Meta-analysis of code-based design methods to quantify the fire resistance of concrete columns

Mahadev Rokade
Ph.D. student
Supervised by
David Rush and Tim Stratford

Thomas Gernay, Jean-Marc Franssen, Fabienne Robert, Robert McNamee, Roberto Felicetti, Patrick Bamonte, Sven Brunkhorst, Siyimane Mohaine, Jochen Zehfuß, Experimental investigation of structural failure during the cooling phase of a fire: Concrete columns,Fire Safety Journal,Volume 134,2022,

THE UNIVERSITY of EDINBURGH

STRUCTURES IN FIRE FORUM

Introduction

- Mechanical response combined with fire is critical to evaluate the failure capacity of any structural elements in the building.
- But the columns are a critical component in buildings, failure of one column will lead to the failure of the whole structure.
- This study aims to review and assess available experimental data against non-advanced methods given in different codes for the failure time of columns in fire scenarios.
- Total 6 different methods/ tabular guidelines were used to compare the fire resistance as follows:

1. Eurocode Method A
2. Eurocode Method B
3. Australian (AS 3600) code Method
4. ACI 216.1 code Method
5. DBJ/T 15-81 Chinese Code Method
6. NBC 2016- National Building Code of India

1) Eurocode (EN 1992-1-2)- Method A

History

- This equation is proposed in 1995 by Dotreppe and Franseen [1]

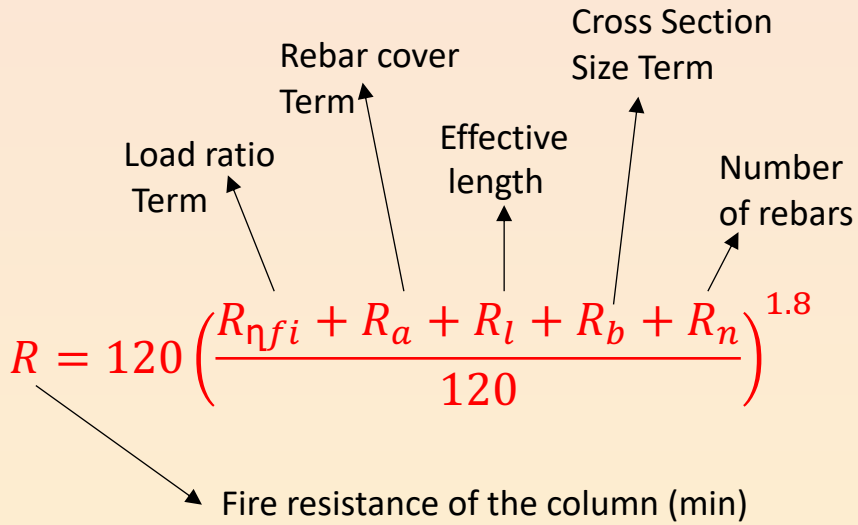
  and further refined by Franseen[2] in 2000. Later adopted into the Eurocode[3].
- Method A is based on 76 full-scale tests carried out in 4 different labs
- 21- NRC (National research council of Canada)[4]
- 39 – Technical University of Braunschweig, Germany[5].
- 12 – University of Ghent, Belgium[6].
- 4- University of Liege, Belgium[6].
- In 2003, Franseen extended this study with additional tests on circular columns and proved the applicability of equations.

1. J.C. Dotreppe, J.M. Franssen, Y. Vanderzeypen, A Straightforward Calculation Method for the Fire Resistance of Reinforced Concrete Columns, 10 pages, First European Symposium on Fire Safety Science, 1995
2. J.M. Franssen, Design of Concrete Columns Based on EC2 Tabulated Data – a Critical Review. First International Workshop “Structures in Fire”, 2000, pp. 323–339. Copenhagen.
3. EN 1992-1-2, Eurocode 2 – Design of Concrete Structures. Part 1–2: General Rules –Structural Fire Design, CEN, Brussels, 2019.
4. T.T. Lie, J.L. Woollerton, Fire Resistance of Reinforced Concrete Columns: Test Results, National Research Council of Canada, Institute for Research in Construction, Ottawa, Canada, 1988.
5. R. Haß, Zur praxisgerechten brandschutztechnischen Beurteilung von Stützen aus Stahl und Beton. Heft 69, Institut für Baustoffe, Massivbau und Brandschutz der Technischen Universit¨at Braunschweig, 1986.
6. J.C. Dotreppe, J.M. Franssen, A. Bruls, R. Baus, P. Vandevelde, R. Minne, D. Van Nieuwenburg, H. Lambotte, Experimental research on the determination of the main parameters affecting the behaviour of reinforced concrete columns under fire conditions, Mag. Concr. Res. 49 (179) (1997) 117–127.

Eurocode (EN 1992-1-2)- Method A

Standard fire resistance	Minimum dimensions (mm) Column width b_{min}/axis distance a of the main bars			
	Column exposed on more than one side			Exposed on one side
	μ_{fi} = 0.2	μ_{fi} = 0.5	μ_{fi} = 0.7	μ_{fi} = 0.7
1	2	3	4	5
R 30	200/25	200/25	200/32 300/27	155/25
R 60	200/25	200/36 300/31	250/46 350/40	155/25
R 90	200/31 300/25	300/45 400/38	350/53 450/40**	155/25
R 120	250/40 350/35	350/45** 450/40**	350/57** 450/51**	175/35
R 180	350/45**	350/63**	450/70**	230/55
R 240	350/61**	450/75**	-	295/70

**
Minimum 8 bars
(AC1) For prestressed columns the increase of axis distance according to 5.2. (5) should be noted. (AC1)



$\mu_{fi} = N_{Ed,fi}/N_{Rd}$

where
$N_{Ed,fi}$ is the design axial load in the fire situation,
N_{Rd} is the design resistance of the column at normal temperature conditions

Parameters	Tabular	Equation
Effective length in fire ($l_{0,fi}$)	$\leq$ **3 m**	**2** $\leq l_{0,fi} \leq$ **6 m**
Reinforcement ratio (As/Ac)	4%	4%
Slenderness of column	N/A	N/A
Heated Sides	1 or >1	>1
Cover (mm)	25-75	25-80
Width of column (mm)	200-450	200-450 (h/b $\leq$ **1.5**)

