a median for the results obtained from experimental data (Figure 11). This finding is clearly emphasized by Figure 13 where the ratio $\frac{R_{f,FRCC}}{R_{f,test}}$ is plotted against λ and the resulted average ratio is about 99%. On the other hand, the values of $\frac{R_{f,test}}{\overline{R}_f}$ in the case of short and medium pin-ended columns tend towards the developed col-

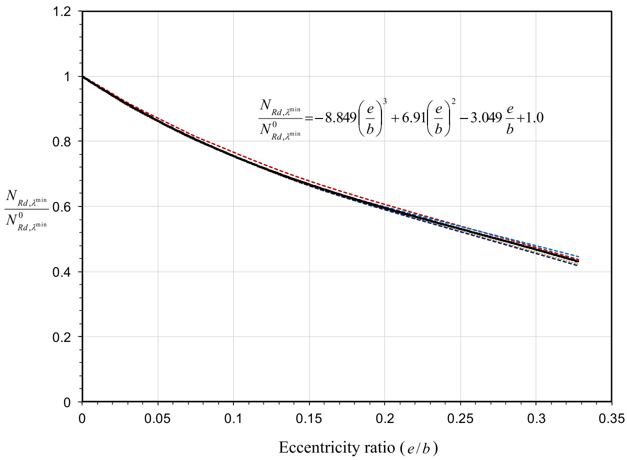

Figure 10. Variation of ultimate capacity with respect to eccentricity (λ=4.3).

Table 8
Properties and Results for Tested Pin-Ended RC Columns Used in Validation (Group-1 [3])

Lab	A_s cm^2	a mm	b_1 mm	b_2 mm	L m	f_{cm} MPa	f_{ym} MPa	e mm	P kN	R_f min	λ (L/r)	k_e	$\overline{R}_f^0$ min	$\overline{R}_f$ min	$\frac{R_f}{\overline{R}_f}$
TUBr	9.2	30	200	200	5.71	42	480	100	140	31	99.13	0.392	128	50	0.62
TUBr	9.2	30	200	200	5.71	42	480	50	172	35	99.13	0.750	138	103	0.34
TUBr	12.6	38	200	200	4.76	31	462	20	240	36	82.64	0.964	160	154	0.23
TUBr	18.9	38	300	300	4.70	35	505	5	1548	38	54.40	1.0	117	117	0.32
TUBr	12.6	38	200	200	5.76	32	443	10	208	40	100.00	1.0	168	168	0.24
TUBr	9.2	30	200	200	5.71	42	477	10	245	40	99.13	1.0	141	141	0.28
TUBr	12.6	38	200	200	4.76	24	487	0	340	48	82.64	1.0	153	153	0.31
TUBr	18.9	38	300	300	4.76	38	404	5	1224	48	55.09	1.0	132	132	0.36
TUBr	12.6	38	200	200	4.76	31	462	10	280	49	82.64	1.0	159	159	0.31
TUBr	12.6	38	200	200	4.76	31	462	60	170	49	82.64	0.678	156	106	0.46
TUBr	18.9	38	300	300	4.70	32	503	150	280	49	54.40	0.357	152	54	0.90
TUBr	9.2	30	200	200	5.71	42	482	10	175	49	99.13	1.000	149	149	0.33
TUBr	18.9	38	300	300	4.70	32	526	150	465	50	54.40	0.357	128	46	1.10
TUBr	9.2	30	200	200	5.71	42	485	50	122	52	99.13	0.750	146	109	0.48
TUBr	12.6	38	200	200	4.76	31	462	100	130	53	82.64	0.392	153	60	0.88
TUBr	18.9	38	300	300	4.70	32	503	10	970	55	54.40	1.0	139	139	0.40
TUBr	18.9	38	300	300	3.76	42	452	5	1695	57	43.52	1.0	118	118	0.48
TUBr	18.9	38	300	300	4.70	32	526	10	1308	57	54.40	1.0	122	122	0.47
TUBr	18.9	38	300	300	5.76	24	487	0	800	58	66.67	1.0	143	143	0.41
TUBr	12.6	38	200	200	3.76	24	487	0	420	58	65.28	1.0	144	144	0.40
RUG	6.8	31	300	200	3.90	31	493	20	300	60	45.14	0.976	145	142	0.42
RUG	6.8	41	300	200	3.90	33	493	20	283	60	45.14	0.976	181	177	0.34
TUBr	8	33	300	300	3.90	34	576	0	950	61	45.14	1.0	119	128	0.48

