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META-ANALYSIS OF CODE-BASED DESIGN METHODS TO QUANTIFY THE FIRE RESISTANCE RATINGS OF CONCRETE COLUMNS

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Abstract: The design approaches of reinforced concrete (RC) columns are well understood at ambient temperature, and experimental test results correlate well with methods to investigate the strength capacity and failure criteria/modes of structural elements; however, this is not the case in fire scenarios. Using a meta-analysis, this study examines and evaluates the statistical reliability of six distinct methods/tabular guidelines from five countries' fire-resistant design concepts and procedures. In addition to this, the historical development of guidelines was emphasized. Meta-analysis is a method that examines a large dataset to determine the general trend of factors influencing the same object. In this investigation, 175 full-scale concrete column experiments were collected from around the world to determine their fire resistance capacity. It was discovered that all methods and tabular guidelines are founded on a specific set of experiments, and their applicability to a newly available set of experiments is beset with uncertainty. Method A of Eurocode (EN 1992-1-2:2019) is relatively accurate in predicting the fire resistance rating (FRR) for up to 240 minutes, whereas Method B is accurate for up to 150 minutes. The Chinese method (DBJ/T 15-81) is regarded as quite effective for the set of experiments from which the Eurocode equation was derived, but the accuracy of its predictions for other sets of experiments was highly variable. The ACI 216.1 and IS 1642 methods appear to underestimate the FRR in most experiments. Therefore, it is concluded that either the limitations of these guidelines must be modified, or new equation/tabular guidelines are required in place of newly available experiment sets.

1 INTRODUCTION

Concrete is the most commonly employed material for the construction of multi-story structures, globally [1]. Among the various potential hazards, fire poses a significant threat to reinforced concrete buildings, which can cause substantial damage [2]. Elevated temperatures during a fire can result in spalling, concrete disintegration, and steel softening, rendering multi-story buildings susceptible to failure. To ensure well-suited fire safe designs, the structural elements of a building must possess an adequate fire resistance rating (FRR) as per established fire safety guidelines [2].

The performance of a reinforced concrete (RC) structure during a fire is greatly influenced by the behaviour of its columns. In some cases, the structural capacity loss of a column can lead to the progressive collapse of the whole structure [3, 4]. Historically, the fire resistance of structures could only be estimated by exposing them to standard fire resistance tests (ISO 834) [5]. However, based on experimental data, there are now various tabular and equation-based methods available in the design codes [e.g., 6-9] to estimate the fire resistance of columns based on the few key parameters (e.g., aggregate type, cover distance, the minimum dimension of the column, load ratio, reinforcement ratio, etc.). There are more advanced methods to predict fire ratings such as numerical models and sectional analysis, but these methods are often time-consuming and complex. Hence, engineers typically adhere to the guidelines outlined in the codes.

In the present study, an extensive meta-analysis was conducted to examine these prescribed guidelines. This investigation aims to draw attention to the potential shortcomings of existing design methods to assess their statistical robustness in predicting fire resistance capacities. To accomplish this, a dataset consisting of 175 RC column fire experiments from around the world was compiled and analysed in relation to the guidelines provided by five different standards. Additionally, the evolution of these guidelines over time and their reliance on codes from other countries are also discussed in detail.

2 EXPERIMENTAL DATASETS ON REINFORCED CONCRETE COLUMNS IN FIRE

In this paper, 175 experimental results from the last 54 years were considered. The details of all these tests and authors are depicted Table 1. There are 86 concentrically loaded and 89 eccentrically loaded columns. Most of the columns in the dataset (166) are square-shaped, and just a small number of them (nine) fall under the category of rectangular columns. It should be noted that circular columns in fires are not included within this study. All tests are performed using a standard fire exposure (i.e., ISO 834 [5] or ASTM E119 [10]) that only included a heating phase until failure.

Within the data presented in Table 1, significant variance of the columns parameters can be seen, such as; concrete strength ranged between 17.8-138 MPa, and cover ranged from 16-64 mm; reinforcement diameters ranged from 12-32mm with strengths ranging from 340-591 MPa and percentage of reinforcement ranging from 0.89-4.38%; pin-pinned end conditions were present for 42% of the tests, with pin-fixed, and fixed-fixed, accounting for 21% and 36% of the tests respectively; applied loads ranged from 60-6900 kN; 71 % of columns lie in size range of 200- 400 mm and very few (5) are more than 400 mm, and lastly, eccentricity for the loaded column ranged between 0-250 mm (0-50% of cross-section).

These values by and large were well documented and explained and seem reasonable. However, a key variable, load ratio, was harder to reason with documented ratios lying between 0.23 and 1.83. It should be noted that a load ratio value of greater than 1.0, it means that in some cases (i.e., 22 tests out of 175) the applied load is more than its capacity. While the authors have tried to understand this discrepancy, the papers have not clearly articulated how these load ratio values have been determined, and therefore load ratio as a parameter will not be investigated further within this paper.

3 HISTORY OF FIRE RESISTANCE DESIGNS METHODS/ GUIDLINES FOR REINFORCED CONCRETE COLUMNS

The temperature distribution in the concrete column's cross-section varies based on exposure conditions and time of fire exposure. Typically, the temperature concentration is higher at the edges and lower inside the cross-section. As temperature increases, both the compressive and tensile strength of concrete and steel decrease, with variations across the cross-section [2]. This section explains various methods/guidelines their limitation and historical development of these in detail.

