Standing Committee on Concrete Technology
Annual Concrete Seminar 2013

Fire Resistance Design and Protection for Concrete

by

Ir Dr Y.L. Wong

RPE, RI

Department of Civil & Environmental Engineering

The Hong Kong Polytechnic University

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Garley Building Fire in Hong Kong

On 20 Nov. 1996: Casualties: 40 killed, over 80 injured

FSD 2012 Statistic Report

Classification of Fires

	2007	2008	2009	2010	2011
Public area	338	467	425	518	478
Squatter areas	96	109	123	89	123
Vehicle	378	340	293	285	310
Housing estates	1 613	1 589	1 341	1 347	1 285
Factory buildings	116	124	122	62	123
Institutional buildings	195	202	190	250	192
Non-domestic buildings	443	434	464	371	419
Domestic buildings	1 621	1,601	1 588	1 562	1 460
Electric-others	90	92	81	50	44
Vegetation	1 230	1 501	1 294	819	1 335
Unwanted alarm	20 717	24 007	25 405	30 710	23 889
False alarm	3 119	3 296	2 922	3 108	2 944
Temporary housing area	0	0	0	0	0
Vessel	22	17	24	15	18
Others	1 660	1 734	1 499	1 418	1 568
Total	**31 638**	**35 513**	**35 771**	**40 604**	**34 188**

FSD 2012 Statistic Report

Occupancy where major fire occurred (No. 3 Alarm and above)

Type of Premises	2007	2008	2009	2010	2011
Commercial Premises	0	3	1	1	3
Construction Site	0	0	0	0	2
Domestic Premises	1	2	0	0	2
Housing – Domestic	0	2	0	0	1
Housing – Commercial	2	0	0	0	0
Private Factory	3	2	2	3	1
Public Area-Others	0	0	0	0	0
Public Area-Hotel	0	0	0	0	0
Public Area – Restaurant	0	0	0	0	0
Squatter - Commercial/Store	2	4	3	7	8
Squatter – Factory	0	0	0	0	0
Squatter – Domestic	0	3	1	2	0
Place of Public Assembly	0	1	0	0	0
Institutional Building	0	1	1	0	1
Temporary Housing Area	0	0	0	0	0
Vessel	0	0	1	0	1
Vehicle	0	0	0	2	0
Others	0	0	1	1	0
Total	**8**	**18**	**10**	**16**	**19**

FSD 2012 Statistic Report

Injuries and Fatalities

	2007		2008		2009		2010		2011	
	Fire	Special Service	Fire	Special Service	Fire	Special Service	Fire	Special Service	Fire	Special Service
No. of Rescue	2 835	20 366	3 241	23 633	2 901	22 851	1 518	25 207	5 482	25 022
Injuries of public	327	1 669	371	1 981	271	1 793	276	1 850	389	1 915
Fatalities of public	16	717	8	773	10	815	10	746	23	751
Injuries of FS member	21	13	26	5	16	9	26	10	13	7
Fatalities of FS member	1	0	2	0	0	0	1	0	0	0
Total (Fatalities + Injuries)	**365**	**2 399**	**407**	**2 759**	**297**	**2 617**	**313**	**2 606**	**425**	**2 673**

Building Fires in Hong Kong

- Every year: about 3500 building fire cases (9 cases were ranked no. 3 Alarm and above). The associated injuries and fatalities are in order of 300 and 10 respectively.

- Buildings must be designed for Fire Safety.

Fire Safety Design in Buildings

Objectives:
Life Safety, Property Protection

To achieve these objectives:
Complying the Requirements for:

Means of Escape – *Life safety*
Fire Resisting Construction – ***inhibit spread of fire/smoke, maintain building stability***
Means of Access – *Fire fighting*
Fire Safety Management – *active fire safety provisions*

Fire Safety Design in Buildings

Elaborated in:

1. **Code of Practice for Fire Safety in Buildings 2011**
   (Means of Escape, Fire Resisting Construction, Means of Access,
   fire Properties of Building Elements and Components,
   Fire Safety Management, Guidelines on Fire Engineering)

2. **Code of Practice: Standard Use of Concrete 2013**

3. **Code of Practice for the Structural Use of Steel 2011**

4. **Codes of Practice for Minimum Fire Service Installations and Equipment and Inspection, Testing and Maintenance of Installations and Equipment 2012**

Fire Resisting Construction

- Deemed-to-Comply Provisions
- Performance-based Approach using Fire Engineering

Deemed-to-Comply Provisions

- Fire Compartmentation – enclosed by fire barriers to inhibit spread of fire.

- Fire Resistance Rating (FRR)- Every structural element and fire barrier within compartment should have assigned FRR under standard fire exposure/test.

  Criteria of FRR: X/Y/Z

  X- stability (minutes)

  Y – Integrity (minutes)

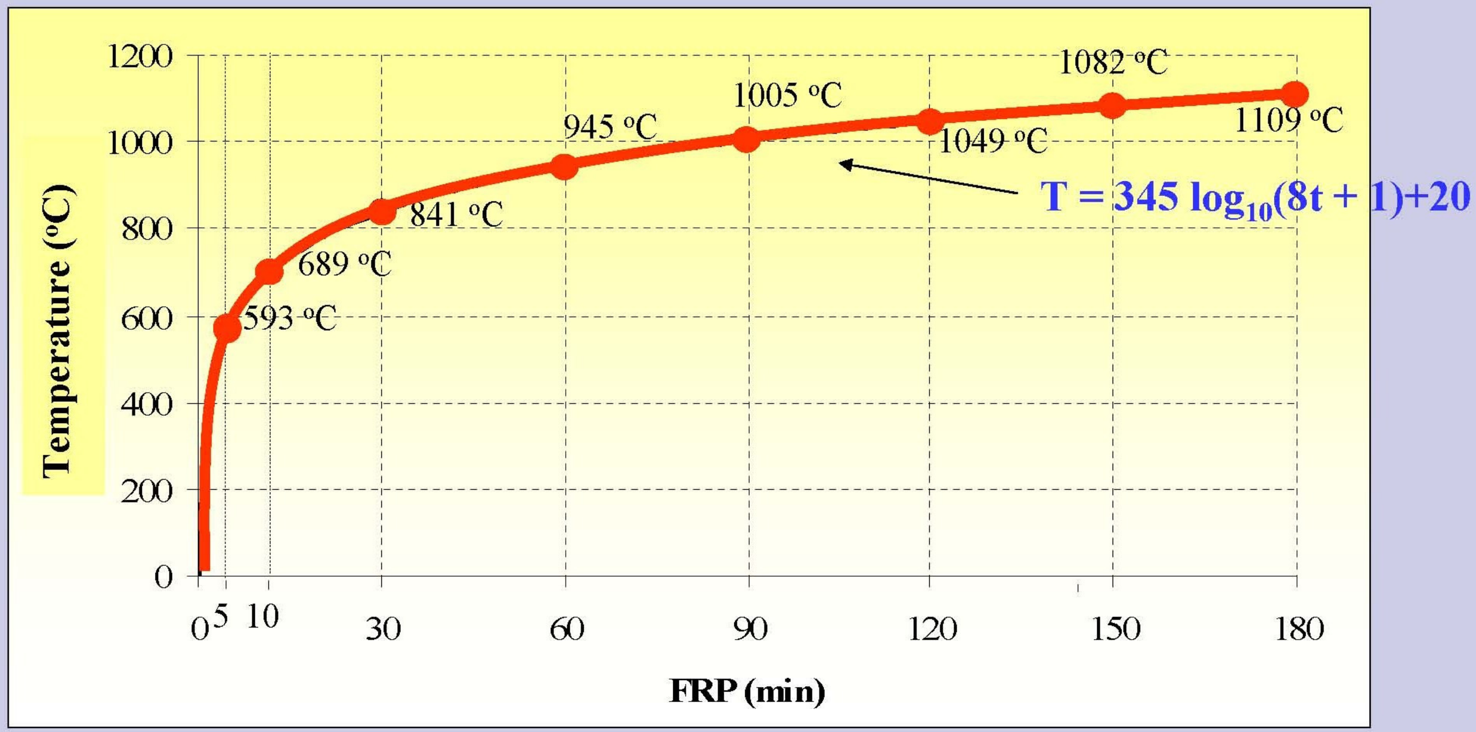
  Z – Insulation (minutes)

Characteristics of Room Fire

Standard Fire Curve

$$\theta_g = 20 + 345\log_{10}(8t+1)$$

where: t is time in min.