TUBr: Technical University of Braunschweig, Germany, RUG: University of Gent, Belgium
Material safety factors $\gamma_s = \gamma_c = 1$

Table 9
Properties and Results for Tested Pin-Ended RC Columns Used in Validation (Group-2 [3])

Lab	A_s cm^2	a mm	b_1 mm	b_2 mm	L m	f_{cm} MPa	f_{ym} MPa	e mm	P kN	R_f min	λ (L/r)	k_e	$\overline{R}_f^0$ min	$\overline{R}_f$ min	$\frac{R_f}{\overline{R}_f}$
TUBr	18.9	38	300	300	5.76	24	487	30	600	61	66.67	0.929	145	135	0.45
TUBr	18.9	38	300	300	4.76	24	487	30	650	63	55.09	0.929	141	131	0.48
TUBr	12.6	38	200	200	3.76	24	487	0	420	66	65.28	1.0	144	144	0.46
TUBr	18.9	38	300	300	4.76	31	462	30	650	69	55.09	0.929	148	137	0.50
TUBr	9.2	30	200	200	5.71	42	478	10	128	72	99.13	1.0	154	154	0.47
TUBr	18.9	38	300	300	4.76	31	462	90	460	75	55.09	0.643	144	93	0.81
TUBr	18.9	38	300	300	4.76	31	462	30	650	80	55.09	0.929	148	137	0.58
TUBr	18.9	38	300	300	3.76	24	487	0	930	84	43.52	1.0	135	135	0.62
TUBr	18.9	38	300	300	4.76	31	462	15	740	85	55.09	1.0	148	148	0.57
TUBr	18.9	38	300	300	3.76	24	487	30	740	86	43.52	0.929	135	125	0.69
RUG	16.1	33	400	400	3.90	30	576	20	1650	93	33.85	0.982	146	143	0.65
TUBr	18.9	38	300	300	4.76	24	487	0	880	108	55.09	1.0	138	138	0.78
TUBr	18.9	38	300	300	2.66	33	458	30	845	111	30.79	0.929	137	127	0.87
RUG	8	33	300	300	3.90	29	576	0	422	116	45.14	1.0	150	150	0.77
RUG	8	33	300	300	3.90	35	576		622	120	45.14	1.0	142	142	0.85
RUG	6.8	31	300	200	3.90	30	493	20	178	120	45.14	0.976	167	163	0.74
RUG	6.8	41	300	200	3.90	32	493	20	334	120	45.14	0.976	174	170	0.71
RUG	8	48	300	300	3.90	37	576	20	349	123	45.14	0.976	155	151	0.81
RUG	8	33	300	300	3.90	37	576	20	220	125	45.14	0.976	164	160	0.78
TUBr	18.9	38	300	300	2.66	33	418	50	780	125	30.79	0.833	140	117	1.07
RUG	16.1	33	300	300	3.90	36	576	20	370	126	45.14	0.976	157	153	0.82
TUBr	18.9	38	300	300	3.76	24	487	0	930	138	43.52	1.0	135	135	1.02
TUBr	18.9	38	300	300	3.33	31	433	15	735	160	38.54	1.0	153	153	1.05

TUBr: Technical University of Braunschweig, Germany, RUG: University of Gent, Belgium
Material safety factors $\gamma_s = \gamma_c = 1$

Table 10
Properties and Results for Tested Fixed-End RC Columns Used in Validation [12, 13]

Lab	A_s cm^2	a mm	b_1 cm	b_2 cm	L m	f_{cm} MPa	f_{ym} MPa	e mm	P kN	R_f min	λ (L/r)	k_e	$\overline{R}_f^0$ min	$\overline{R}_f$ min	$\frac{R_f}{\overline{R}_f}$
NRC	20.4	61	30.5	30.5	381	3.5	44.4	0	1778	146	43.37	1.0	198	198	0.74
NRC	20.4	61	30.5	30.5	381	3.7	44.4	0	1333	170	43.37	1.0	227	227	0.75
NRC	12.6	58	20	20	381	4.2	44.2	0	169	180	66.15	1.0	254	254	0.71
NRC	20.4	61	30.5	30.5	381	3.8	44.4	0	1333	187	43.37	1.0	229	229	0.82
NRC	20.4	61	30.5	30.5	381	4.4	44.4	0	1044	201	43.37	1.0	252	252	0.80
NRC	20.4	61	30.5	30.5	381	3.6	44.4	0	1067	208	43.37	1.0	242	242	0.86
NRC	20.4	61	30.5	30.5	381	3.5	44.4	0	916	210	43.37	1.0	250	250	0.84
NRC	65.5	80	40.6	40.6	381	4.6	41.4	0	2978	213	32.58	1.0	336	336	0.63
NRC	20.4	61	30.5	30.5	381	3.4	44.4	0	800	218	43.37	1.0	256	256	0.85
NRC	20.4	61	30.5	30.5	381	3.5	44.4	0	711	220	43.37	1.0	263	263	0.84
NRC	40.9	61	30.5	30.5	381	3.7	44.4	0	1333	225	43.37	1.0	244	244	0.92
NRC	20.4	61	30.5	30.5	381	5.3	44.4	0	1178	227	43.37	1.0	254	254	0.89
NRC	20.4	61	30.5	30.5	381	5	44.4	0	1067	234	43.37	1.0	257	257	0.91
NRC	40.9	61	40.6	40.6	381	3.9	44.4	0	2418	262	32.58	1.0	254	254	1.03
NRC	65.5	64	40.6	40.6	381	3.8	41.4	0	2795	285	32.58	1.0	263	263	1.08