In Europe and United Kingdom, the Eurocode 1992-1-2 [6] depicts 6 different simplified methods to determine the FRR of column. “Method A” divides into tabular and equation-based parts, while “Method B” is solely tabular based method. The Australian code method (AS 3600) [11], Chinese Code Method (DBJ/T -15-81) [7, 12] are equation-based, while, American (ACI 216.1 Method) [8], and Indian code (IS 1642:1989- NBC: 2016) [9] are table-based methods used in this study. The brief description of these methods are outlined as follows:

3.1 Method A (EN 1992-1-2:2019)

This method is popular among the engineers to estimate the FRR of concrete column in fire being first developed and proposed between

Table 1: Details of RC Column used in Meta-analysis in fire

Researchers/ Lab		**Specimen details**					**Reinforcement details**			**Load Conditions**		**Concrete Properties**		**Fire curve**	**Failure**
Author/ University	Year	Length	End* (Nos)	Load Ratio *(Nos)*	Sec. Type *(Nos)*	Size	Long. Bars	As/Ac ratio (%)	Strength	N applied	*Ecc*	Cover	Strength (Test Day)	Code	Time
		m				mm	dia (mm)		Mpa	KN	mm	mm	Mpa		Mins
University of Ghent [13]	1997	3.95	PP (15)	<0.4 (7) 0.4-0.8 (4) >0.8 (4)	S (2)	300	16	0.89	576	345-890	0	25	40.9-42.7	ISO 834	61-120
					S (9)	300	16-25	0.89-2.18	576-591	208-1680	20/20”	25-40	35.1-44.1		34-128
					R (3)	200-300	12	1.13	493	60-170	20/20”	25-35	35.7-39.2		60-120
University of Liege [13]	1997	2.1	PP (5)	0.4-0.8 (3) >0.8 (2)	S (3)	300	16-25	0.89-2.18	576-591	298-878	0	25	32.7-38.5	ISO 834	60-120
					R (2)	200×300	12	0.01	493	611-620	0	25-35	37.6-40		97-107
NRC [14]	1989	3.81	FF (17)	0.4-0.8 (9) >0.8 (11)	S (18)	203-406	25.5-32.3	2.19-4.38	444	169-2978	0	48-64	34.2-52.9	ASTM E119	146-285
			FP (2)		S (2)	305	25.5	2.19	444	100-1178	25*	48	37.9-39.9		181-183
			PP (1)												
University of Braunschweig [15]	1986	3.76-5.76	PP (36)	0.4-0.8 (22) >0.8 (17)	S (7)	200-300	20	0.02	487	392-1234	0	28	24.1	ISO 834	48-138
			FP (3)		S (32)	200-300	14-20	1-3.1	404-544	130-1695	5-150*	23-28	24.1-42.8		31-160
Kodur et. al. [4,16,17]	2000-2009	3.35-3.81	FF (16)	<0.4 (2) 0.4-0.8 (11) >0.8 (9)	S (18)	203-406	16-25	1.78-3.04	400-420	445-5373	0	16-25	51-126	ASTM E119	61-271
			PP (8)		S (5)	305-406	16-25	1.78-2.38	400-420	2954-4981	25-27*	40	51-126		49-248
Zhu and Lie [18]	1993	3.5-3.81	FF (6)	?	S (4)	300	22	0.02	340	1180	0	30	23.2-26.4	ISO 834	96-184
					R (2)	200-900	20	1.39-1.86	340	1585-2218	0	30	21.9-26.8		82-266
Dong et. al., [19]	2014	3.64	FF (4)	>0.8 (3)	S (2)	405	20	0.01	559	3000-6900	0	30	17.8-40.47	ISO 834	118-227
Shah and Sharma [20]	2017	2.8	FF (8)	0.4 (8)	S (8)	300	16	0.02	569	1170	0	40	34-63	ISO 834	325-418
Xu et. al, [21]	2020	3.84	FF (3)	<0.4 (3)	S (3)	400	28	1.54	400	1986-2484	0	50	40	ISO 834	91-145

Ali et. al, [22]	2009	1.8	FP (13)	<0.4 (7) 0.4-0.8 (5)	S (13)	127	12	2.8	440	?	0	20	106	ISO 834	25-57
Li et. al, [23]	2021	2.3	FP (5)	<0.4 (5)	S (3)	200	20	3.14	564	750-1090	0	30	93.2-140	ISO 834	48-72
					S (2)	200	20	3.14	564	635-760	30,50	30	138		41,48
Martins and Rodrigues [24]	2010	2.5	FF (11)	<0.4 (1) 0.4-0.8 (5) >0.8 (5)	S (9)	160-250	10-16	1.29-3.14	500	45-507	0	30	25	ISO 834	67-247
					S (2)	250	25	3.14	500	656-675	250	30	25		118-143
Benmarce and Guenfoud [25]	2005	1.8	FP (6)	<0.4 (4) 0.4-0.8 (2)	S (6)	125	12	2.894	440	?	0	20	108	ISO 834	21-70
Buch and Sharma [26]	2019	2.175	FP (6)	*<0.4 (6)*	S (1)	300	16-20	2.289	498	544	0	40	28	ISO 834	236
					S (2)	250	25	3.14	500	656-675	250	30	25		118-143
Myllymaki and Lie [27]	1991	3.81	FF (1)	?	S (1)	300	16	0.893	582.3	1400	0	24	37.8	ISO 834	58
Nan S, et. al, [28]	1968	3.81	FF (6)	?	S (6)	305	25.5	2.19	444	801-1780	0	48	36.9-46.6	ASTM E119	215-410
Lie T.T and Woollerton J.L [29]	1988	3.81	FF (2)	?	S (1)	305	25.5	2.19	444	1022	0	48	41.6	ASTM E119	221
					R (1)	305×457	22.22	2.19		1413	0		42.5		296