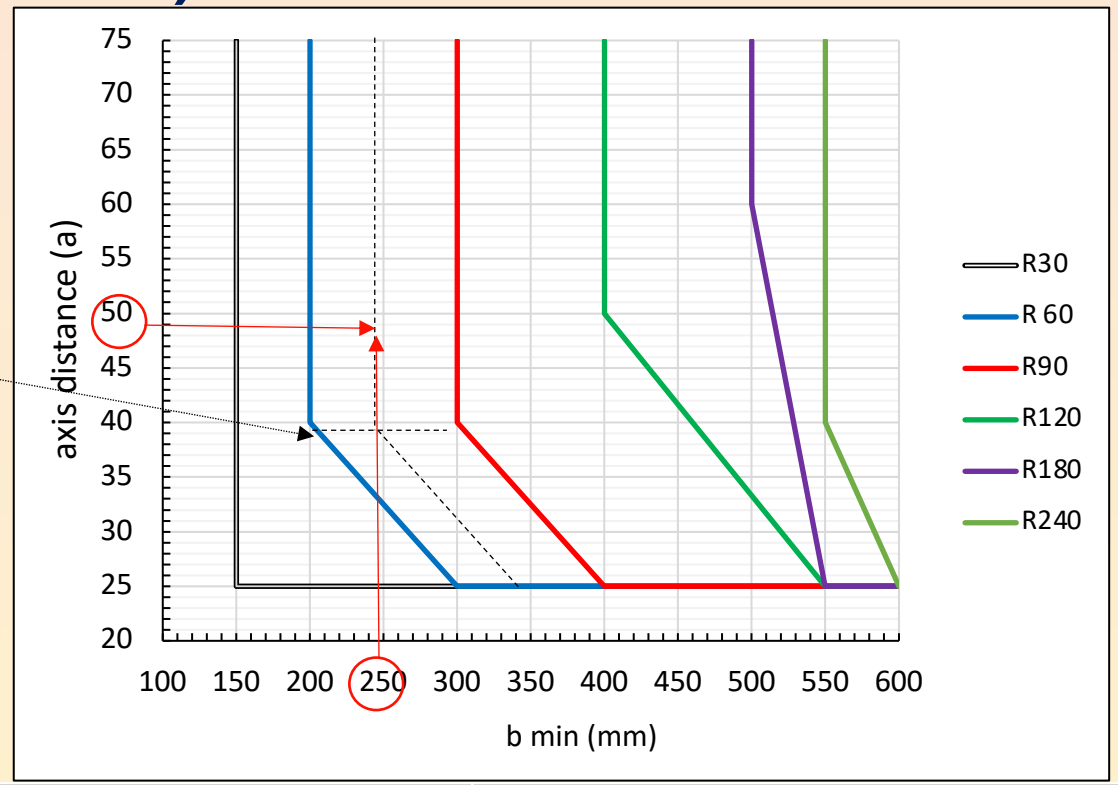
2) Eurocode (EN 1992-1-2)- Method B

Standard fire resistance	Mechanical reinforcement ratio ω	Minimum dimensions (mm). Column width b_{min}/axis distance a			
		n = 0,15	n = 0,3	n = 0,5	n = 0,7
1	2	3	4	5	6
R 30	0,100	150/25*	150/25*	200/30:250/25*	300/30:350/25*
	0,500	150/25*	150/25*	150/25*	200/30:250/25*
	1,000	150/25*	150/25*	150/25*	200/30:300/25*
R 60	0,100	150/30:200/25*	200/40:300/25*	300/40:500/25*	500/25*
	0,500	150/25*	150/35:200/25*	250/35:350/25*	350/40:550/25*
	1,000	150/25*	150/30:200/25*	200/40:400/25*	300/50:600/30
R 90	0,100	200/40:250/25*	300/40:400/25*	500/50:550/25*	550/40:600/25*
	0,500	150/35:200/25*	200/45:300/25*	300/45:550/25*	500/50:600/40
	1,000	200/25*	200/40:300/25*	250/40:550/25*	500/50:600/45
R 120	0,100	250/50:350/25*	400/50:550/25*	550/25*	550/60:600/45
	0,500	200/45:300/25*	300/45:550/25*	450/50:600/25*	500/60:600/50
	1,000	200/40:250/25*	250/50:400/25*	450/45:600/30	600/60
R 180	0,100	400/50:500/25*	500/60:550/25*	550/60:600/30	(1)
	0,500	300/45:450/25*	450/50:600/25*	500/60:600/50	600/75
	1,000	300/35:400/25*	450/50:550/25*	500/60:600/45	(1)
R 240	0,100	500/60:550/25*	550/40:600/25*	600/75	(1)
	0,500	450/45:500/25*	550/55:600/25*	600/70	(1)
	1,000	400/45:500/25*	500/40:600/30	600/60	(1)

* Normally the cover required by EN 1992-1-1 will control.

(1) Requires width greater than 600 mm. Particular assessment for buckling is required.

Load Level



$$\omega = \frac{As \times fy}{Ac \times fc}$$

Parameters	Method B
Effective length in fire ($l_{0,fi}$)	$Not\ specified$
Reinforcement ratio (ω)	0.1,0.5 and 1
Slenderness of column	< 30
Heated Sides	Not specified
Cover (mm)	25-75
Width of column (mm)	150-600

3) Australian Method

(AS 3600:2009)[7]

Effective length column

Load level

$$t_f = \left[\left(k f_c^{1.3} D_c^{3.3} D_g^{1.8}\right)/\left(10^5 L_e^{0.9} N^{1.5}\right)\right]$$

Concrete strength

Depth of column

Width of column

(AS 3600:2018)[8] / EN 1992-1-2

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

$$R_{\eta fi} = 83\left[1{,}00 - \mu_{fi}\frac{(1+\omega)}{(0{,}85/\alpha_{cc})+\omega}\right]$$

AS 3600:2018	EN 1992-1-2
$\omega = \frac{1.3 \times As \times fy}{Ac \times fc}$	$\omega = \frac{As \times fy}{Ac \times fc}$
$\propto cc = 0.945$	$\propto cc = 0.85$

7. AS3600, Australian Standard. Tech. rep., Standards Australian Committee, Sydney, 2009.
8. AS3600, Australian Standard. Tech. rep., Standards Australian Committee, Sydney, 2018.

4) ACI 216.1 Method

Table 2.7—Minimum concrete column size

Aggregate type	Minimum column dimension for fire-resistance rating, in.				
	1 hour	1-1/2 hours	2 hours	3 hours	4 hours
Carbonate	8	9	10	11	12
Siliceous	8	9	10	12	14
Semi-lightweight	8	8-1/2	9	10-1/2	12

Table 2.8—Minimum concrete column size with fire exposure conditions on two parallel sides

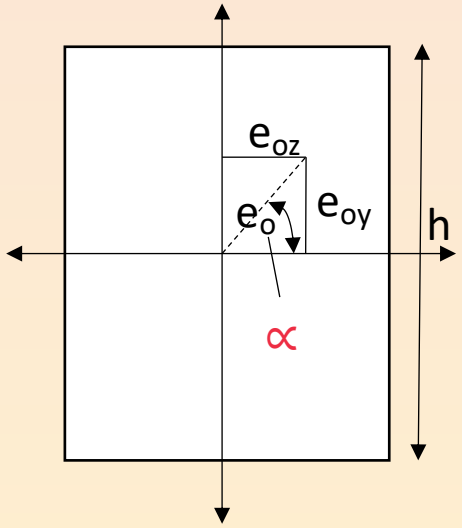
Aggregate type	Minimum column dimension for fire-resistance rating, in.*				
	1 hour	1-1/2 hours	2 hours	3 hours	4 hours
Carbonate	8	8	8	8	10
Siliceous	8	8	8	8	10
Semi-lightweight	8	8	8	8	10

*Minimum dimensions are acceptable for rectangular columns with a fire exposure condition on three or four sides, provided that one set of the two parallel sides of the column is at least 36 in. long.