Characteristics of Room Fire

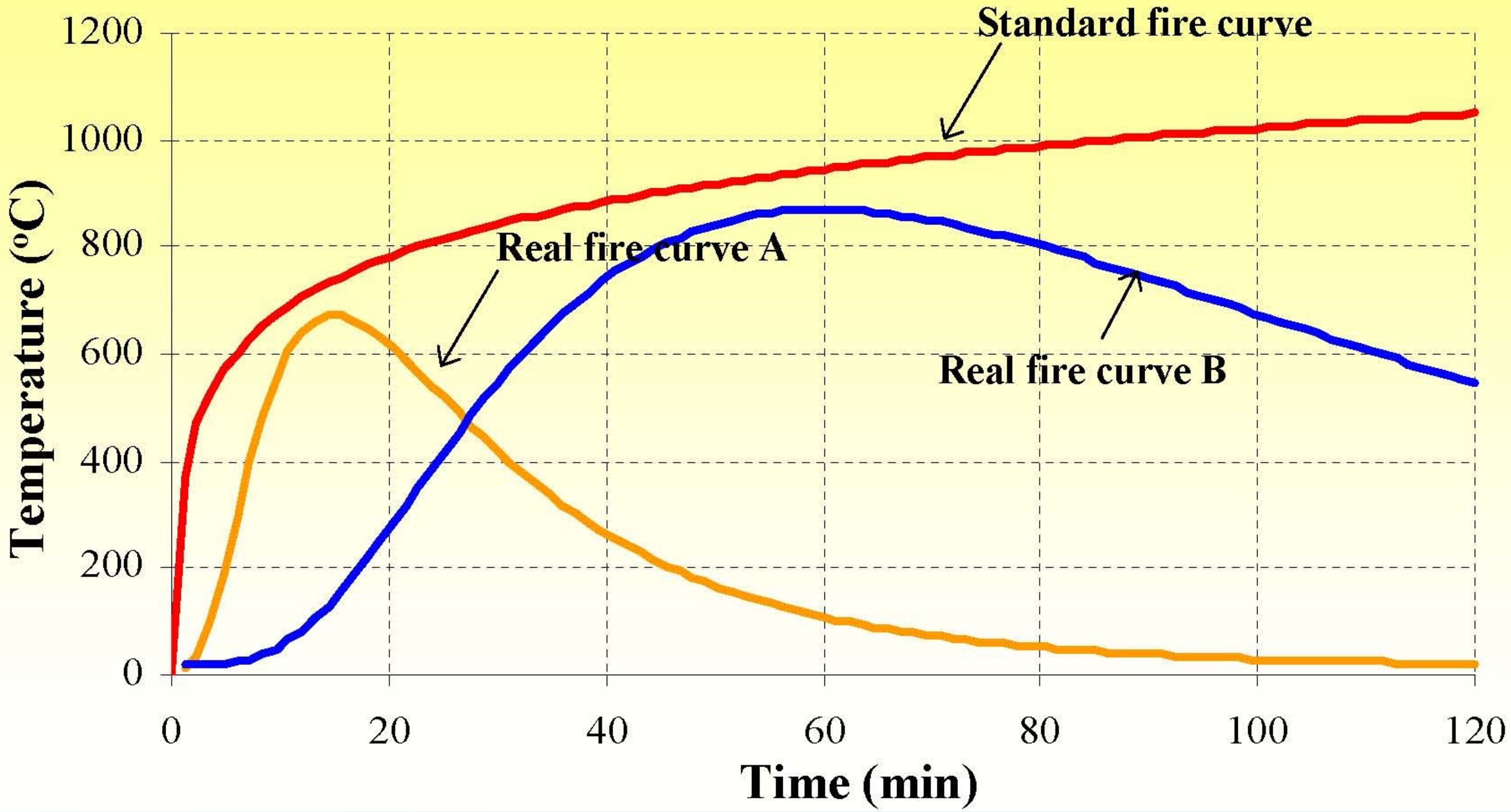


Table C1 – Fire Resistance Rating and Fire Compartment Limitations

Use Classification	Compartment Area/ Volume	Fire Resistance Rating (minutes)
1. Residential	Not limited	60
2. Hotel and similar Transient Accommodation	Not limited	60
3. Institutional	Not exceeding 2,500m^2	60
4. Commercial:		
4a. Business Facilities	Not exceeding 10,500m^2	60
4b. Mercantile Facilities	Not exceeding 2,500m^2	60
	Exceeding 2,500m^2 but not exceeding 10,500m^2	120
5. Assembly:		
5a & 5d. PPE & Other assembly premises	Not exceeding 2,500m^2	60
	Exceeding 2,500m^2 but not exceeding 10,500m^2	120
5b.Educational establishments	Not exceeding 2,500m^2	60
	Exceeding 2,500m^2 but not exceeding 10,500m^2	120
5c. Transport facilities	Not exceeding 10,500m^2	120
6. Industrial:		
6a. Industrial workplaces	Not exceeding 10,500m^2	120
6b. Bulk storage, Warehouses	Not exceeding 28,000m^3 and 10,500m^2	120
6c. Storage, manufacturing of hazardous/dangerous goods premises	Not exceeding 7,000m^3	120
7. Carparks	Not exceeding 10,500m^2	60

Extracted from BD CoP for Fire Safety in Buildings 2011

Table C2: Fire Resistance Rating Criteria for Elements of Construction, Fire Barriers and Other Components

Elements of construction or other components		Criteria to be satisfied			Method of Exposure
		Stability	Integrity	Insulation	
1	Structural frame, beam or column	Y	N	N	Exposed faces only
2	Floor including fire compartment floor	Y	Y	Y	Each side separately
3	Roof forming part of an exit route or performing the function of the floor	Y	Y	Y	From underside
4	Loadbearing wall not being a fire barrier	Y	N	N	Each side separately
5	External wall	Y*	Y	Y	Each side separately
6	Loadbearing wall being a fire barrier	Y	Y	Y	Each side separately
7	Non-loadbearing wall being a fire barrier	N	Y	Y	Each side separately
8	Protected shaft, lobby and corridor	Y*	Y	Y	Each side separately
9	Fire shutter, fire stop, fire dampers, sealing system	N	Y	N (unless specified)	Each side separately
10	Smoke outlet shaft	Y	Y	Y	From outside
11	Enclosure around services other than Item 14	N	Y	Y	From outside
12	Door (including frame and fixing)	N	Y	N (unless specified)	Each side separately (except lift doors – from landing side only)
13	Fixed light (including frame, glazing & fixing)	N	Y	Y	Each side separately
14	Enclosure around services in required staircase/protected lobby	N	Y	Y	Each side separately

Extracted from BD CoP for Fire Safety in Buildings 2011

Local Test Results (PolyU Tests)