Abbreviations and symbols used in Table 1: *PP- Pinned-Pinned, FF-Fixed-Fixed, PF-Pinned-Fixed, S- Square Shaped, R- Rectangular Shaped, long.-Longitudinal Bars, Ecc- Eccentricity, As- Area of steel in section, Ac-Cross-Sectional area of the section, End*- Support Conditions, *- Uniaxial,"- Bi-axial, ??- Not Known. Highlighted tests indicate Old dataset.*

1995-2000 [30,31]. According to Franssen "*the proposed equation is just a best-fit equation; it is not based on any consideration of equilibrium*" and "*the proposed model must anyway be seen as belonging to the family of the tabulated data*" [31]. Both proposals are based on identical test data from 4 different research institutes, namely, 21 tests from the National Research Centre Canada (NRCC) [14], 39 from the University Braunschweige Test [15], 4 the best-fit from the University of Liege [13], and 12 from University of Ghent [13].

By changing the values of α_{cc} and ω with the method presented in [30], the proposed equation by Franssen (Eq. 1) [31] was recalibrated on 76 tests and introduced in Eurocode 1992-1-2 [6].

In year 2003, Franssen and Dotreppe proved the applicability of this equation for four additional circular columns [32].

This part of the development of Method A is quite well documented. However, how other parts of the method were developed is not clear.

In Eurocode 1992-1-2 [6], Method A is then subdivided into two parts. The first part is tabular where you calculate the minimum width of column (b_{min}) and the distance of main reinforcement bars based on the time of fire resistance and degree of utilization $\left(\mu_{fi}\right)$.

The second approach is based on the equation developed by Franssen [30-32]. The Eq. 1 to calculate the FRR is given as follows:

$$R = 120\left(\frac{R_{\eta fi} + R_a + R_l + R_b + R_n}{120}\right)^{1.8} \quad (1)$$

where $R_{\eta fi}$ depends on the utilisation factor; R_a depends on the axis cover distance (a, where $25 \leq a \leq 80$ mm) of main reinforcement in ambient conditions; R_l, depends on the effective length of column in fire conditions; and where R_b and R_n depend on the shape and number of longitudinal bars ($R_n = 0$ if number of bars, $n = 4$ and $R_n = 12$ if $n > 4$).

3.2 Method B (EN 1992-1-2:2019)

Method B is fully tabular based. This method is valid for the concrete columns in braced structures, where the load level n, at normal temperature conditions is given in Eq. 2

$$n = \frac{N_{o,Ed,fi}}{0.7\,(A_c f_{cd} + A_s f_{yd})} \quad (2)$$

where, the $N_{o,Ed,fi}$ is the axial load applied on column in normal temperature conditions. Table 5.2b [6] then provides data to determine the minimum width of column (b_{min}) and the distance of main reinforcement (a) based on the load level (n) and mechanical reinforcement ratio (ω). It requires interpolation between these 4 parameters. A detailed explanation about how is given in reference [32].

3.3 Australian Method (AS 3600:2018)

The first Australian code AS 3600:1988 was published in March 1988. Since then, AS 3600 has been revised four times. According to the second revision of AS 3600:1994 [33], the fire resistance periods (FRP) for column shall be determined with the Fig. 5.6.3 in the code. This Fig.. was dependent on Table 3.5 and Fig.. 3.2 of code BS 8110-1-1985 [34] and Section 4 of BS 8110-2-1985 [35]. These tables in both codes utilised information and tabular data from the Department of the Environment's Building Research Establishment Report [36].

In 1997, Cement and Concrete Association of Australia and Steel Reinforcement Institute of Australia funded the Building Research Association of New Zealand (BRANZ) to carry out a research program to resolve anomalies and propose an equation [37]. In this research, authors used computer model developed by NRCC and correlated against previous column fire tests (*18 - from NRCC* [14]) and proposed a simple equation for fire resistance of concrete column (Eq. 3), developed using the AS 1530 Part 4 [38] fire curve rather than the experimental ASTM E119 [10] fire curve. This equation was adopted in AS 3600:2001 [39]:

$$R = \frac{k \times f_c'^{a} \times B^b \times D^c}{10^5 \times C^d \times l_e^e} \quad (3)$$

where, R is fire resistance period of column in (min); k is a constant dependent on the cover and amount of steel, and is 1.5 when $A_s/A_g < 0.025$ or 1.7 when it is greater; f_c' is the 28-day compressive strength of concrete; B is the smallest dimension of column while D is the greatest dimension; C is the axial load for the fire conditions, and L_e effective length. *a, b, c, d and e* are regression constants and are 1.3, 3.3, 1.8, 1.5, and 0.9, respectively.

AS 3600 was again revised in 2009 [40], in which they replaced this Equation and implemented the tables from Method A and Method B from Eurocode 1992-1-2 [6] but without Eq. 1 from Method A. In the latest 2018 version, AS 3600:2018 [11], they have adopted same equation and methods from Eurocode 1992-1-2 [6] with a slight change in parameter α_{cc} (0.945) and applying a 1.3× multiplication factor to mechanical reinforcement ratio (ω).