NRC: National Research Council of Ottawa, Canada
Material safety factors $\gamma_s = \gamma_c = 1$

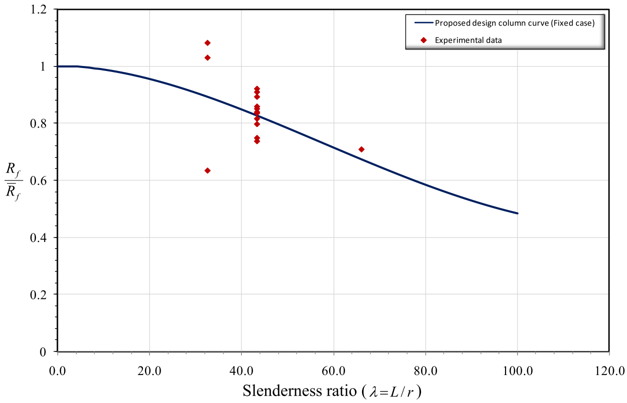

Figure 11. Comparison between the proposed fire-resistance-column-curve FRCC and experimental data for fixed-end columns.

umn curves (Figure 12); thus, the curves interferes many test results up to a slenderness ratio of about 60. It can be said that up to a slenderness ratio of about 83, FRCC method still accurately predict some of the test data. For very slender pinned columns, however, (λ close to 100) FRCC method is conservative (Figure 12). The impact of higher slenderness ratio and the pinned end conditions on the results is clear from Figure 14 where the average ratio (average-1) is only about 90% for columns with $\lambda \leq 100$ and $e/b \leq 0.17$. When the results are

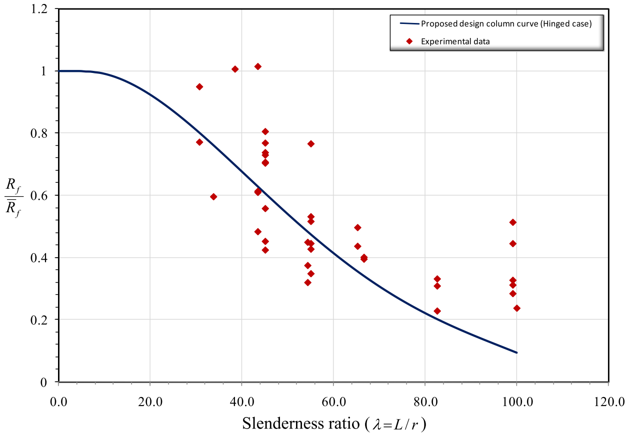

Figure 12. Comparison between the proposed fire-resistance-column-curve FRCC and experimental data for pin-ended columns.

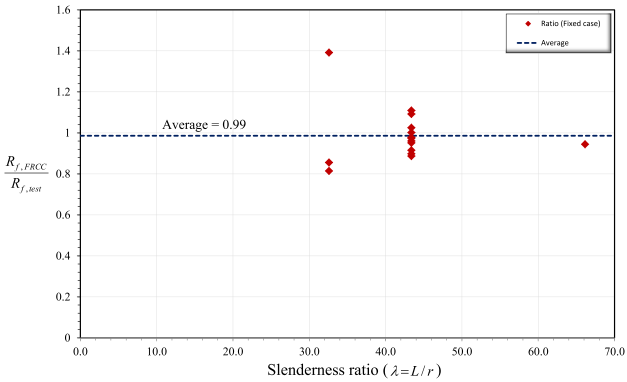

Figure 13. The ratio of the FRCC method predictions to experimental data for fixed-end columns.

considered for columns of $\lambda \leq 83$ and $e/b \leq 0.17$, the average reaches 97%. When all tested pinned columns are considered ($\lambda \leq 100$ and $e/b \leq 0.5$), the average ratio decreases to 83%.