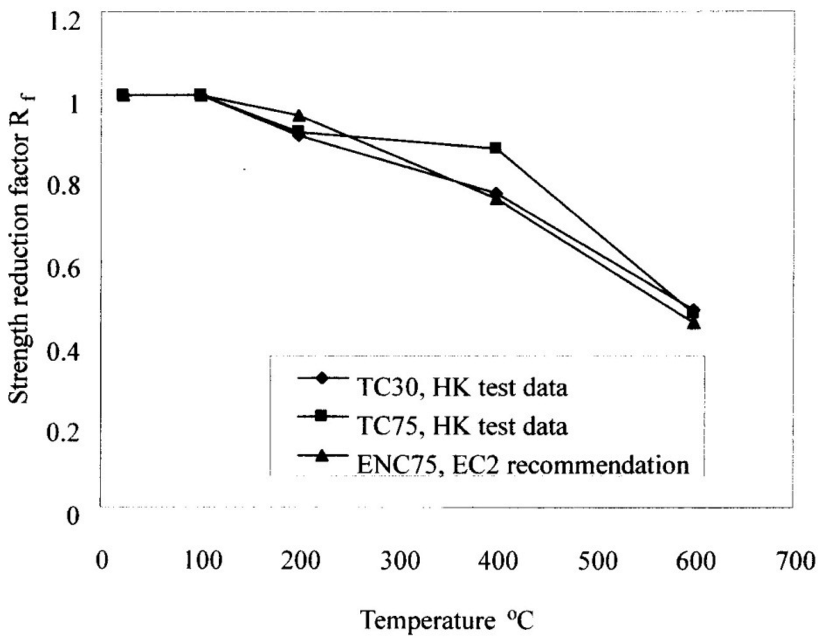


Figure 3: Strength reduction factor R_f vs temperature

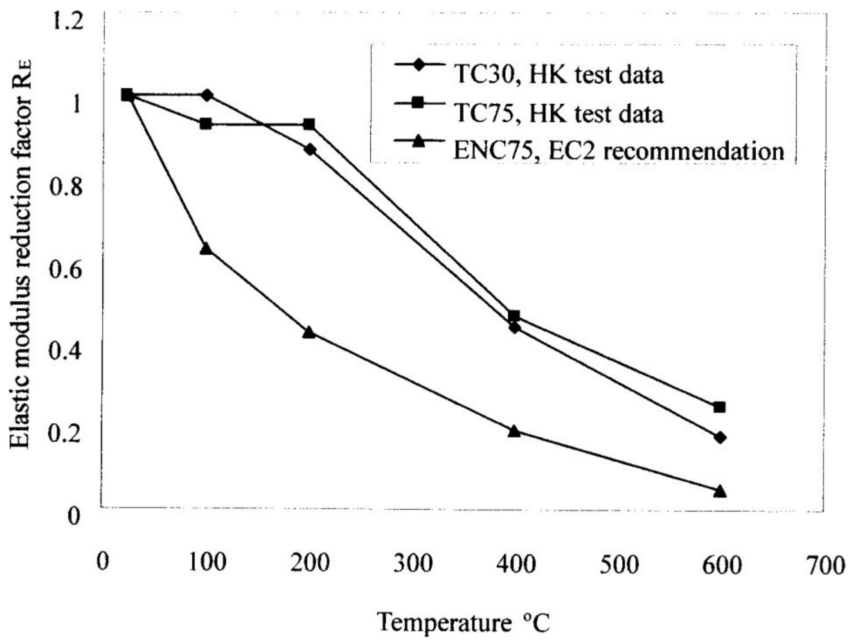


Figure 4 Elastic modulus reduction factor R_E vs temperature

Strength Reduction of Concrete under Fire

Temperature	Strength reduction factors
20 °C	1.00
100 °C	1.00
200 °C	0.95
300 °C	0.85
400 °C	0.75
500 °C	0.60
600 °C	0.45
700 °C	0.30
800 °C	0.15
900 °C	0.08
1000 °C	0.04
1100 °C	0.01
1200 °C	0.00

Table 3.5 – Strength reduction factors for concrete

Extracted from BD Code of Practice: Standard Use of Concrete 2013

Strength Reduction of Steel under Fire

Temperature	Strength reduction factors
20 °C	1.00
100 °C	1.00
200 °C	1.00
300 °C	1.00
400 °C	0.87
500 °C	0.60
600 °C	0.36
700 °C	0.11
800 °C	0.08
900 °C	0.06
1000 °C	0.04
1100 °C	0.02
1200 °C	0.00

Table 3.6 – Strength reduction factors for reinforcement

Extracted from BD Code of Practice: Standard Use of Concrete 2013

Fire Resistance Design of Reinforced Concrete

- Load effects under fire are about 70% of those under the normal situations. The integrity of the structural system can be maintained if the reduction of the corresponding load carrying capacity is about 30%.

- This can be achieved for R.C. structures if the concrete cover (acts as an insulating layer) is thick enough so that the temperature of the embedded steel rebars does not exceed 500^{0}C (noting that the average strength reduction of steel and concrete is about 30% at 500^{0}C).

TABLE E4

FLOORS AND LANDINGS

Construction and Materials	Minimum thickness in mm for FRR of		
	240 mins	120 mins	60 mins
SOLID REINFORCED CONCRETE CONSTRUCTION			
Thickness of concrete	170	125	100
Concrete cover to all reinforcement -			
simply supported	55*	35	20
continuous	45*	25	20
SOLID PRESTRESSED CONCRETE CONSTRUCTION			
Depth including screed	170	125	100
Concrete cover to all reinforcement -			
simply supported	65*	40	25
continuous	55*	35	20

* Reinforcement consisting of expanded metal lath or a wire fabric not lighter than $0.5kg/m^2$ with 2mm diameter wire at not more than 100mm centres or a continuous arrangement of links at not more than 200mm centres should be incorporated in the concrete cover at a distance not exceeding 20mm from the face.

Extracted from BD CoP for Fire Safety in Buildings 2011

TABLE E6

REINFORCED CONCRETE COLUMNS AND BEAMS

Construction and Materials		Minimum overall size of column in mm for FRR of		
		240 mins	120 mins	60 mins
REINFORCED CONCRETE COLUMNS AND HANGERS				
(a)	Fully exposed columns and hangers	450	300	200
	Concrete cover to main reinforcement	35	35	25
(b)	50 per cent exposed of columns and hangers	350	200	160
	Concrete cover to main reinforcement	35	25	25
(c)	One face exposed of columns and hangers	240	160	120
	Concrete cover to main reinforcement	25	25	25
REINFORCED CONCRETE BEAMS				
Width of beam		280	200	200
Concrete cover to main reinforcement -				
	simply supported	80*	50*	30
	continuous	60*	40	30
PRESTRESSED CONCRETE BEAMS				
Width of beam		280	200	200
Concrete cover to tendons -				
	simply supported	90*	70*	30

* Reinforcement consisting of expanded metal lath or a wire fabric not lighter than $0.5kg/m^2$ with 2mm diameter wire at not more than 100mm centres or a continuous arrangement of links at not more than 200mm centres should be incorporated in the concrete cover at a distance not exceeding 20mm from the face.

Extracted from BD CoP for Fire Safety in Buildings 2011

Fire Resistant Design of Reinforced Concrete

- Under a fire attack, the main role of concrete cover of a reinforced concrete member is an insulator to prevent excessive temperature rise in embedded steel rebars (to minimize steel strength reduction).

- The thickness of concrete cover increases with fire resistance rating.

- The abovementioned design/protection method is valid if the concrete cover remains attaching to the concrete member concerned during fire.

Overseas Fire Tests

Figure 2. View of column HSC2 after fire test.

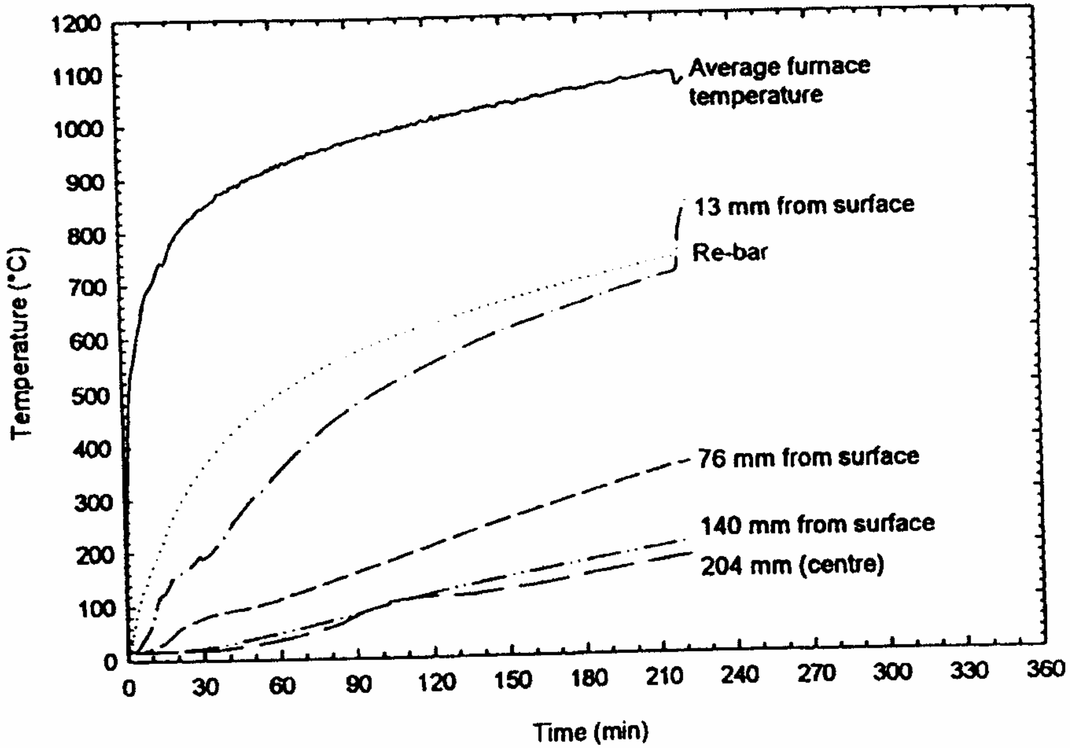


Figure 4. Measured temperatures for column HSC2.