3.4 Chinese Code Method (DBJ/T 15-81)

Two methods are given in DBJ/T 15-81-2022 [7]. The first method is tabular based that resembles Method A of Eurocode 1992-1-2 [6], with small changes in the values of cover to the main bars (a), and no provision given for the 30 min FRR [6].

The second method in DBJ/T 15-81-2022 [7] is equation-based and supersedes a simple equation from DBJ/T 15-81-2011 [12]. The following Eq. 4 will give you the resisting capacity of concrete column in fire.

$$R_f = \beta_\mu . \beta_L . \beta_{hdb} . \beta_b . \beta_e . \beta_\rho \qquad (4)$$

where, R_f is the FRR is expressed in min. and the parameters $\beta_\mu, \beta_L, \beta_{hdb}, \beta_b, \beta_e, and\ \beta_\rho$ from Eq.4 are explained in detailed in the code [7, 12].

Equation 4 was developed, not based on experimental fire test data, but on modelling work that started in 2008 [41,42]. Nine thousand (9000) columns, exposed to the ISO 834 [5] standard fire curve on all four sides, were modelled and a multivariate regression analysis culminated in Eq. 4. Due to modelling based method there are limitations to its applicability, namely: $2.0\,m \le L \le 4.0\,m$; $0.3\,m \le b \le 0.6\,m$; $b \le h \le 0.6\,m$; $0.0 \le e \le 2.0$; $1\% \le \rho \le 3\%$; $0.2 \le \mu \le 0.7$.

3.5 Indian Code Method (NBC: 2016)

The fire resistance of concrete columns designed using a tabulated method in the Indian code [9,43], and is dependent on the extent of exposure (partially, fully, or 50 %), with minimum column size and cover distance stipulated, as well as the type of construction and number of floors the column can be used in.

The history of these tables given in NBC code [43] can be traced back to IS 1642:1989 [9], where tabular data therein came from Section 3.3.6 of BS 8110-1-1985 [34] and Section 4 BS 8110-2-1985 [35]. Since 1989, the Indian code [43] has only altered the cover size to 40 mm for all column sizes and exposure situations. This tabular approach only valid for column sizes 150-450 mm and does not account for aggregate type, cover thickness, reinforcement ratio, or load level.

3.6 American Method (ACI 216.1:2014)

The methods incorporated in ACI Codes are based upon the experimental data collected between 1958 to 2005 and are commonly implemented across the North America [44]. To the author's best knowledge, the first mention of the relation between load and performance of columns in fire was tabular data given in ACI 216R-89 [45]. The tabular data was based on fire tests of 38 full size concrete columns [31]. A 1997 code revision (ACI 216.-97/ TMS 0216.1-97) [8] incorporated five fire resistance ratings (FRR) based on type of aggregates (siliceous, carbonate and semi-lightweight aggregates), minimum concrete size and extent of fire exposure to the column (parallel or full sides).

The code was revised again in 2007 [46] and included two clauses based on the strength of concrete. The first clause was for the strength (f_c) < 12000 psi (82.7 MPa), where the data given in the code is applicable, and the second was for (f_c) > 12000 psi, where the least dimension should of the column should be 24 inches for FRR of 1-4 hrs.

In 2019 the new reapproved code, includes same clause form previous version. In this study, the tabular guidelines form the code ACI 216.1-14(19) [47] are used for meta-analysis.

4 METHODS OF META-ANALYSIS

In this paper, experimental and predicted fire resistance for all current approaches are compared for the statistical measures of; 1) conservatism, 2) accuracy, and 3) error.

During this meta-analysis of available literature data, two mathematical factors, namely mean error (*ME*) and mean average percentage error (*MPE*), are used to provide a measure of each models' conservatism. The *ME* is calculated by taking average of error between predicted and experimental results from dataset for each respective design approach. While *MPE* is calculated by taking an average of percentage error between actual and predicated and with respect to actual experimental results. Positive values of *ME* indicate over-predictions of fire resistance, which for assessment of fire resistance is un-conservative (unsafe). While negative values indicate under-prediction of fire resistance [48].

The ideal values of *ME*s and *MPE*s are those that are closer to zero, meaning that average predictions of results are accurate, or the method is reliable in such cases to estimate resistance. To establish each model's accuracy, mean absolute percentage error (*MAPE*) was calculated by taking the absolute value of the percentage error of prediction.

Lastly, precision was evaluated by calculating the standard deviation of the error (σ) between predicted and actual fire resistance. Lower values imply greater precision.

The meta-analysis evaluates the reliability of a model's capacity to predict a fire-resistance rating based on the hypothesis that the variance of the errors between the prediction and the actual test ratings is normally distributed around the mean [48].

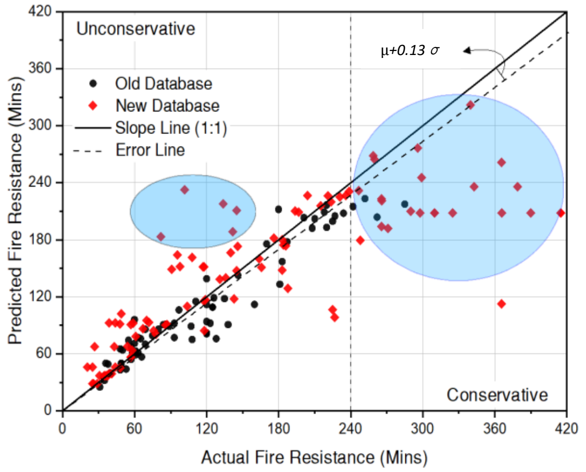
During the meta-analysis only the experiments that are applicable for the method are assessed. Thus, 175 tests were assessed for Eurocode 1992-1-2 methods A and B, and the Australian Method; 102 for the Chinese method; 168 for the ACI 216.1 method; and 156 for the NBC India method. Additionally, this dataset is then subdivided into two parts; an Old dataset (Highlighted in Table 1) on which Eurocode 1992-1-2 equation was developed; and a New dataset. This results in Old/New datasets of 76/99 for methods A and B and the Australian method; 56/46 for the Chinese method; 79/88 for the ACI 216.1 method; and 77/79 for the NBC, India, method, respectively.