- Depends on the type of aggregates, minimum size of columns, and exposure conditions.
- Limitations-
- Table 2.7 is valid for the column with full exposure (4 sides) while Table 2.8 is valid for the exposure conditions of two parallel sides.
- For strength $\leq 12000\ psi\ (82.7\ Mpa)$ - The values in the table are satisfied.
- If strength $\geq 12000\ psi\ (82.7\ Mpa)$ - The least dimension for the column for 1-4 hr FRR should be 24 inches.

9. ACI /TMS 216-14: Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies,2014

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



$$\beta_\mu = c_1\mu^2 + c_2\mu + c_3$$

$$\beta_L = c_4 L + c_5,\ \beta_b = c_9 b + c_{10}$$

$$\beta_{hdb} = c_6\left(\frac{h}{b}\right)^2 + c_7\left(\frac{h}{b}\right) + c_8$$

$$\beta_e = c_{11}e^3 + c_{12}e^2 + c_{13}e + c_{14}$$

$$\beta_\rho = c_{15}\rho + c_{16}$$

The factor for effective length for column)

The factor for effective Width, height for column)

$$R_T = \beta_\mu\beta_L\beta_{hdb}\beta_b\beta_e\beta_\rho$$

The factor for the longitudinal reinforcement ratio

The factor for load ratio (axial pressure/ axial bearing capacity of column)

The factor for eccentricity for column

系数	组合轴向压力作用点至截面重心的连线与 z 轴的夹角 α				
	0°	22.5°	45°	67.5°	90°
c_1	1.518	1.385	1.327	1.641	1.696
c_2	−2.690	−2.445	−2.328	−2.933	−3.225
c_3	1.355	1.231	1.167	1.490	1.693
c_4	−0.877	−0.901	−1.233	−1.141	−1.026
c_5	7.011	7.286	10.119	9.484	9.634
c_6	−0.666	−0.754	−1.046	−0.977	−0.326
c_7	3.138	3.322	4.242	3.852	3.251
c_8	2.058	1.824	1.146	0.060	−0.076
c_9	2.093	2.038	1.614	1.479	3.523
c_{10}	−0.277	−0.267	−0.209	−0.191	−0.443
c_{11}	−1.512	−1.688	−2.956	−1.532	−0.932
c_{12}	7.375	8.481	12.424	7.882	4.070
c_{13}	−13.285	−14.726	−18.366	−14.523	−6.727
c_{14}	23.334	25.565	31.138	29.643	11.166
c_{15}	5.547	5.859	4.656	5.880	3.920
c_{16}	1.141	1.144	0.896	1.241	1.210

Parameters	DBJ/T 15-81
Effective length in fire ($l_{0,fi}$)	$2 \le L \le 4\ m$
Reinforcement ratio (As/Ac)	1 % < ρ < 3%
Load ratio	0.2< μ <0.7
Heated Sides	Not specified
Cover (mm)	Not Specified
Width of column (mm)	300-600

10. DBJ/T 15-81-2011. Code for fire resistance design of concrete structures in buildings. China Architecture& Building Press; 2011 [in Chinese].

6) IS 1642:1989- NBC 2016

Table 8 Reinforced Concrete Columns

(Clause 6.1)

Nature of Construction and Materials		Minimum Dimensions (mm), Excluding any Finish, for a Fire Resistance of					
		½ h	1 h	1½ h	2 h	3 h	4 h
1 Fully exposed	Width	150	200	250	300	400	450
	Cover	20	25	30	35	35	35
2 50 percent exposed	Width	125	160	200	200	300	350
	Cover	20	25	25	25	30	35
3 One face exposed	Thickness	100	120	140	160	200	240
	Cover	20	25	25	25	25	25

- The Indian code is dependent on the type of exposure (partially, fully, or 50 %), with a minimum thickness of column size and its cover thickness, type of construction.

Parameters	NBC 2016
Effective length in fire ($l_{0,fi}$)	Not specified
Reinforcement ratio (As/Ac)	Not specified
Load ratio	Not specified
Heated Sides	Fully, 50% and one face
Cover (mm)	20-35
Width of column (mm)	150-450

11. NBC 2016- National Building Code of India volume 1, Bureau of Indian Standard, SP:7,2019.
12. IS 1642:1989 Fire Safety of Buildings (General): Details of construction- Code of Practice, Bureau of Indian Standard, 1990.