Loaded high strength concrete column (86%RH, 90^0 tie @ h): spalling starts at 10-20 minutes, significant spalling at 1 hr. (by V. Kodur and R. McGrath, 2003)

Local Tests (in PolyU)

Normal strength concrete (NSC) fully saturated, after exposure to 500℃, under 5℃/min

Local Tests (in PolyU)

High strength concrete (HSC) with granite aggregates fully saturated with water, Heating rate = 2℃/minute, spalled at about 450℃

Explosive Concrete Spalling

Explosive concrete spalling requires co-existence of

1. Dense microstructure of concrete
2. Considerable amount of free water in concrete
3. Elevated air temperature (300 to 500℃)

Explosive concrete spalling seldom occurs twice in the same location.

Possible Solutions to Minimize Concrete Cover Spalling Suggested by BSEN 1992-1-2: 2004

- 1: The provision of protective layers for which it is demonstrated that no spalling of concrete occurs under fire exposure.
- 2: The inclusion of more than 2 kg/m^3 of monofilament propylene fibres in the concrete mix.
- 3: The provision of a reinforcement mesh with a nominal cover of 15 mm, in which the mesh should have wires with a diameter $\geqslant$ 2 mm with a pitch $\leqslant$ 50 x 50 mm, and the nominal cover to the main reinforcement should be $\geqslant$ 40 mm.
- 4: The provision of a type of concrete for which it has been demonstrated that no spalling of concrete occurs under fire exposure.

So Uk Fire Test in 2010: Objectives

To conduct a compartment real fire test to verify/study

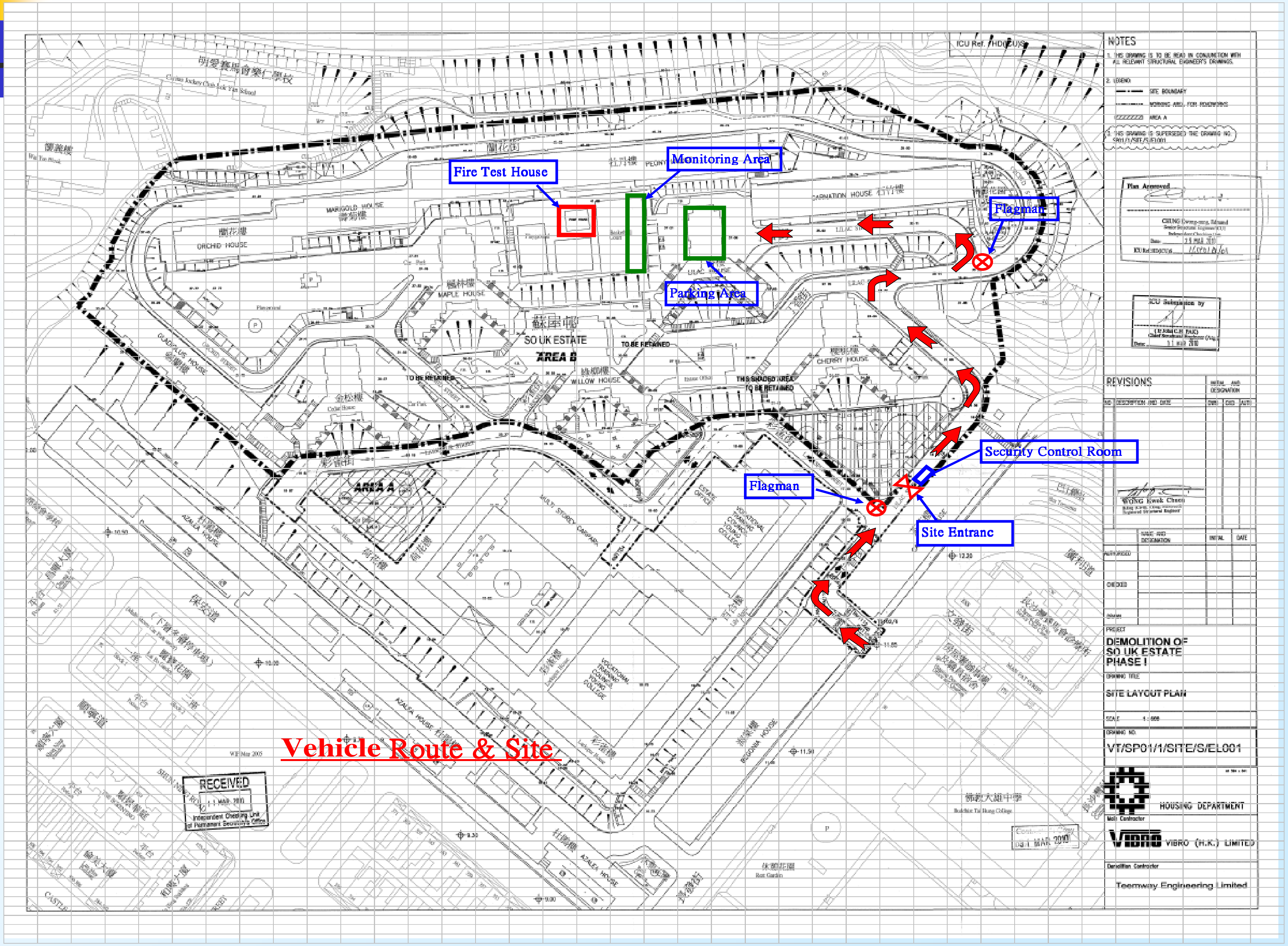
1. Effects of water quenching on new reinforced concrete (normal and high strengths) columns under fire
2. Effects of fire and thereafter water quenching on old normal strength concrete (Pump House concrete of 40 years old)
3. Effects of spalling of various grades of concrete, with/without propylene fibres and wire mesh, under fire
4. Effects of passive protective coatings on enhancing fire resistance of concrete structures

So Uk Fire Research Team

Advisory board – So Uk Fire Test	
Member	**Affiliation**
Ir Prof. J.M. Ko	The Hong Kong Polytechnic University
Ir S.C. Lam	Hong Kong Housing Department
Mr. H.S. Li	Institution of Fire Engineers (Hong Kong Branch)
Prof. Z.P. Ni	Tianjian Fire Research Institute

So Uk Fire Research Team	
Member	**Affiliation**
Ir Dr Y.L. Wong	The Hong Kong Polytechnic University
Ir Dr N.K. Fong	
Ir S.W. Sham	Hong Kong Housing Department
Ir Veronica Y.M. Sun	
Ir K.C. Lau	
Ir K.T. Leung	Institution of Fire Engineers (Hong Kong Branch)
Mr. Y.W. Ng	
Ir Adam S.C. Choy	Building Division of The Hong Kong Institution of Engineers
Ir Dr Jaime Yeung	Materials Division of The Hong Kong Institution of Engineers
Ir Dr Eric Lim	
Ir Sam Choy	
Ir Corey Ho	
Dr X. Huang	Tianjian Fire Research Institute
Mr. G. Xue	

Fire Test Site



Test columns and Study Parameters

- **32 nos. of 300mm x300mm x 1300mm and 8 nos. of 300mm x 300mm x 650mm reinforced/concrete columns (pre-conditioned to fully moisture-saturated status) to be fire-tested.**