4.1 Statistical comparative analysis of approaches

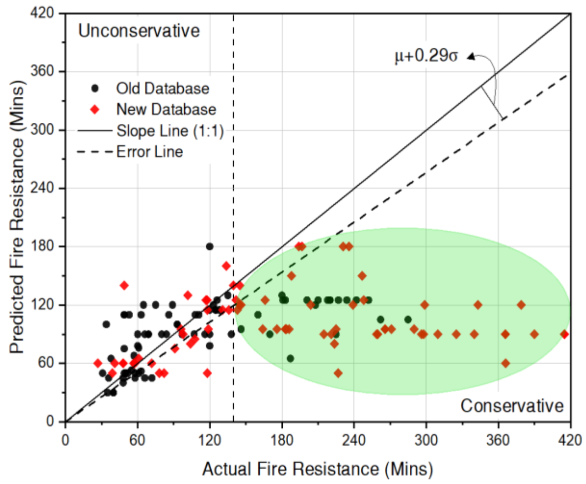
The approaches described in Section 3 have been compared based on statistical parameters such as *ME*, *MAPE*, and σ. In each of the following figures the experimental fire resistance of concrete columns is compared with the predicted fire resistance using the various methods. A solid diagonal line represents zero error between the predicted and actual results. The data points which fall above this line signify unconservative predictions and predictions that fall below the line indicate conservative predictions. The dashed line shows the average prediction error for the entire dataset from the origin, with the number of standard deviations to zero error highlighted. Two datasets are presented for the old and new data as mentioned above.

Figure 1 examines the prediction ability of Eurocode 1992-1-2 Method A (Fig.1a) and Method B (Fig.1b). For Method A the observed absolute *ME* and MPE of prediction is –13 mins and –4.7 %, respectively; a negative *ME* and *MPE* estimates that, on average, the predicted fire resistance times are conservative. The *MAPE* (average magnitude of the error) of Method A is 24%, with a standard deviation of 36%. This suggests that Method A's mean prediction error is 0.13 standard deviations (σ) below (conservative) the zero-error line. While statistical certainty in the model is low overall, the predicted results are likely to be on safer side. On the other hand, from Fig.2, it is indicated that, *MPE* value for the Old/New dataset is 2.5% and -10 %, respectively, with a σ of 20 % for Old and 71 % for New dataset. This suggests that the Old dataset is comparatively more accurate in predicting the FRR as compare to New dataset for the Method A. Apart from this, it is also observed that from Fig.1a, Method A is having good prediction up-to 240 min and then the data is quite dispersing (highlighted in blue).

Fig.1b shows the results based on the Method B from Eurocode, in this case the *ME* value is -57 mins and *MPE* is -14%, which indicates there is considerable variation in the error between predicted and actual value and the prediction is lying on the safer side (i.e., conservative) results. Also, its mean error is 0.29 times the (σ) below slope line (1:1).



(a)



(b)

Fig.1: Predicted vs Actual Fire Resistance for Eurocode 1992-1-2 (a) Method A (b) Method B

In terms of Old vs New dataset in case of Method B, a σ value observed twice of Old dataset (112%) than New dataset, giving high dispersion and less precision. Figure 2 shows Old dataset is comparatively accurate in predicting FRR with *MAPE* of 35%. Apart from this, it is also observed that from Fig.1b, Method B is having good prediction up-to 140 min and then the data is quite dispersing (highlighted in green).

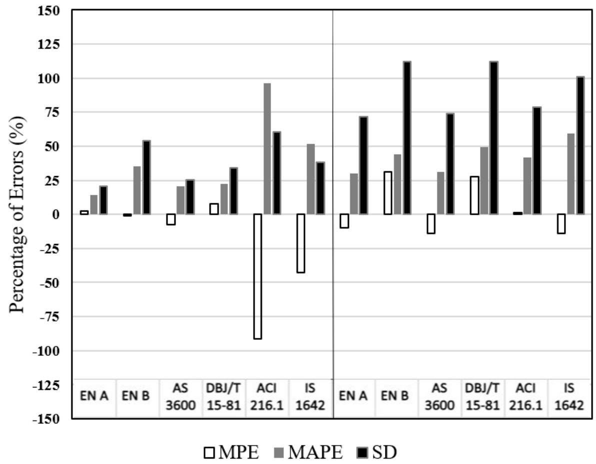


Fig.2: Comparison of *MPE, MAPE* and σ for Old and New dataset for approaches

As mentioned previously the Australian method [11] and Method A are similar but due have a couple of slight differences that impact the results. Figure 3 shows the predicted versus actual fire resistance for the Australian method, and shows that overall, it is less conservative than the Method A, but still conservative with a *ME* of -8 mins. The Australian method showed a similar level of σ as Method A with a *MAPE* of 25%, however the method was less precise than Method A with a standard deviation (σ) of 50%, and thus the mean error linear trend lies 0.18 σ below the 1:1 slope line.