Although the above validation reveals that there is reasonably good agreement between predictions of the proposed method and test data that confirm the method capability for assessment, there are some inconsistencies, however, between the predicted and measured results, especially in the case of very slender pin-ended columns. A possible reason for these inconsistencies could be related to the uncertainties in different factors and material parameters that applied in experiments. Performing an ideal heating or loading process could not be optimal in all test cases. In addition, attaining a perfect idealized end condition may not be an easy job for slender pinned columns. Another possible reason could be the

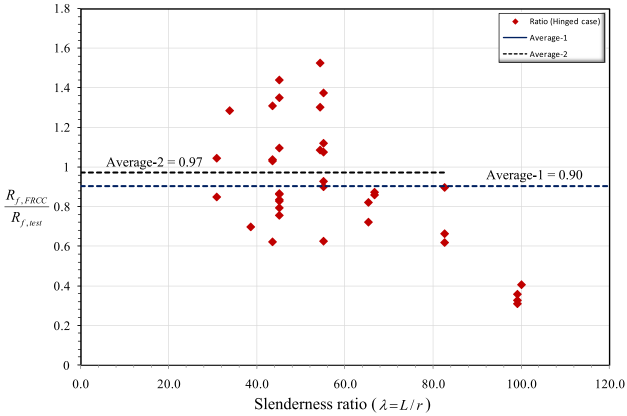

Figure 14. The ratio of the FRCC method predictions to experimental data for pin-ended columns.

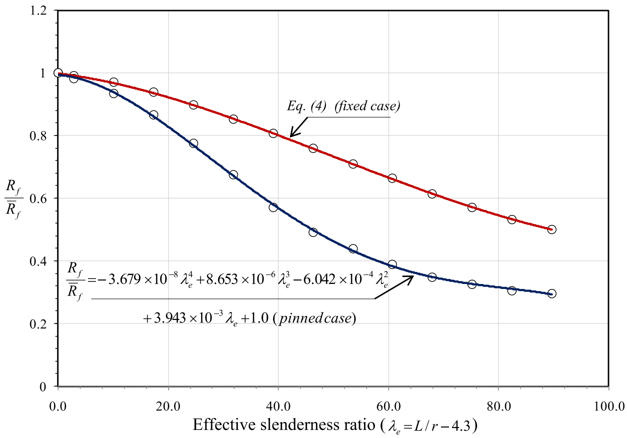

Figure 15. Proposed modified column curve for pin-ended column case.

higher values of e/b ratio in some column cases, which may lead to some errors in k_e estimated by Equation (6). Another possibility is attributed to the difference in definition of failure between test and analysis. Accordingly, if it is of particular interest to reproduce the results of a fire test accurately using numerical analysis, it is imperative that factors used in the calculation be the same as those in the test. Such aim may not always be attained because of the disability to simulate accurately some parameters and the inherent randomness in others.

To improve the accuracy of the method in the case of pinned columns, the column curve illustrated in Figure 4 is modified to take into consideration the distributions of test data. Therefore, the modified curve is based on both numerical

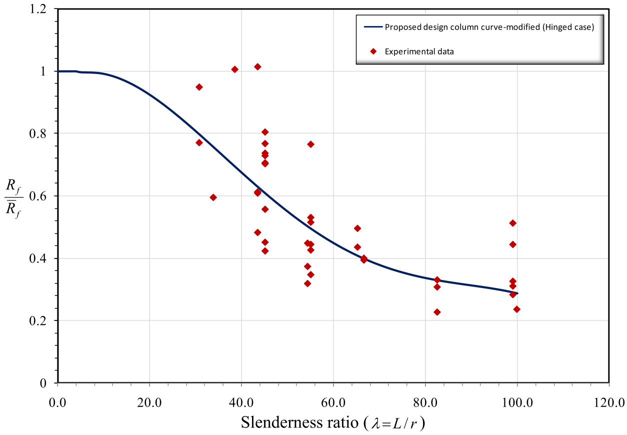

Figure 16. Comparison between the proposed modified fire-resistance-column-curve FRCC and experimental data for pin-ended columns.