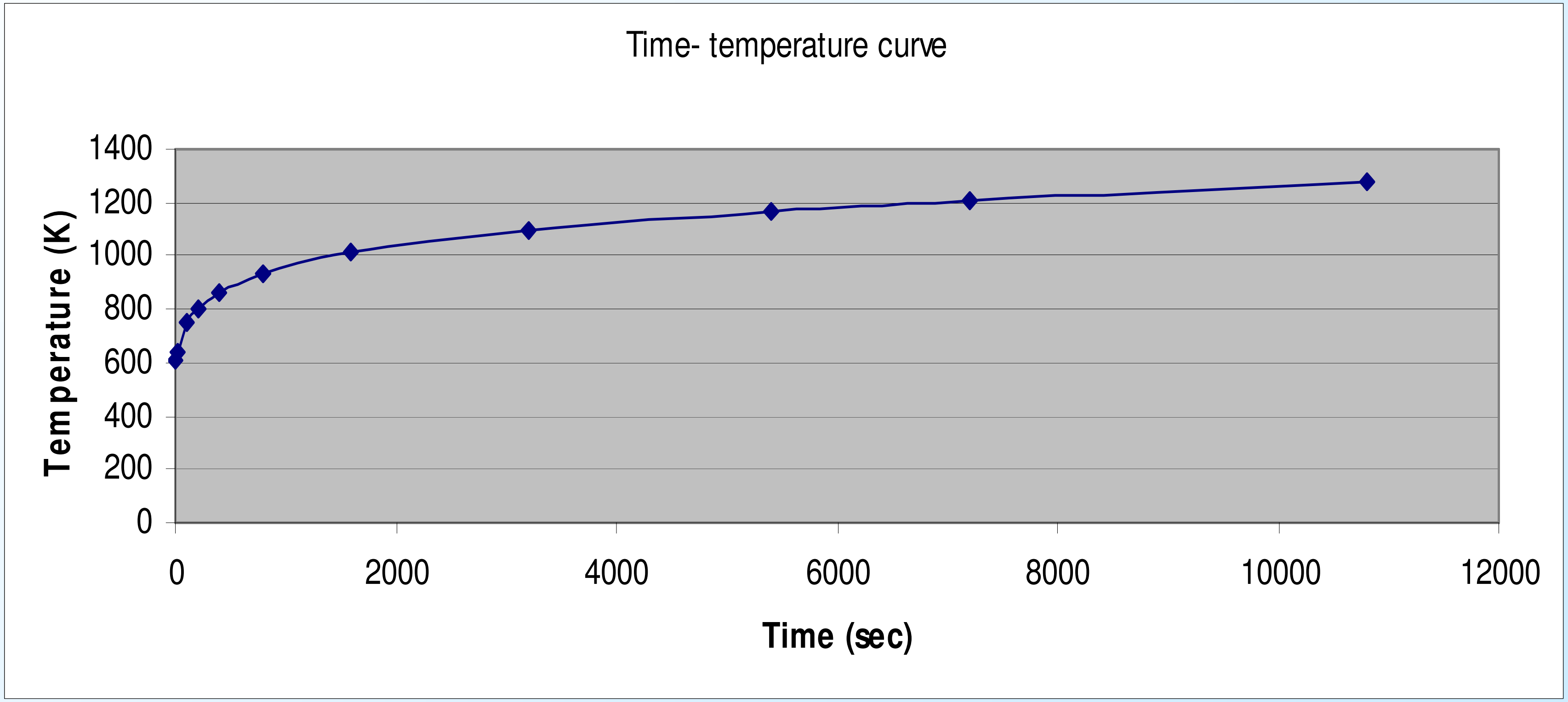
- **Old concrete of Pump House wall, roof slab, and columns to be fire-tested.**

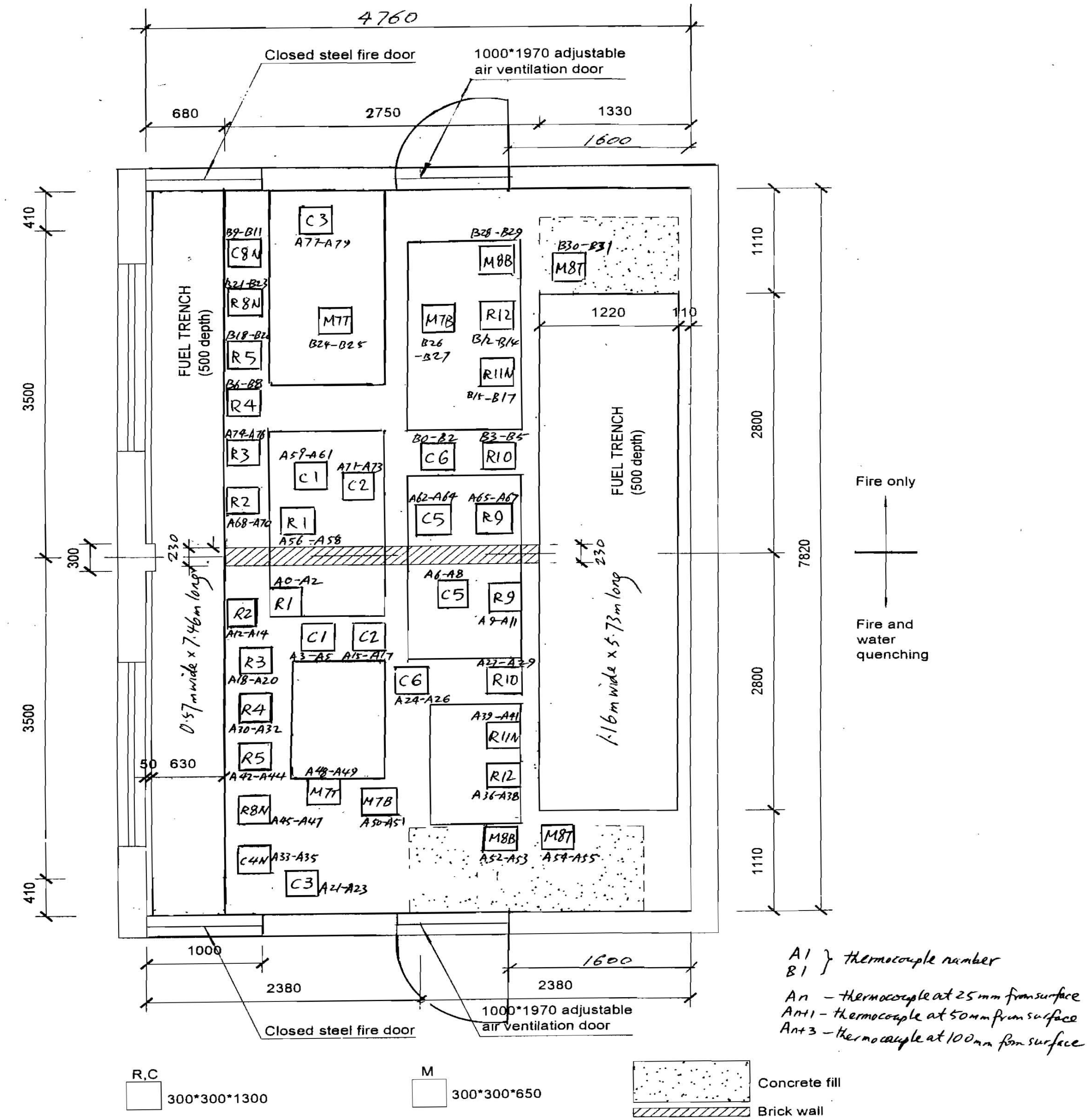
- **Study Parameters**:

  Grades 40, 60, 90 concretes
  Grade 90 concretes with pp fibres, and/or with wire mesh, or with protective coating
  Old concrete (about 40 years old normal strength concrete)
  With and without water quenching