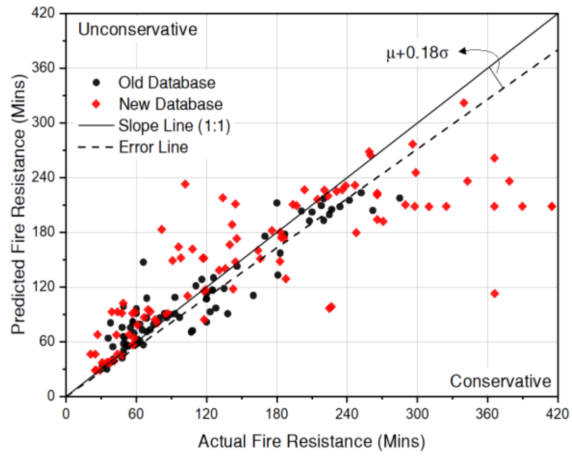


Fig.3: Predicted Vs Actual Fire Resistance - Australian Method

In general, the Method A approach is more accurate (lower *MPE* and *MAPE*) and more precise (lower standard deviation) than approach Australian Method. From Fig.2, in case of this Australian method Old database predicted more accurate results than New dataset with the value of *MAPE* of 20% and 30%, respectively.

The Chinese method [6] exhibits significant variance in prediction outcomes for the New dataset as shown in Fig.4. Overall, the *ME* is -52 minutes, with a *MPE* of -16%. These results indicate an overall tendency for conservative predictions. However, the standard deviation (σ) for the percentage error is 47%, suggesting a large variability. Additionally, the mean error of prediction lies 0.34 standard deviations below the 1:1 slope line. This method lacks statistical confidence in accuracy and prediction precision, as reflected by a *MAPE* of 34% and an standard deviation for mean error of 72 minutes.

Fig.2 illustrates that this is in part due to how the method performs with the Old and New datasets, where predictions of the Old dataset (light grey area) show much less dispersion more precision (σ - 33%) compared to the New dataset (σ -112%) (light red area). In terms of accuracy in this Old vs New dataset, New dataset has *MAPE* twice that of Old dataset with value of 49 %.

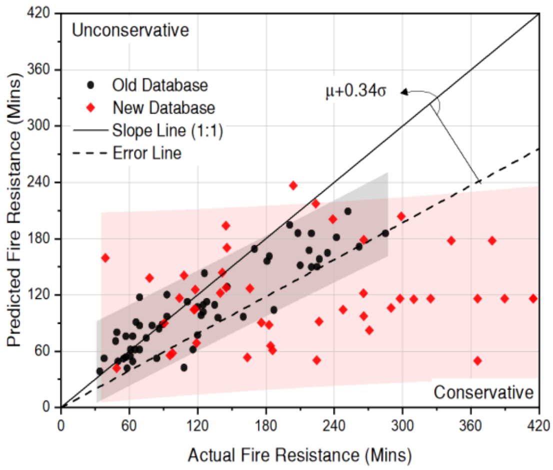
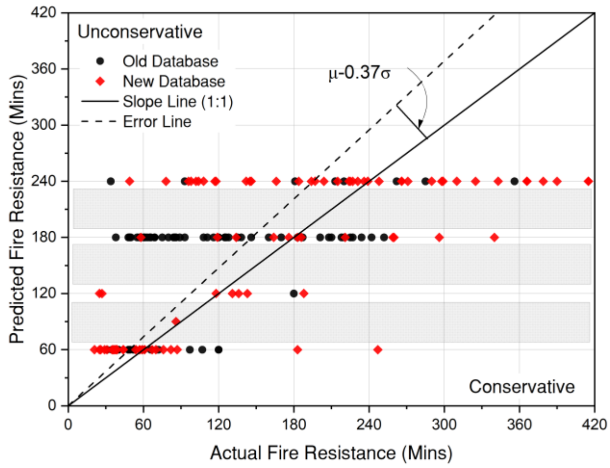


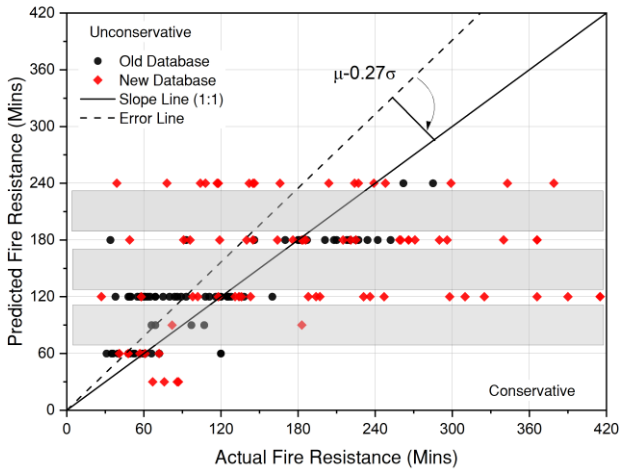
Fig.4: Predicted vs Actual Fire Resistance - Chinese Method

The predictions for the New dataset, indicated by the light red colour, shows substantial variance in prediction ability, whereas the Old dataset displays comparatively less dispersion about mean.