Experimental Database for Meta-analysis

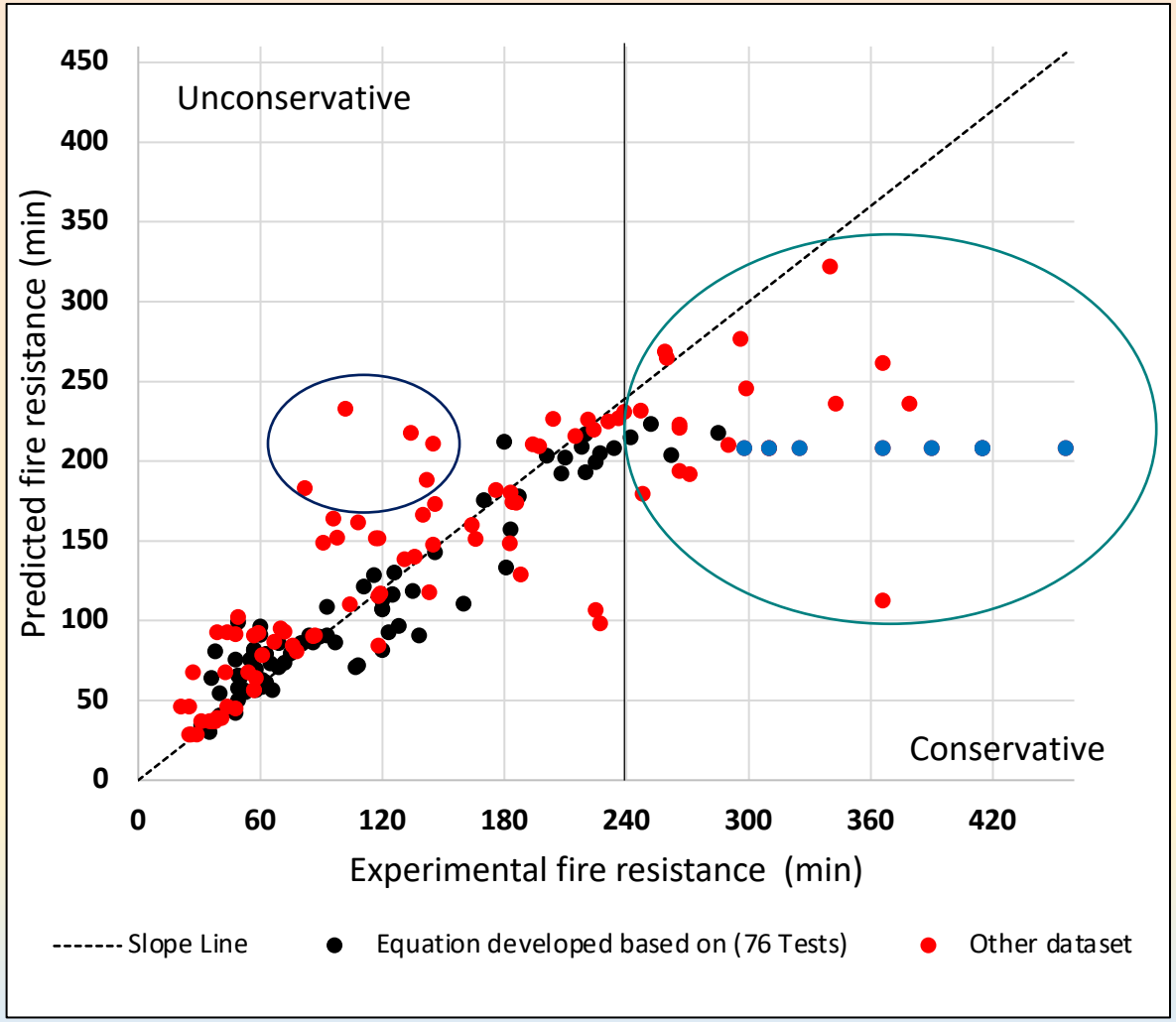
Dataset on which the equation developed

Total number of tests	76	
Types of column	Square	70
	Rectangular	6
End conditions	FF	16
	FP	5
	PP	55
Load ratios	<0.4	**45**
	0.4-0.9	31
Section Size (mm)	<200	0
	200-406	76
	> 406	0
Concrete Cover (mm)	25 - 48	
Concrete Strength (Mpa)	24.4 - 44	
Longitudinal bars	Nos	(4-8)
	Dia of bar (mm)	12-25.5
Shear R/F	Dia (mm)	(8-10)
Reinforcement ratio (%)	0.89 - 3.1	
Spacing of shear R/F (mm)	100 -305	
Yield Strength of Steel (Mpa)	444-505	
Applied load (KN)	60-1695	
Fire Curve	ISO 834, ASTM E119	

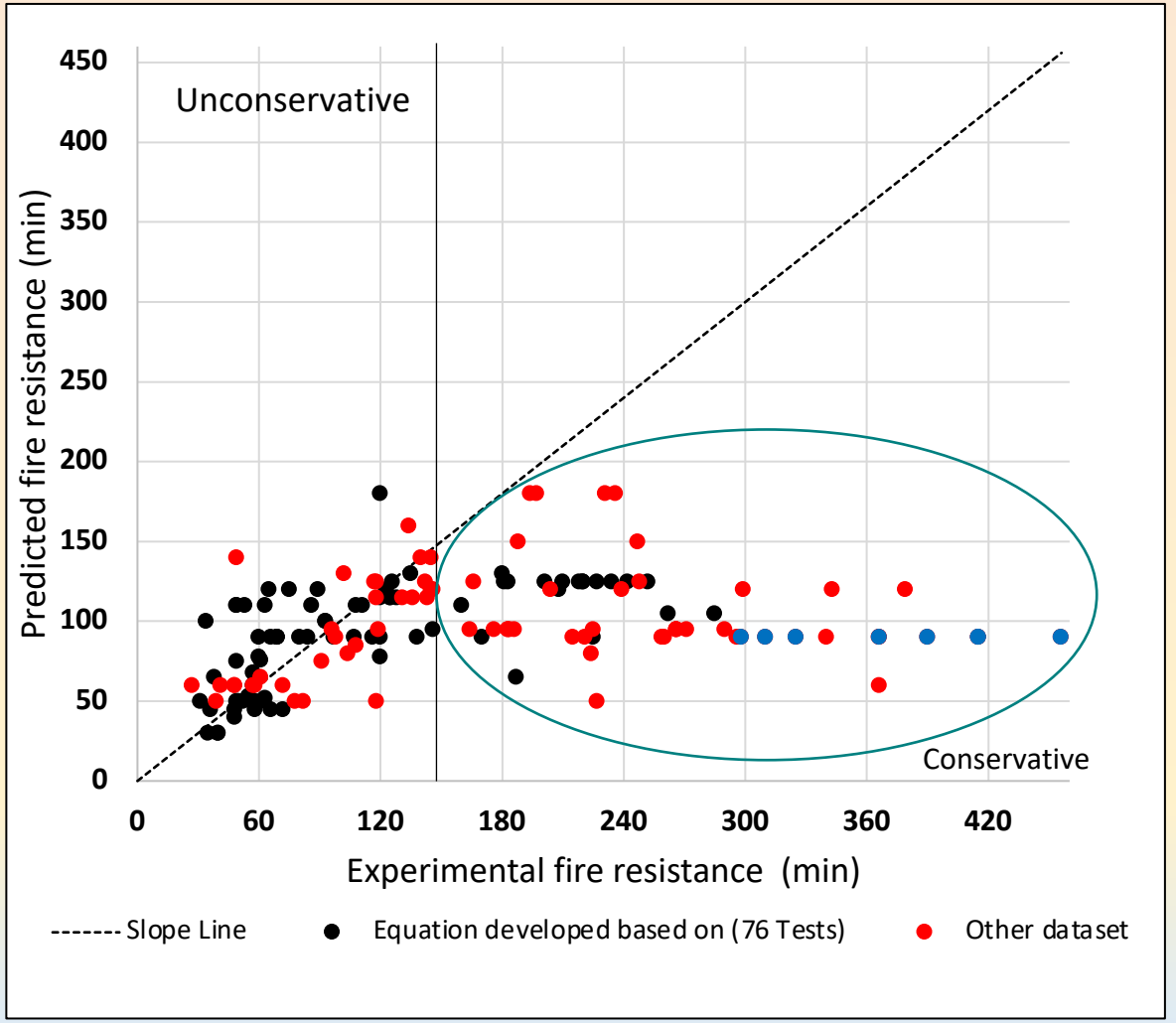
Other Dataset

Total number of tests	99	
Types of column	Square	96
	Rectangular	3
End conditions	FF	**58**
	FP	32
	PP	9
Load ratios	<0.4	33
	0.4-0.9	**66**
Section Size (mm)	<200	45
	200-406	49
	> 406	5
Concrete Cover (mm)	25-64	
Concrete Strength (Mpa)	24.1 - 126	
Longitudinal bars	Nos	(4-8)
	Dia of bar (mm)	(12-32.5)
Shear R/F	Dia (mm)	(8-10)
Reinforcement ratio (%)	0.89 - 4.38	
Spacing of shear R/F (mm)	100 -406	
Yield Strength of Steel (Mpa)	340 -591	
Applied load (KN)	345-4800	
Fire Curve	ISO 834, ASTM E119	