Estimated Temperature-Time Curve

- 3 m^3 of ethanol will be used to produce a real fire for about 3 hours



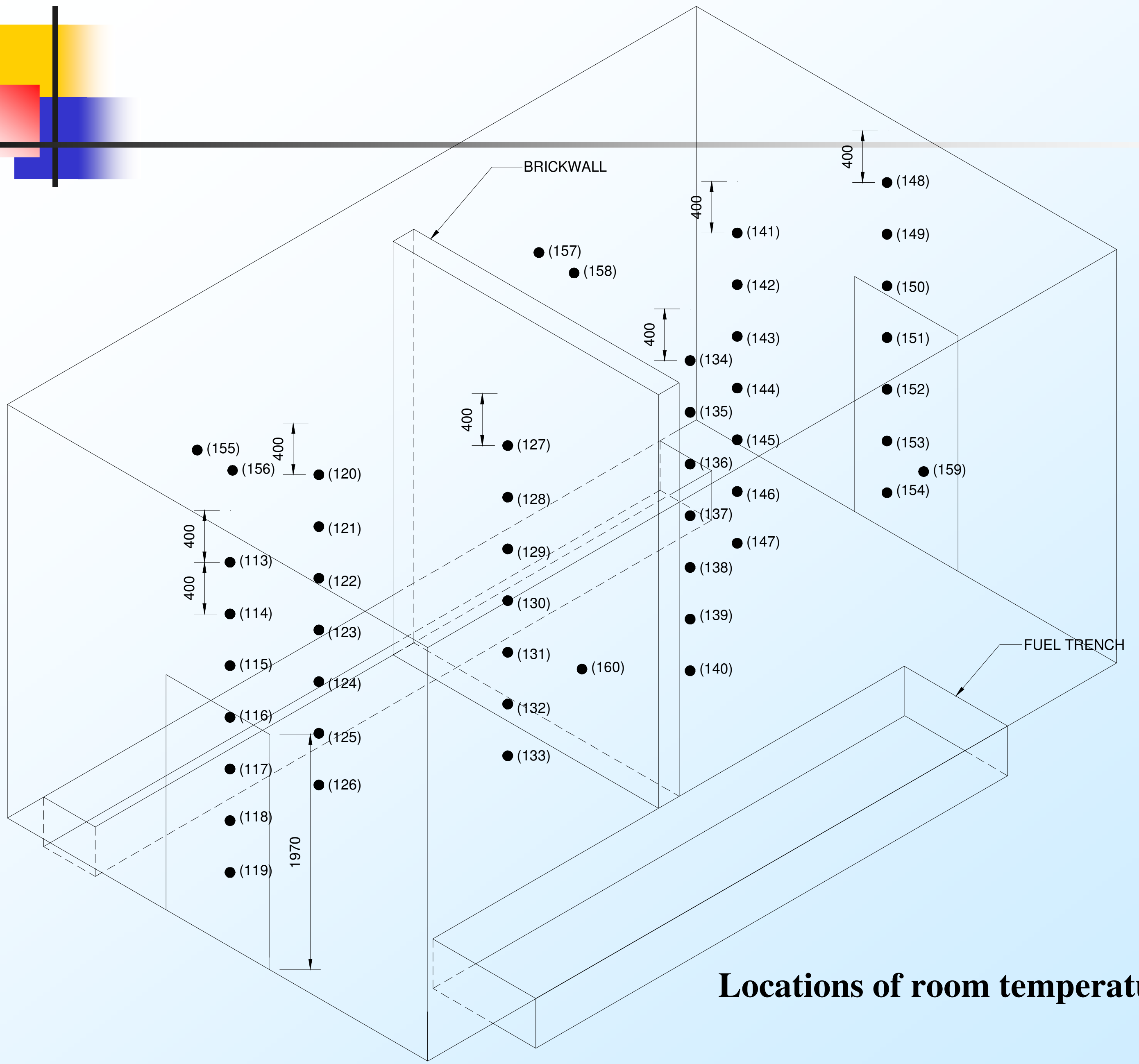


Note: Test columns shall be in a fully moisture-saturated condition under fire

Figure 6: Layout Plan of 40 Test Columns

Instrumentation

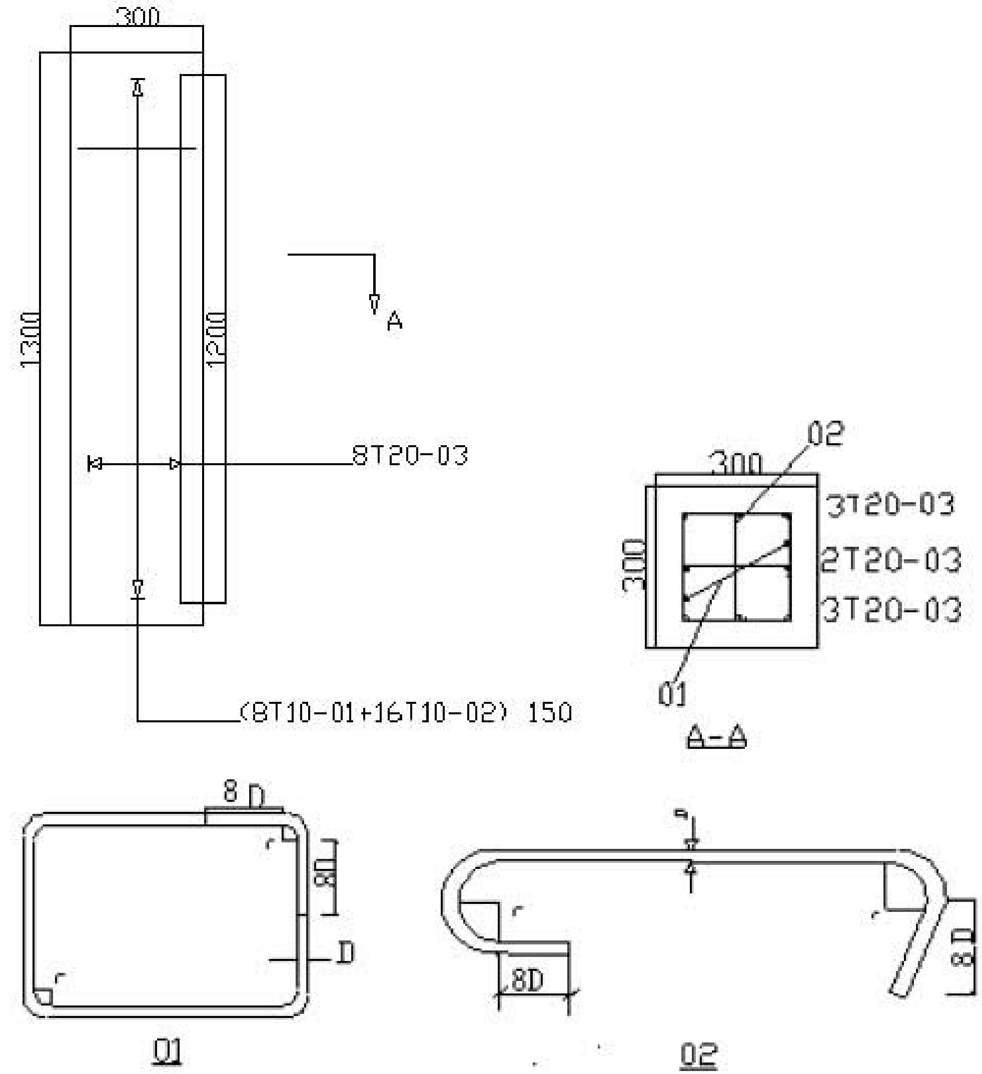
- 200 thermocouples (112 for column temperature distribution, 46 for room temperature distribution, 8 for insulated door temperatures, and 34 for air temperatures at intake opening)
- 12 heat flux sensors
- 4 pressure sensors