The predicated FRRs given by the ACI Method [7, 52] and Indian Method [8, 54] are pretty straightforward to determine. The ACI method gives you the FRR from 60 mins while, Indian Method gives FRR from 30 mins. From Fig. 5a and 5b, it is indicated that, in both cases data is well spread and, in general, is unconservative, sometime overpredicting the fire resistance time by over 180 minutes.



(a)



(b)

Fig.5: Predicted vs Actual Fire Resistance (a) ACI Method (b) Indian Method

With these approaches the FRR can be predicted with 30 min intervals, making the meta-analysis either conservative or un-conservative by up to half an hour and difficult to estimates its pattern in terms of prediction.

The *ME* is calculated to be +18 mins and -8 mins, with *MPE* +36% and +23% for ACI and Indian methods, respectively. These values of statistics and normal distribution of the errors indicates that, these are methods are unconservative (i.e., on average unsafe).

The ACI and Indian methods standard deviations yield values of 94% and 83%, with the mean prediction error lying 0.37× and 0.27× standard deviations (σ) above the line (1:1) (i.e., on the unsafe side) for ACI and Indian methods, respectively. High values of standard deviation suggest the data is highly dispersed. In terms of Old vs New dataset for the ACI and Indian method, from Fig. 2 it indicates that data in case of New database in more dispersed about mean with σ of 78% and 100%, respectively.

Both methods show a lack of precision and accuracy and thus there is low confidence in the reliability of either method. Both methods were developed based on selected number of data points, therefore there is need for improvement in the model or methodology to reduce the uncertainty and enhance their predictive abilities.

5 CONCLUSIONS

In this study a brief review of the available experimental data on reinforced concrete columns in fire dataset and the various simplified codified methods to estimate FRR was presented. A statistical assessment of these respective code approaches was conducted by comparing code predicted fire resistance times against observed fire resistance times from available standard furnace tests carried out worldwide. Based on the statistical parameters following conclusion are drawn:

- Eurocode 1992-1-2 Method A demonstrated a good ability to predict fire resistance up to 240 mins on the Old dataset and some from the New dataset, after which time the prediction ability is poor. In similar pattern, Method B is good up to 140 min, and poor after.
- The equation utilized in the Australian Method is identical to Method A with minor adjustments made to certain parameters, which results in the Australian Method being more conservative and having less level of accuracy than the Method A with *MPE* of -9.5 % and -4.7 %, respectively.
- Analysing the New dataset with the Chinese Method showed a large dispersion about mean with a σ of 112%, while the same analysis on the Old dataset returned a σ of 33%.
- In terms of level of accuracy, the Old dataset with the Chinese Method predicts results more accurately than with the New dataset with values of *MAPE* of 22% and 49%, respectively.
- The ACI and Indian Method predicted results were on average unconservative, sometimes significantly, as well as being imprecise.
- In terms of precision in ACI and Indian method with respect to Old vs New dataset, Old dataset in comparatively more precise in prediction.

Based on these conclusions, it is highly recommended that a thorough statistical analysis be undertaken, encompassing the New dataset, as well as understanding if certain parameters are not being well represented in the prediction models (e.g., reinforcement ratio). Furthermore, it is crucial to reassess the suitability criteria of various approaches. With these kinds of efforts, the current methods can be fine-tuned and improved upon to continue to meet the requirements of structural fire safety.

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References

[1] Buch SH, Sharma UK. 2023. Statistical Review of the Fire Resistance of Concrete Columns. *Arab J Sci Eng*; 48: 5005–5018.

[2] Rokade M, Gaikwad M, Singh S, et al.

2022. A simplified regression-based approach for concrete mechanical properties at elevated temperature. *Asian J Civ Eng*; 23: 1065–1085.

[3] Usmani AS, Rotter JM, Lamont S, et al. 2001. Fundamental principles of structural behaviour under thermal effects. *Fire Saf J*; 36: 721–744.

[4] Kodur VKR, Wang TC, Cheng FP. 2004. Predicting the fire resistance behaviour of high strength concrete columns. *Cem Concr Compos*; 26: 141–153.

[5] ISO 834: Fire resistance tests-elements of building construction. Geneva, Switzerland, 1999.

[6] British Standards Institution BSI. EN 1992-1-2:2004/A1:2019, Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design.

[7] DBJ/T 15-81-2022: Code for fire resistance design of concrete structures in buildings.

[8] ACI/TMS Committee 216. ACI 216.1-97 / TMS 0216.1-97: Standard Method for Determining Fire Resistance of Concrete and Masonry Construction Assemblies. 1997. *Man Concr Pract*; 1–26.

[9] IS 1642:1989. Indian Standard Fire Safety of Buildings (General): Details of Construction—Code of Practice. *Bur Indian Stand New Delhi*; 1989: 12.

[10] ASTM E119: *Standard test methods for fire tests of building construction and materials*. 2007. West Conshohocken, USA. Epub ahead of print. DOI: 10.1520/E0119-12A.

[11] AS 3600:2018 Austrilian Standards for Concrete Structures; 269.

[12] DBJ/T 15-81-2011: Code for fire resistance design of concrete structures in buildings.

[13] Dotreppe JC, Franssen JM, Bruls A, et al. 1997. Experimental research on the determination of the main parameters affecting the behaviour of reinforced concrete columns under fire conditions. *Mag Concr Res*; 48: 117–127.