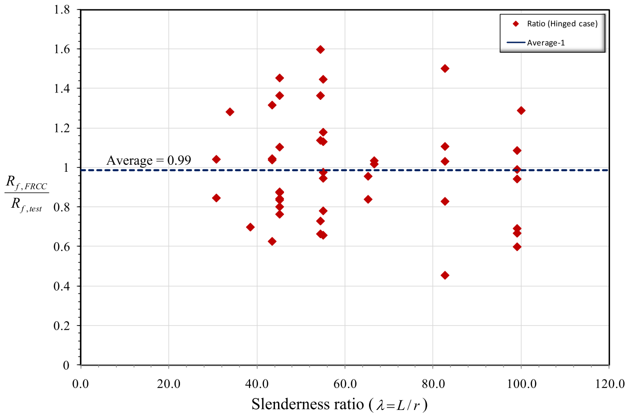

Figure 17. The ratio of the FRCC method predictions to experimental data for pin-ended columns (modified column curve).

results and experimental data. The proposed equation for the new curve, as shown in Figure 15, takes the form

$$k_\lambda^P = \frac{R_f}{\overline{R}_f} = -3.679 \times 10^{-8}\lambda_e^4 + 8.653 \times 10^{-6}\lambda_e^3 - 6.042 \times 10^{-4}\lambda_e^2 - 3.493 \times 10^{-3}\lambda_e + 1.0 \tag{16}$$

It is clear from Figure 16 that the distributions of experimental data when compared to the modified column curve are better than those when compared to the old column curve. For pinned columns with $\lambda \leq 100$ and $e/b \leq 0.5$, the average ratio of $R_{f,FRCC}/R_{f,test}$ reaches about 99%, as shown in Figure 17.

It is now fairly well established that relations obtained using Equations (4) and (16) provide a good representation to many of the test data. This indicates that by using appropriate safety factors, the developed column curves can be safely used for design purpose.

It is sufficient to state that the solution of Equations (4) and (16), when considered as a design formulae, is simpler to engineers so long as the design value of the characteristic fire resistance, obtained using Equations (7) to (12), is available.

3.2. Comparison with the Results of EC2 Method

The fire resistance of columns listed in Table 8, 9, and 10 are calculated by Franssen [3] using EC2 method. In his calculation, N_{Rd} values were exactly determined using model-column technique. The results were utilized and the ratios $\frac{R_{f,EC2}}{R_{f,test}}$ were obtained and depicted against λ for fixed and pined columns, respectively, as shown in Figures 18 and 19. Comparing the results in Figure 18 with those in Figure 13 reveals that for fixed columns, EC2 and FRCC methods have approximately similar accuracy, with average ratios of 96% and 99% respectively. In addition, the upper and lower limits of the ratio are 144% and 68% for EC2 method, whereas, they are 141% and 83% for FRCC method. Similarly, for pinned columns, the ratios are comparable with an average ratio of 104% for EC2 and 99% and for FRCC (Figure 17).

It can also be noticed for pinned columns that the upper and lower limits of the ratio for EC2 method are 194% and 59%; whereas, they are 159% and 45% in the case of FRCC method. Results in Figure 20 reveal that for the columns with higher eccentricity ratio ($0.25 \leq e/b \leq 0.5$), FRCC method provides safe but conservative predictions in some cases. The ratios are in the range between 41% and 94% with a mean value 69%. On the other hand, EC2 method leads to unsafe results in many columns cases. It gives ratios between 81% and 194% with a mean value 117%. Although FRCC method leads to slight improvement in some cases when compared to EC2 method for columns with $e/b < 0.25$, there is still good agreement between predictions of both methods. This is quite good result considering the large variability of tests. For columns with higher eccentricity ratio, further improvement would be achieved if higher e/b values were taken in the calculation of k_e.

It has to be mentioned that these averages are susceptible to changes if other test results are included. Moreover, the accuracy of EC2 method would be questionable if simplified techniques in the determination of N_{Rd} were adopted.

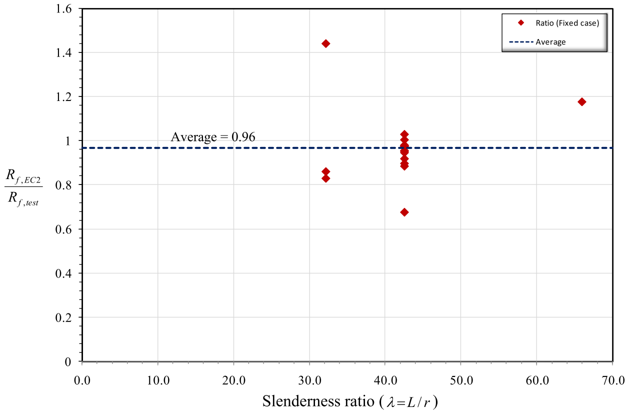

Figure 18. The ratio of EC2 method predictions to experimental data for fixed-end columns.