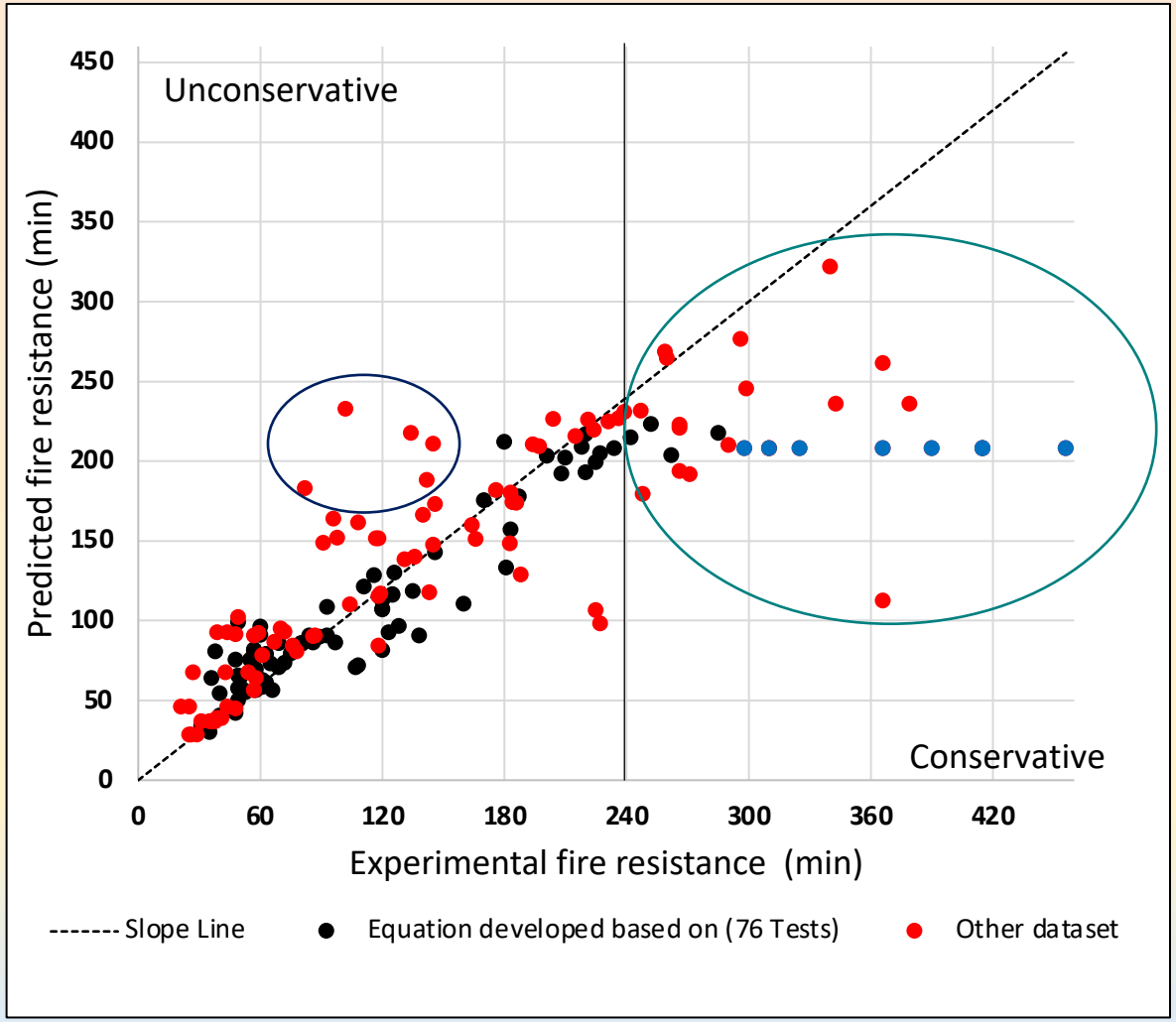
EN 1992-1-2 Method A



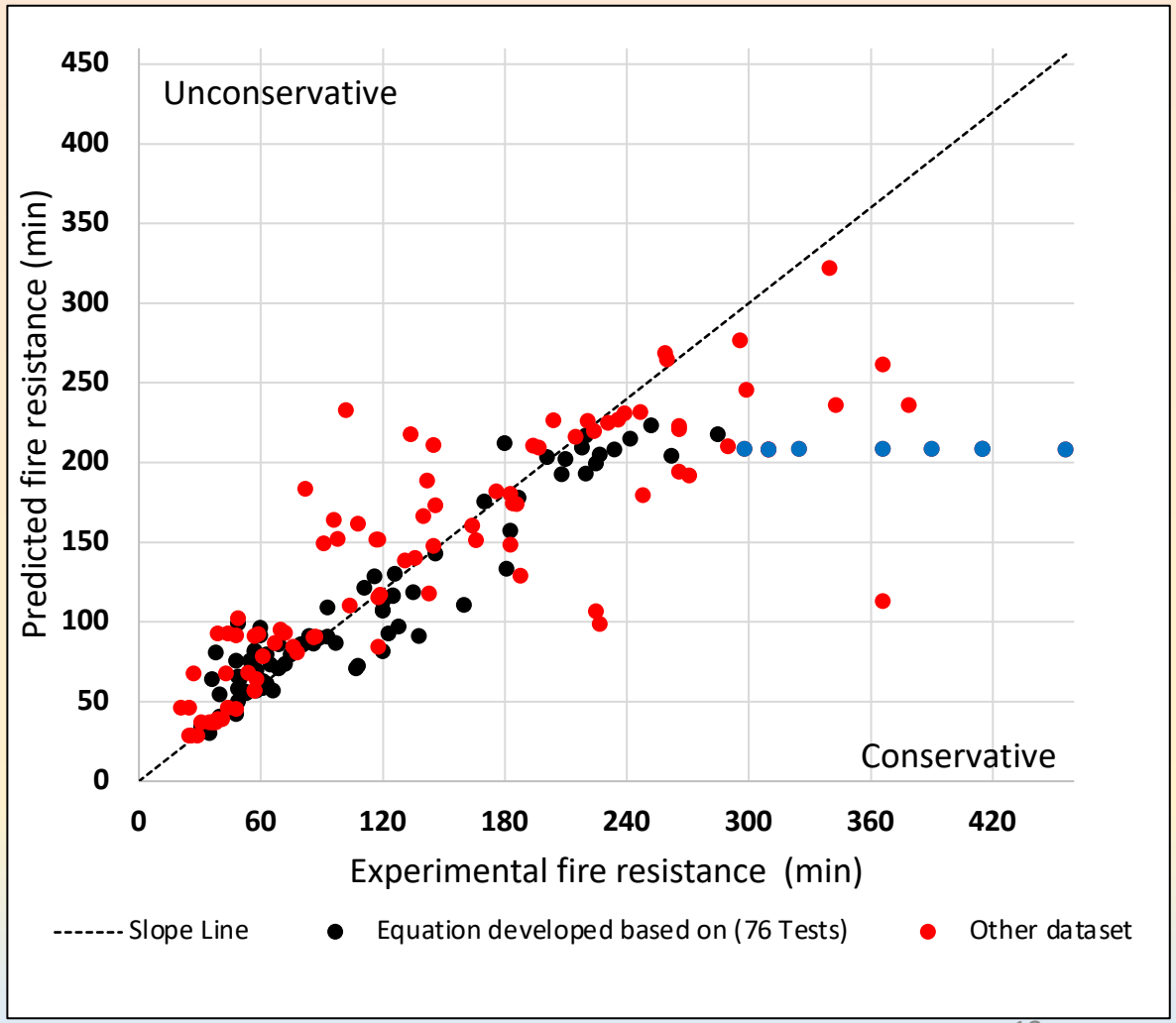
EN 1992-1-2 Method B (158 Tests)