[14] Lie TT, Wollerton JL.1989. Fire resistance of reinforced concrete columns: a parametric study. *National research council canada.*

[15] Haß R. 1986 .Zur praxisgerechten brandschutztechnischen beurteilung von stützen aus stahl und beton, Phd Thesis,http://www.digibib.tubs.de/?docid=00054318

[16] Kodur VKR, Mcgrath R. 2000. *Experimental Studies on the Fire Endurance of High-Strength Concrete Columns*. 2000. Epub ahead of print. DOI: 10.4224/20378032.

[17] Kodur VKR, McGrath R. 2003. Fire endurance of high strength concrete columns. *Fire Technol*; 39: 73–87.

[18] Zhu, H.L and Lie TT. 1993. Fire Resistance Evaluation of Reinforced Concrete Column*s*. *National research council canada. https://doi.org/10.4224/20358506*

[19] Dong H, Cao W, Bian J, et al. 2014. The fire resistance performance of recycled aggregate concrete columns with different concrete compressive strengths. *Materials (Basel)*; 7: 7843–7860.

[20] Shah AH, Sharma UK. 2017. Fire resistance and spalling performance of confined concrete columns. *Constr Build Mater*; 156: 161–174.

[21] Xu H, Yu M, Xue C, et al. Experimental study on fire resistance of precast concrete columns with efficient reinforcement. *Eng Struct* 2020; 204: 109947.

[22] Ali F, Nadjai A, Choi S. 2010. Numerical and experimental investigation of the behavior of high strength concrete columns in fire. *Eng Struct*; 32: 1236–1243.

[23] Li Y, Du P, Tan KH. 2021.Fire resistance of ultra-high performance concrete columns subjected to axial and eccentric loading. *Eng Struct*; 248. Epub ahead of print. DOI: 10.1016/j.engstruct.2021.113158.

[24] Martins AMB, Rodrigues JPC. 2010. Behavior of concrete columns subjected to fire. *Struct Fire - Proc Sixth Int Conf SiF'10*; 181–188.

[25] Benmarce A, Guenfoud M. 2005. Experimental behaviour of high-strength concrete columns in fire. *Mag Concr Res*; 57: 283–287.

[26] Buch SH, Sharma UK. 2019. Fire Resistance of Eccentrically Loaded Reinforced Concrete Columns. *Fire Technol*; 55: 1517–1552.

[27] Myllymaki J, Lie TT. 1991. Fire resistance test of a square reinforced concrete column. *National research council canada.*

[28] Nan S, Lin TD, Lie TT. 1968. Fire resistance of reinforced concrete columns. *NRC Publ Arch*.

[29] Lie TT, Wollerton JL.1988. Fire resistance of reinforced concrete columns: Test Results. *National research council canada.*

[30] Dotreppe J-C, Franssen J-M, Vanderzeypen Y. 1995. A straight forward calculation method for the fire resistance of reinforced concrete columns. *Poster Paper. First European Symposium on Fire Safety Science*; 1–10.

[31] Franssen JM. 2000. Design of concrete columns based on EC2 tabulated data - a critical review. *Univ Liege/Danish Inst Fire Technol*; 323–340.

[32] Franssen JM, Dotreppe JC. 2003. Fire tests and calculation methods for circular concrete columns. *Fire Technol*; 39: 89–97.

[33] AS 3600:1994 Austrilian Standards for Concrete Structures; 78.

[34] British Standards Institution BSI.1985. BS 8110-1 British Standards : Structural Use of Concrete.

[35] British Standards Institution BSI.1985. BS 8110-2 British Standards : Structural Use of Concrete.

[36] Read RE., Adams F., Cooke GM. Guildines for the construction of fire resisting structural elments. *Build Resreach Establ Report, HMSO*.

[37] Wade CA, Cowels GS, Potter RJ, et al. 1997. Concrete Blade Columns in Fire.; 14–16.

[38] AS 1530.4 : Methods for fire tests on building materials, components and structures, Part 4: Fire Resistance Tests of Elements of Building Construction. 2005. *Part 4 Fire Resist Tests Elem Build Constr*.

[39] AS 3600:2001 Austrilian Standards for Concrete Structures.

[40] As 3600:2009 Austrilian Standards for Concrete Structures. *Aust 175pp* 2009; 181.

[41] Yu-ye X, Wang Q, Luo Y. 2008. Analysis and Practical Calculation for the Fire Resistance of Concrete Columns with Rectangular Cross Section. *J Huaqiao Univ*; 29: 5.

[42] Wu B, Xu YY. 2008.Numerical analytical method of reinforced concrete specially-shaped column subjected to high temperature. *Gongcheng Lixue/Engineering Mech*; 25.

[43] BIS. National Building Code of India, 2016 Volume 1. *Natl Build Code India* 2016; 80: 1 v. (various pagings).

[44] Ergün A, Kürklü G, Serhat Başpnar M, et al. 2013. The effect of cement dosage on mechanical properties of concrete exposed to high temperatures. *Fire Saf J*; 55: 160–167.

[45] ACI/TMS Committee 216: Guide for Determining the Fire Endurance of Concrete Elements.1989. *Concr Int*; 3: 13–47.

[46] ACI/TMS Committee 216. *Code requirements for determining fire resistance of concrete and masonry construction assemblies*. 2007.

[47] ACI/TMS Committee 216. Code requirements for determining fire resistance of concrete and masonry construction assemblies. 2019;

[48] Rush D, Bisby L, Jowsey A, et al. 2012. Structural performance of unprotected concrete-filled steel hollow sections in fire: A review and meta-analysis of available test data. *Steel Compos Struct*; 12: 325–352.