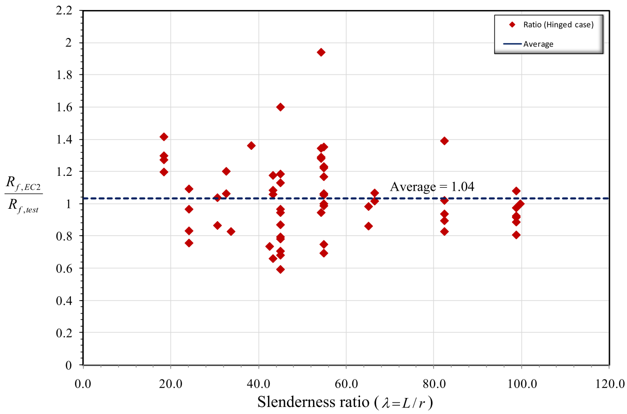

Figure 19. The ratio of EC2 method predictions to experimental data for pin-ended columns.

4. Numerical Examples

4.1. Fire-Resistance-Column-Curves for Design

To verify the applicability of FRCC method for design, two column examples are presented. The first example is a fixed-end column CF subjected to a concentrated load; whereas, the second example is a pin-ended column CP acted on by an eccentric load. It is assumed that both columns have a cross-section of 250 mm 250 mm with 35 MPa concrete characteristic compressive strength. The columns have a concrete cover of 48 mm and a length of 4000 mm. The main reinforcement for both columns is four No 20 mm bars with 420 MPa yield strength. The proposed material safety factors λ_s and λ_c are 1.15 and 1.5, respectively. Other

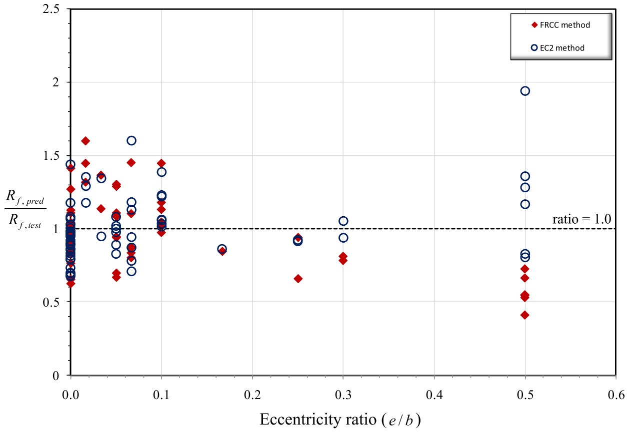

Figure 20. The ratio $\frac{R_{f,predicted}}{R_{f,test}}$ as a function of eccentricity ratio for pin-ended columns.

geometric, material, and loading properties of the columns, as well as the calculation procedure, are shown in Table 11.

For the column in first example, the eccentricity is zero and thus, the design resistance $N_{Rd,\lambda^{\min}} = N^0_{Rd,\lambda^{\min}} = 1673$ kN. The load ratio $\mu_{fi,\lambda^{\min}}$ is calculated as $1000/1673 = 0.6$. The characteristic fire resistance $\overline{R}^0_f$ is obtained from Equations (6) as 156 min. The coefficients k_e and k_λ are equal to 1.0 and 0.75, respectively; hence, the design fire resistance $R_f = k_\lambda.k_e.\overline{R}^0_f = 117$ min.

For column CP, $N^0_{Rd,\lambda^{\min}}$ equals 1673 kN. Because the load is eccentrically applied, k_R is 0.8 and consequently $N_{Rd,\lambda^{\min}} = 0.8\,1673 = 1332$ kN. The value of $\mu_{fi,\lambda^{\min}}$ is $1000/1332 = 0.75$ and $\overline{R}^0_f$ equals 128 min. The values of k_e and k_λ are 0.96 and 0.50 (k_λ is determined using Equation (16)), respectively, and the design fire resistance R_f in this case is 61 min. For comparison, k_λ is determined using Equation (5). Its values in this case is 0.47 and R_f is 58 min. This reveals that at this range of λ, Equations (16) and (5) lead to close predictions.

The most striking result to emerge from these two examples is the impact of load eccentricity on the design fire resistance. It affects R_f not only through the reduction factor k_e, but also through the multiplier k_R, which reduces the design resistance $N_{Rd,\lambda^{\min}}$, increases the load ratio $\mu_{fi,\lambda^{\min}}$, and consequently decreases $\overline{R}^0_f$. These two examples have further strengthened the conviction that end condition has a big influence in fire resistance. The coefficient k_λ reduced from 0.75 when the column is fixed to 0.50 when the column is pinned, indicating that changing the end condition for this column from fixed to pinned reduced the fire resistance by about 48%.