Locations of room temperature thermocouples

Table 1: Details of 26 Test Columns

Column Mark	Concrete Grade	Measured Cube Strength prior to Fire Test (MPa)	Remarks
R1, R1W	C40	73.3	-
R2, R2W	C60	88.3	-
R3, R3W	C90	107.3	-
R4, R4W	C90a	100.5	With 0.6 kg/m^3 PP fibre
R5, R5W	C90b	107.0	With 1.0 kg/m^3 PP fibre
R8N, R8NW	C60b	79.5	With 1.0 kg/m^3 PP fibre
R9, R9W	C90	107.3	20 mm magnesium silicate board coating attached on surface
R10, R10W	C90	107.3	20 mm vermiculate cement coating applied on surface
R11N, R11NW	C40	73.3	100 mm x 100 mm 2.0 mm dia. Galvanized mild steel mesh embedded in concrete cover
M7B, M7BW	C40A	73.2	-
M7T, M7TW	C40A	73.2	50 mm x 50 mm 2.6 mm dia. galvanized mild steel mesh embedded in concrete cover
M8B, M8BW	C40Ab	73.0	With 1.0 kg/m^3 PP fibre
M8T, M8TW	C40Ab	73.0	With 1.0 kg/m^3 PP fibre, and 50 mm x 50 mm 2.6 mm dia. galvanized mild steel mesh embedded in concrete cover



concrete cover to T20 = 40 mm

Figure 3: Reinforcement Details of R-type Column

Air temperatures near Central Brickwall at 1.6m above

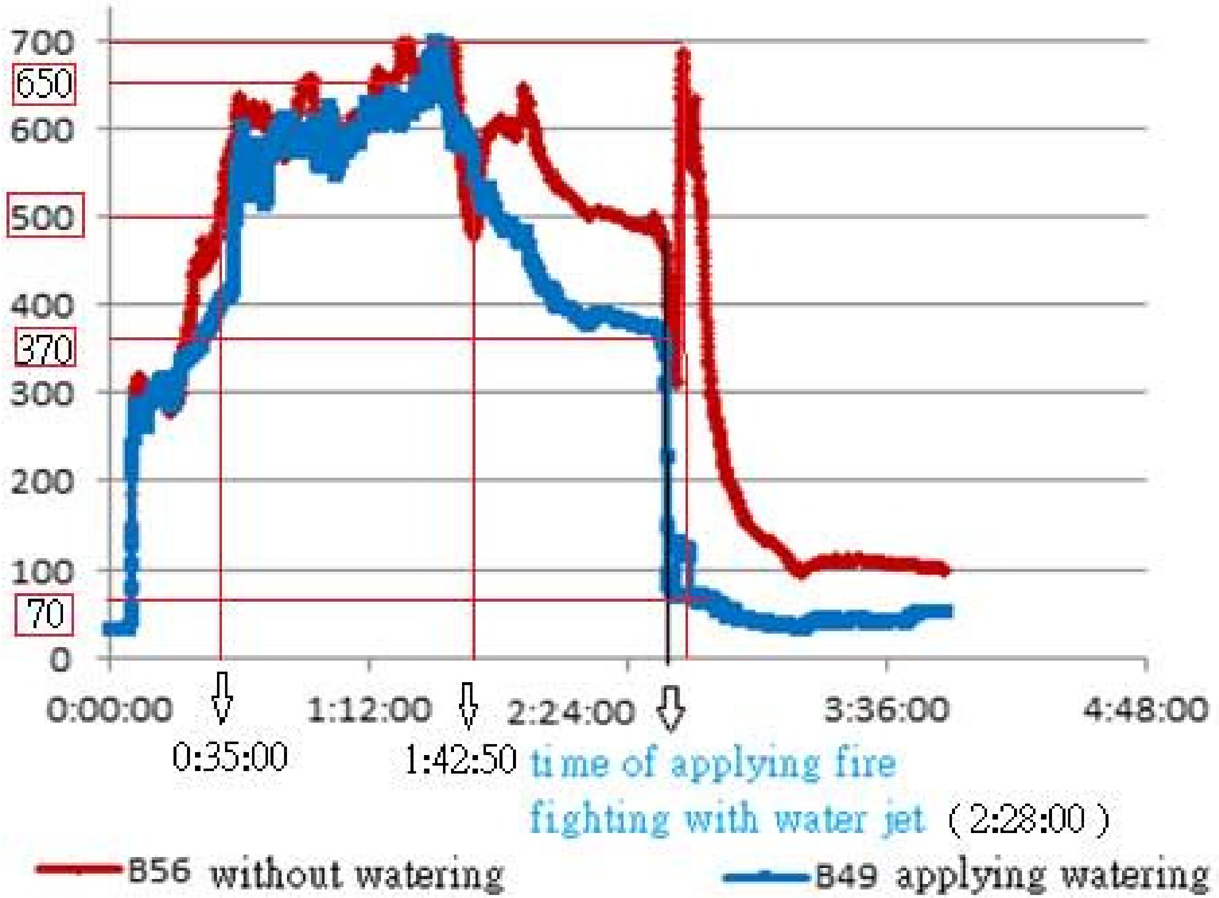


Figure 4: Air Temperatures of Fire Chamber Recorded by Thermocouples B56 and B49

Air Temperature Profile

- Temperature increases with height from floor, maximum difference was about 350C at maximum temperature.
- Max. temperature of 910C was developed at about 1.5 hours after fire started.
- At 2.5 hours, the peak temperature was down to 500C, and water spray at 700 litres/minutes at 7 bars for 10 minutes was applied to 20 heated columns on one sub-chamber. In the other sub-chamber, another 20 heated columns were air-cooled only.

Pump House (before modification for fire test)

Pump House (modification for fire test)

Test Column Handling

Erection of Test Columns

Pump House with test columns (taken on 13 Aug.2010)

Tanking Fuel Trench

Some Research Team Members

Fire Test on 20-8-2010 : Fuel Loading

Fire Fighters Standby during Fuel Loading

Pump House on Controlled Fire

Pump House on Controlled Fire

Pump House on Controlled Fire

Fire Fighting to end Fire Test

Figure 5: Fire-Damaged Test Columns (with Water Quenching)

Figure 6: Fire-Damaged Test Columns (without Water Quenching)

Figure 7: Column R1W (C40)

- fcu = 73.3MPa

Figure 8: Column R11N (C40 with 100 x 100 x 2 steel mesh)

- fcu = 73.3MPa

Figure 9: Columns M7B, M7T, and M8BW (C40A)

- fcu = 73.2MPa

Figure 10: Column R2W (C60)

- fcu = 88.3MPa

Figure 11: Column R8N (C60b with 1.0 kg/m3 pp fibre)

- fcu = 79.5MPa

Figure 12: Column R3W (C90)

- fcu = 107.3MPa

Figure 13: Column R9 (C90 with 20mm Magnesium Silciate Board Coating)

- fcu = 107.3MPa

Figure 14: Column R10 (C90 with 20mm Vermiculate Cement Coating)

- fcu = 107.3MPa

Figure 15: Column R5 (C90b with 1.0 kg/m^3 pp fibre)

- fcu = 107.0MPa

Grading of Concrete Cover Spalling

- Class 1 was the spalling less than 40 mm deep (longitudinal rebars unexposed).
- Class 2 was the spalling less than 60 mm deep (longitudinal rebars exposed).
- Class 3 was spalling greater than 60 mm deep (spalling penetrated behind longitudinal rebars).

Table 3: Extent of Concrete Cover Spalling of Test Columns without Water Quenching

Column	Remarks	Spalled Area (% of total vertical surface areas of column)			
		Class 1	Class 2	Class 3	$\sum$
R1	C40	13	3	5	21
R11N	C40 with 100 x 100 x 2 steel mesh	7	20	0	27
M7B	C40A	12	5	0	17
M7T	C40A with 50 x 50 x 2.6 steel mesh	5	0	0	5
M8B	C40Ab with 1.0 kg/m^3 pp fibre	0	0	0	0
M8T	C40Ab with 1.0 kg/m^3 pp fibre and 50 x 50 x 2.6 steel mesh	0	0	0	0
R2	C60	8	25	0	43
R8N	C60b with 1.0 kg/m^3 pp fibre	0	0	0	0
R3	C90	35	10	2	47
R9	C90 with 20mm Mg Si board coating	24	0	0	24
R10	C90 with vermiculate cement coating	0	0	0	0
R4	C90a with 0.6 kg/m^3 pp fibre	1	0	0	1
R5	C90b with 1.0 kg/m^3 pp fibre	0	0	0	0

Table 4: **Extent of Concrete Cover Spalling of Test Columns with Water Quenching**

Column	Remarks	Spalled Area (% of total vertical surface areas of column)			
		Class 1	Class 2	Class 3	∑
R1W	C40	2	29	5	36
R11NW	C40 with 100 x 100 x 2 steel mesh	2	22	11	35
M7BW	C40A	5	0	0	5
M7TW	C40A with 50 x 50 x 2.6 steel mesh	2	0	0	2
M8BW	C40Ab with 1.0 kg/m^3 pp fibre	0	0	0	0
M8TW	C40Ab with 1.0 kg/m^3 pp fibre and 50 x 50 x 2.6 steel mesh	0	0	0	0
R2W	C60	49	2	3	54
R8NW	C60b with 1.0 kg/m^3 pp fibre	1	1	1	3
R3W	C90	2	28	25	55
R9W	C90 with 20mm Mg Si board coating	2	11	15	28
R10W	C90 with vermiculate cement coating	1	5	0	6
R4W	C90a with 0.6 kg/m^3 pp fibre	2	0	0	2
R5W	C90b with 1.0 kg/m^3 pp fibre	0	0	0	0

Key Findings of Concrete Cover Spalling

- (i) Without adopting one of the above-mentioned EN methods to suppress concrete spalling under fire, the severity of concrete cover spalling increased with the cube strength of the test columns. Concrete spalling often occurred at the corners of the columns.