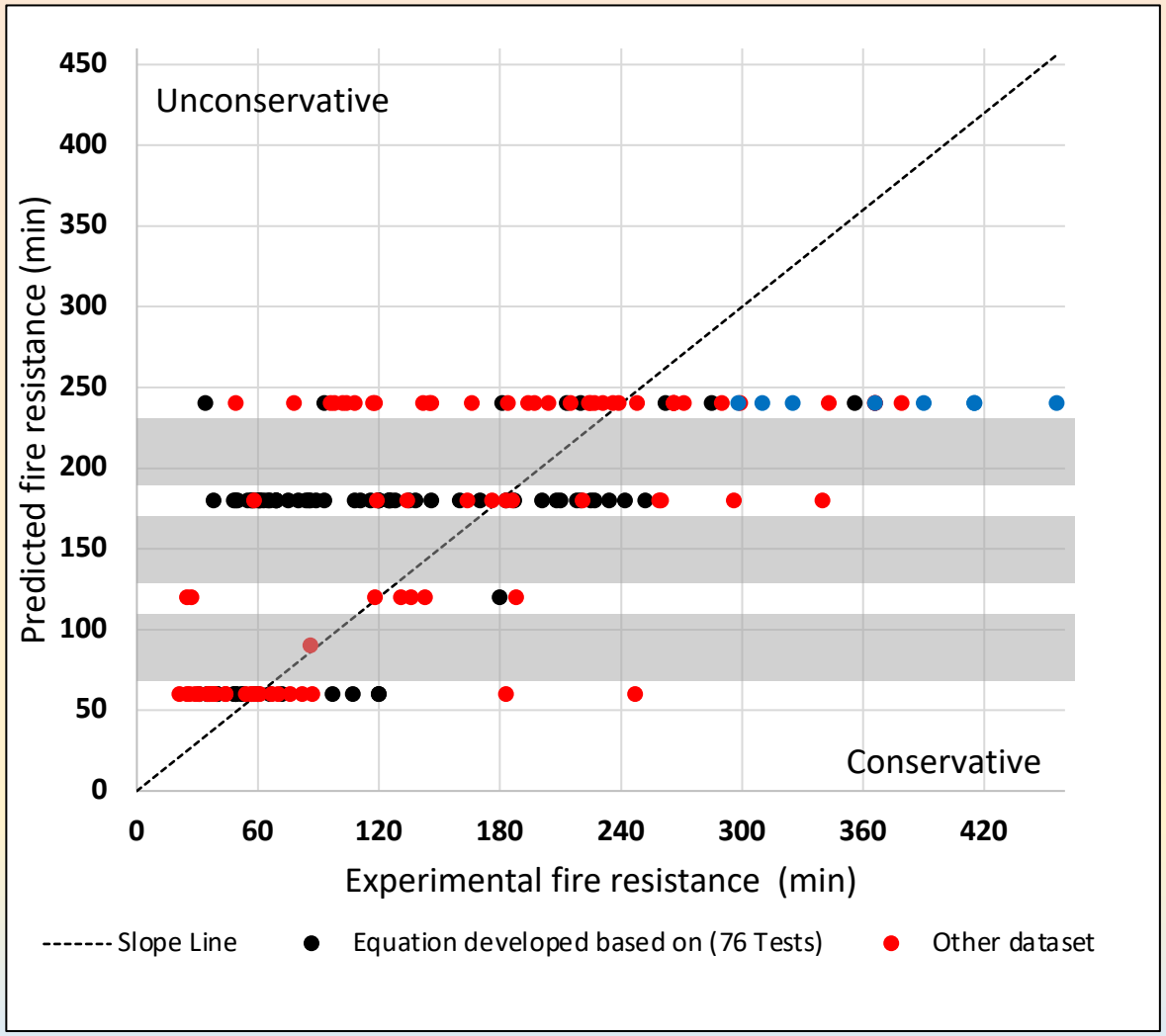
EN 1992-1-2 Method A



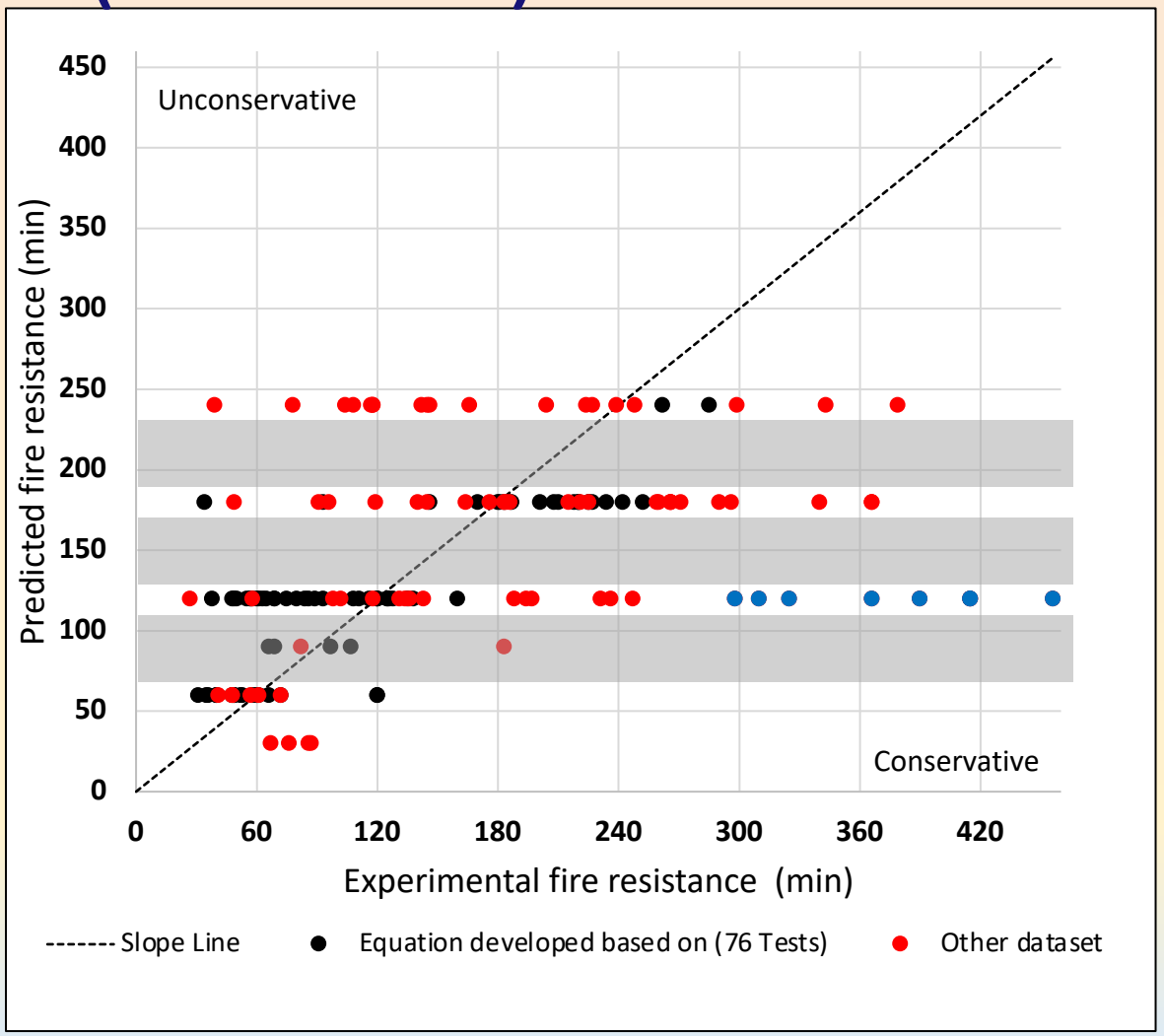