5. Limitations

The proposed FRCC method presents a practical tool for determining the fire resistance of RC columns exposed to fire. As the method has been developed with respect to numerical studies, test data, and EC2 equation, the applicability of this method is limited to the range of parameters that were considered in these sources. Therefore, the limitations for the method are:

- Columns subjected to ASTM E119 standard fire, ISO 834 standard fire, or any design fire of similar profile as that of standard fire.
- Dimension of the column cross-section b (square or rectangular): up to 600 mm.

Table 11
Properties and Results for RC Columns Used in Illustrative Examples

Term	Expression	CI-7 (fixed–fixed)	CIII-3 (pinned–pinned)
f'_c(MPa)	Given	35	35
f_{ym}(MPa)	Given	420	420
A_s cm^2	Given	12.56	12.56
a mm	Given	58	58
b_1(mm)	Given	250	250
L(m)	Given	4.0	4.0
$L^{\min}$(m)	$r \times 4.3$	0.31	0.31
e(mm)	Given	0.0	20
$N_{Ed,fi}$(kN)	Given	1000	1000
λ	L/r	55.55	55.55
λ_e	$\lambda - 4.3 \quad k_e = 1.0 \quad e/b \leq 0.05$	51.25	51.25
k_e	$k_e = 1 - 1.43\left(\frac{e}{b} - 0.05\right) \quad 0.05 < e/b \leq 0.17$	1.0	0.96
$N^0_{Rd,\lambda^{\min}}$(kN)	$A_s\frac{f_y}{\gamma_s} + A_c\frac{0.85f'_c}{\gamma_c}, \gamma_s = 1.15,\ \gamma_c = 1.5$	1673	1673
k_R	$-8.49\left(\frac{e}{b}\right)^3 + 6.91\left(\frac{e}{b}\right)^2 - 3.049\frac{e}{b} + 1.0$	1.0	0.8
$N_{Rd,\lambda^{\min}}$(kN)	$k_R.N^0_{Rd,\lambda^{\min}}$	1673	1332
$\mu_{fi,\lambda^{\min}}$	$\mu_{fi,\lambda^{\min}} = \frac{N_{Ed,fi}}{N_{Rd,\lambda^{\min}}}$	0.6	0.75
ω	$\omega = \frac{A_s.f_{yd}}{A_c.f_{cd}},\ f_{yd} = \frac{f_{ym}}{\gamma_s}, f_{cd} = \frac{f_{cm}}{\gamma_c}$	0.32	0.32
$R_{\eta fi,\lambda^{\min}}$	$R_{\eta fi,\lambda^{\min}} = 83\left(1.0 - \mu_{fi,\lambda^{\min}}\frac{(1+\omega)}{(0.85/\alpha_{cc})+\omega}\right)$	27.04	12.7
R_a	$R_a = 1.6(a - 30)$	48.8	48.8
$R_{L^{\min}}$	$R_{L^{\min}} = 9.6(5 - L^{\min})$	45.027	45.027
R_b	$R_b = 0.09b'$	22.047	22.047
R_n	$R_n = 0 \quad for\ n \geq 4$ $R_n = 12 \quad for\ n < 4$	0.0	0.0
$\overline{R}^0_f$	$\overline{R}^0_f = 120.\left(\frac{R_{\eta fi,\lambda^{\min}} + R_a + R_{L^{\min}} + R_b + R_n}{120}\right)^{1.8}$	156	128
$\overline{R}_f$(min)	$\overline{R}_f = k_e.\overline{R}^0_f$	156	123
k_λ	See Equations (4) and (16)	0.75	0.50
R_f(min)	$R_f = k_\lambda.\overline{R}_f$	117	61

- Concrete cover: 25–80 mm.
- Percentage of longitudinal bars: 1%–4%.
- Concrete compressive strength: 24 MPa–53 MPa.
- Eccentricity ratio e/b: 0–0.4.
- Slenderness ratio λ: 0–100.
- Load ratio: 0.15–0.7.

6. Conclusions

In general, this study has primarily been concerned with developing an accurate and more rational solution of RC column design fire resistance problem. EC2 method does not have an explicit term that account for load eccentricity. In addition, a rigorous exact solution of design capacity at normal temperature conditions, which highly affects EC2 method predictions, is quite a formidable task. The theoretically based FRCC method, using the concept of fire-resistance-column-curves, thereby appears to be the method most viable and practical.

Based on the information presented in this study, the key findings can be concluded as follows:

- The results illustrated that by using an individual column curve for each end condition case, the deviation between the actual and the assessed fire resistance of the columns will be reduced significantly. Influential parameters such as slenderness ratio, load ratio, load eccentricity, cross-section size, concrete cover thickness, and reinforcement ratio imply a realistic basis for the computation. By explicitly taking into consideration the initial out-of-straightness, the solution appears to assume even further closeness to reality.
- Two equations were suggested to describe the proposed column curves. These equations are applicable for slenderness ratio in the range between 4.3 and 100, which cover most RC column lengths in practice.
- The characteristic fire resistance, which includes almost all the parameters that affect fire resistance, implies a realistic basis for the computation. This characteristic fire resistance is determined using EC2 equation at slenderness ratio of 4.3. The equation was modified by adding a parameter that accounts for the effect of load eccentricity.
- An equation was derived to calculate the column capacity at normal temperature conditions for very short eccentric columns. The proposed equation is simple, accurate, and helpful in determining the characteristic fire resistance.
- It was found that the resulted column curves represent a median for many experimental data. Therefore, these fire-resistance-column-curves can be safely used for design purpose when appropriate safety factors are adopted.
- Results revealed that for columns with smaller eccentricity ratio, explicitly taking the effect of load eccentricity in FRCC method leads to only slight improvement when compared to EC2 method. For columns with high eccen-

tricity ratio, FRCC method is safe but conservative. EC2 method, however, is unsafe in many column cases.
- By using FRCC method, the difficulty in determining exact solution of column capacity at normal temperature conditions that encountered in EC2 method has been eliminated.
- The proposed FRCC method can be treated as a modification for EC2 method. The method is practical, simple, and can be conveniently used by engineers for every day design; thus, it can be easily incorporated in design codes.

Author Contributions

Single Author.

Funding

Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Data Availability

Some Subroutines can be given.

Code Availability

Not applicable.

Declarations

Conflict of interest I wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

References

1. Dotreppe JC, Franssen JM, Vanderzeypen Y (1999) Calculation method for design of reinforced concrete columns under fire conditions. ACI Struct J 96(1):9–18
2. Franssen JM, Dotreppe JC (2003) Fire tests and calculation methods for circular concrete columns. Fire Technol 39:80–97
3. Franssen JM (2000) Design of concrete columns based on EC2 tabulated data-a critical review. First International Workshop Structures in Fire, Copenhagen
4. prEN 1992-1-2: Eurocode 2 (2004) Design of concrete structures—part 1–2: general rules-structural fire design. Brussels.
5. Kodur VKR, Raut N (2012) A simplified approach for predicting fire resistance of reinforced concrete columns under biaxial bending. Eng Struct 41:428–443
6. Buch SH, Sharma UK (2017) Fire resistance of reinforced concrete columns: a systematic review. In: *Proceedings of the international conference of applications of structural fire engineering (ASFE 2017)*, September 7–8, 2017, Manchester
7. Mahmoud KA (2021) Fire resistance-effective parameters relationships of slender rectangular and circular RC columns. Fire Saf J . 10.1016/j.firesaf.2021.103442
8. Mahmoud KA (2021) Overview of factors affecting the behavior of reinforced concrete columns with imperfections at high temperature. Fire Technol J 58:851–887. 10.1007/s10694-021-01180-4
9. Hurst JP, Ahmed GN (1999) Modeling pore pressure, moisture, and temperature in high-strength concrete columns exposed to fire. Fire Technol 35(3):232–262
10. ASTM-E119 (2007) Standard test methods for fire tests of building construction and materials. ASTM International, West Conshohocken
11. ISO 834 (1999) Fire-resistance tests—elements of building construction—part 1: general requirements. International Organization for Standardization, Geneva
12. ASCE Manual (1992) Structural fire protection. American Society of Civil Engineers, New York, No. 78:1-241.
13. Mahmoud KA (2020) Behavior of slender RC columns bent in single and double curvature at elevated temperatures. Fire Technol . 10.1007/s10694-020-01057-y
14. Raut N, Kodur VKR (2011) Response of reinforced concrete columns under fire-induced biaxial bending. ACI Struct J 108(5):610–619
15. Lie TT (1989) Fire resistance of reinforced concrete columns: a parametric study. J Fire Prot Eng 1–4:121–129
16. Lie TT, Woollerton JL (1988) Fire safety of reinforced concrete columns. NRCC, Canada, Internal Report No 569.