AS 3600:2018 Method



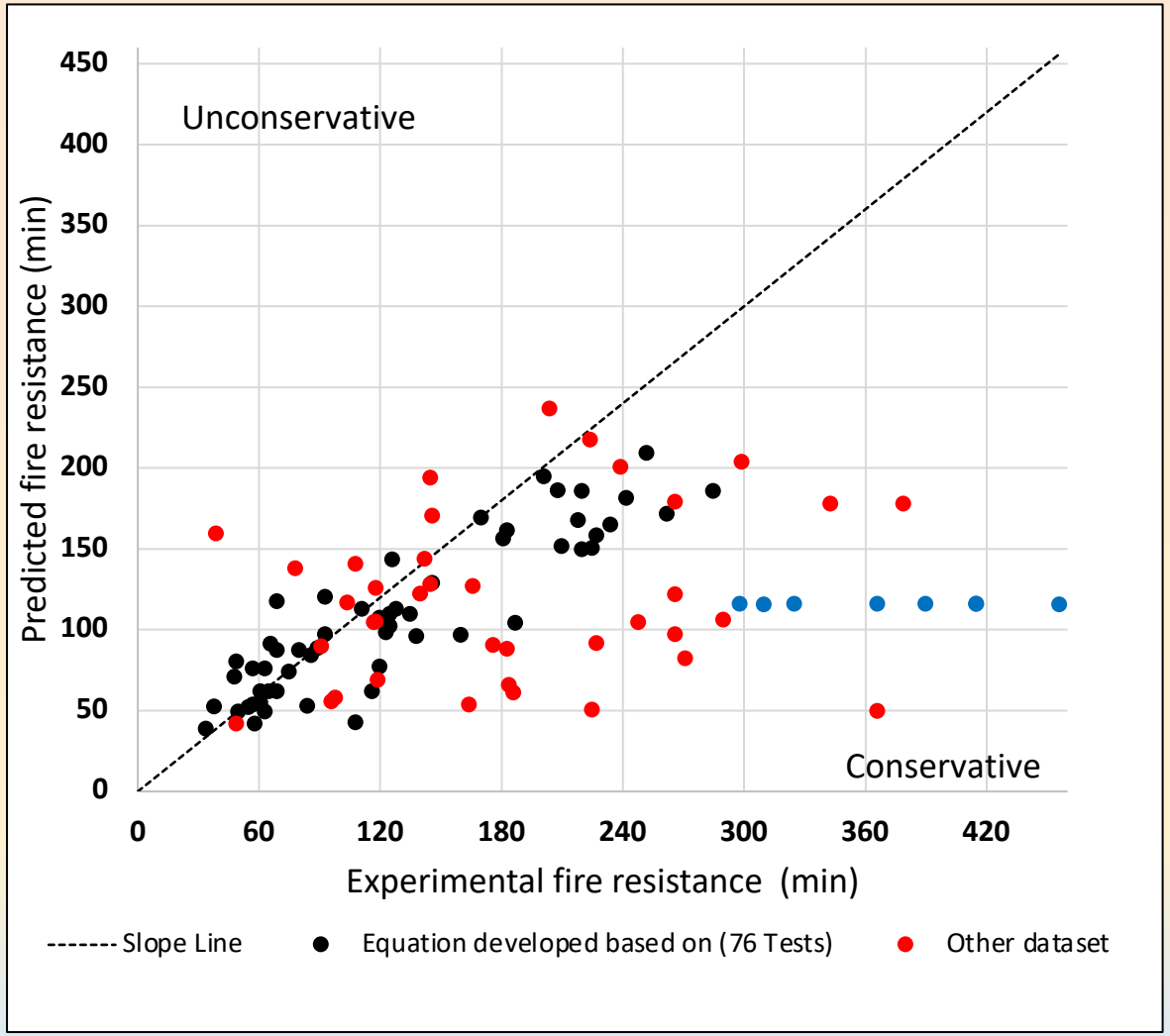
ACI Method (165 Tests)



IS 1642 Method (India) (156 Tests)

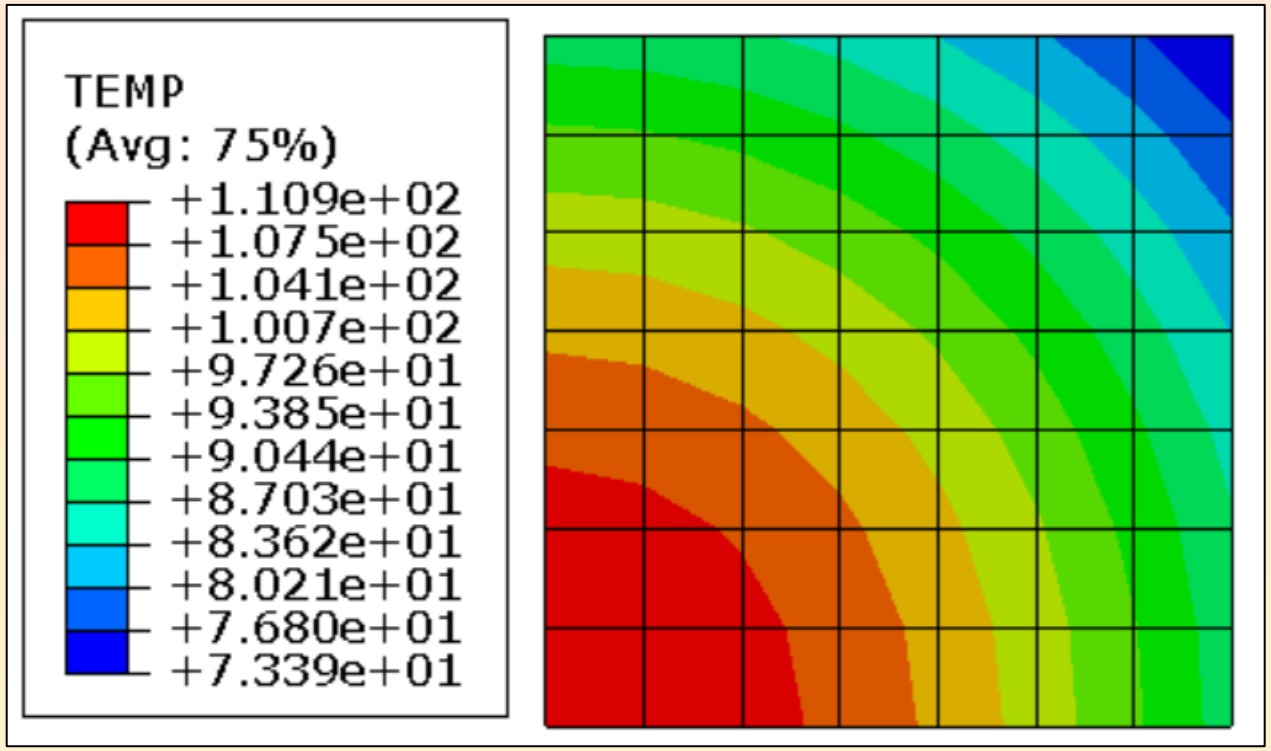


DBJ/T 15-81 (Chinese Code Method) (102 Tests)



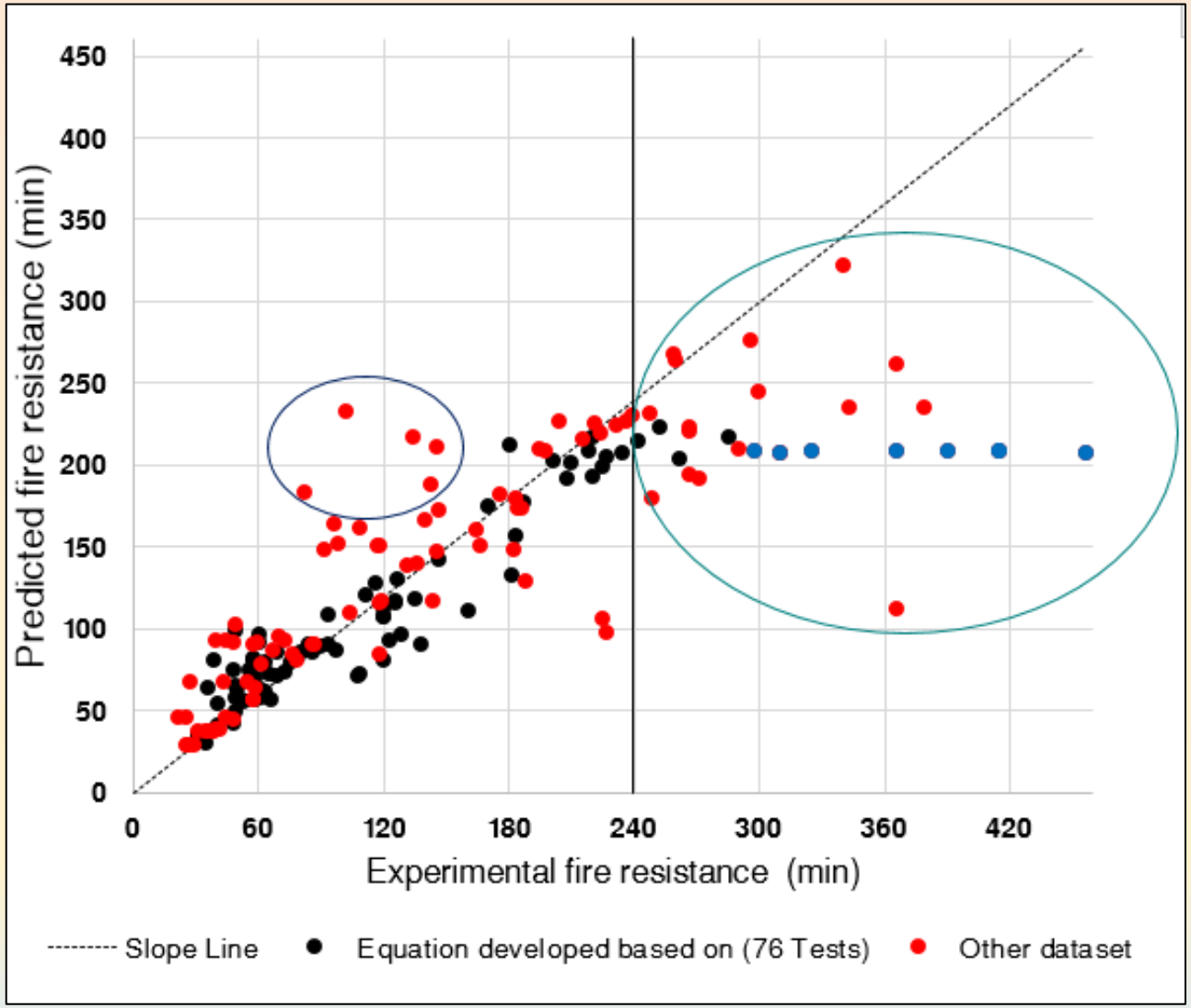
Future work

- The same study will be extended to look into the effect of various parameters such as size, shape, r/f ratio, cover, strength, etc.
- The prediction of the model will be assessed based on the statistical equations.
- A detailed FEM model with a layer for thermal analysis, 500℃ isothermal or zone method will be used to predict the FRR.



Observations

- The Eurocode Method is comparatively good in predicting FRR up to 4 hr while Method B is up to 150 min.
- DBJ/T 15-81 method is quite good for the old database on which the Eurocode equation was developed.
- ACI and IS 1642 methods they both under predicting the FRR for the new dataset.
- There is a need to revise the equations/table/guidelines present in the code as most of them are developed based on the old database, it is recommended to consider the new test database.



Thanks

Any questions or suggestions?