- (ii) Water quenching has an insignificant adverse effect on the concrete cover spalling. This might be due to the fact that most of the concrete cover spalling and macro-crack formation happened in the first hour of fire (air temperature less than 600C). Further sustained fire or increase in fire temperature would lead to more degradation or decomposition of the concrete matrix but the mechanism of concrete spalling basically ceased. As water quenching was applied to the columns at the fire time of 2 hours and 28 minutes, the temperature shock so induced might cause concrete further cracking or crack opening but not spalling.

Key Findings of Concrete Cover Spalling

- (iii) The provision of a mild steel mesh of 2.0 mm diameter at 100 mm x 100 mm centres embedded in the concrete cover could not effectively reduce concrete cover spalling to an acceptable level.
- (iii) The provision of a mild steel mesh of 2.6 mm diameter at 50 mm x 50 mm centres embedded in the concrete cover or 1.0 kg/m3 of propylene fibre in concrete could significantly suppress concrete cover spalling.
- (iv) The provision of an appropriate vermiculate cement coating of 20 mm thick applied on the surface of the concrete column (cube strength about 100MPa) could substantially reduce concrete cover spalling.
- (v) In this study, the selected 20 mm thick magnesium silicate board attached to the surface of the concrete column could not reduce concrete cover spalling to a satisfactory level. Its anti-spalling effect might be improved by a better quality of the board or/and installation method.

HK Code of Practice: Standard Use of Concrete 2013

4.3 REQUIREMENTS FOR FIRE RESISTANCE

In some circumstances, the cover specified for durability will not be sufficient for fire protection. Where applicable, the nominal cover should be modified in accordance with the guidelines given in the Code of Practice for Fire Safety in Buildings which also specifies minimum dimensions of members for specified periods of fire resistance.

For concrete compressive strength greater than 60 MPa, the possible reduction of strength at elevated temperatures and the associated risk of spalling should be investigated, taken into account the relevant factors including moisture content, type of aggregate, permeability of concrete, possible heating rate and the silica fume content.

HK Code of Practice: Standard Use of Concrete 2013

4.3.1 Prevention of spalling in high strength concrete

4.3.1.1 General requirement

For high strength concrete, the reduction of strength and associated risk of spalling at elevated temperature shall be taken into account. The content of silica fume if used in high strength concrete should not exceed 6% by weight of the total cementitious content. Pfa and ggbs if used in high strength concrete should comply with the requirements given in clause 4.2.5.5; there is no additional requirement or restriction on the use of pfa or ggbs as they are conducive to the prevention of spalling in high strength concrete.

4.3.1.2 Methods to reduce risk of concrete spalling

At least one of the following methods should be provided.

(a) **Method A:** A reinforcement mesh with a nominal cover of 15mm. This mesh shall have wires with a diameter ≥ 2mm with a pitch ≤ 50 x 50mm. The nominal cover to the main reinforcement shall be ≥ 40mm; or

(b) **Method B:** Include in the concrete mix not less than 1.5 kg/m^3 of monofilament propylene fibres. The fibres shall be 6 – 12 mm long and 18 – 32 μm in diameter, and shall have a melting point less than 180°C; or

(c) **Method C:** Protective layers for which it is demonstrated by local experience or fire testing that no spalling of concrete occurs under fire exposure; or

(d) **Method D:** A design concrete mix for which it has been demonstrated by local experience or fire testing that no spalling of concrete occurs under fire exposure.

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For high strength concrete exceeding C80, at least one fire test should be carried out to demonstrate that the main reinforcing bars of a structural member shall not be exposed during the design fire resistance rating. The test specimen should have moisture content not less than the highest moisture content that the structure may attain during its working life.

Fire Engineering Approach

- 1. Determine thermal loads/actions, and fire temperature
- 2. Analyze temperature distribution of structures
- 3. Verification of fire resistance

Fire Engineering Approach

Fire Loads and Design Procedures:

- BS 7974:2001 - Application of Fire Safety Engineering Principles to the Design of Buildings- Code of Practice
- PD 7974:2002 - Application of Fire Safety Engineering Principles to the Design of Buildings- Guide to Design Framework and Fire Safety Engineering Procedure
- EN 1991-2-2:2004 - Eurocode 2; Design of Concrete Structures Part 1-2: General Rules – Structural Fire Design

EN 1991-1-2: 2004 Fire Load Densities

Table E.4 — Fire load densities $q_{f,k}$ [MJ/m²] for different occupancies

Occupancy	Average	80% Fractile
Dwelling	780	948
Hospital (room)	230	280
Hotel (room)	310	377
Library	1 500	1 824
Office	420	511
Classroom of a school	285	347
Shopping centre	600	730
Theatre (cinema)	300	365
Transport (public space)	100	122
NOTE Gumbel distribution is assumed for the 80 % fractile.		

Material thermal properties

	Thermal conductivity λ (W/K/m)	Specific heat c (J/kg/K)
Concrete	2.0	2020
Steel	54	600
Air	0.025	1012
Water	0.6	4181
Copper	385	385
Wood	0.4	3956

For simple calculation

Fire Thermal Field Models

FDS-SMV by NIST, USA: CFD model

CFX, UK: General purpose CFD software

FIRE, Australian: CFD model with water sprays and coupled to solid/liquid phase fuel to predict the burning rate and extinguish process

SOFIE, UK/Sweden: CFD model for fire and smoke spread

Simplified Structural Fire Resistance Models

- AFCB: Composite beams (www.sections.arcelor.com)
- AFCC: Composite columns (www.sections.arcelor.com)
- H-Fire: Composite members (www.stahlbau.uni-hannover.de)
- POTFIRE: Unprotected concrete filled hollow section columns (www.cidect.org)

Advanced Structural Fire Resistance Models

- VULCAN: 3-D steel-framed buildings
- AQBQUS, ANSYS, BoFire, SAFIR: Concrete and steel structures
- BRANZ-TR8: Reinforced or prestressed concrete floor systems
- VALCAN: 3-D frame analysis program to model skeletal steel and composite frames, including floor slabs

EN 1991-1-2: 2004 Equivalent Time of Fire Exposure

(3) The equivalent time of standard fire exposure is defined by:

$t_{e,d} = (q_{f,d} \cdot k_b \cdot w_f)\, k_c$ or

$$t_{e,d} = (q_{t,d} \cdot k_b \cdot w_t)\, k_c \quad \text{[min]} \qquad \text{(F.1)}$$

where

$q_{f,d}$ is the design fire load density according to annex E, whereby $q_{t,d} = q_{f,d} \cdot A_f / A_t$

k_b is the conversion factor according to (4)

w_f is the ventilation factor according to (5), whereby $w_t = w_f \cdot A_t / A_f$

k_c is the correction factor function of the material composing structural cross-sections and defined in Table F.1.

Table F.1 — Correction factor k_c in order to cover various materials.
(O is the opening factor defined in annex A)

Cross-section material	Correction factor k_c
Reinforced concrete	1,0
Protected steel	1,0
Not protected steel	$13{,}7 \cdot O$

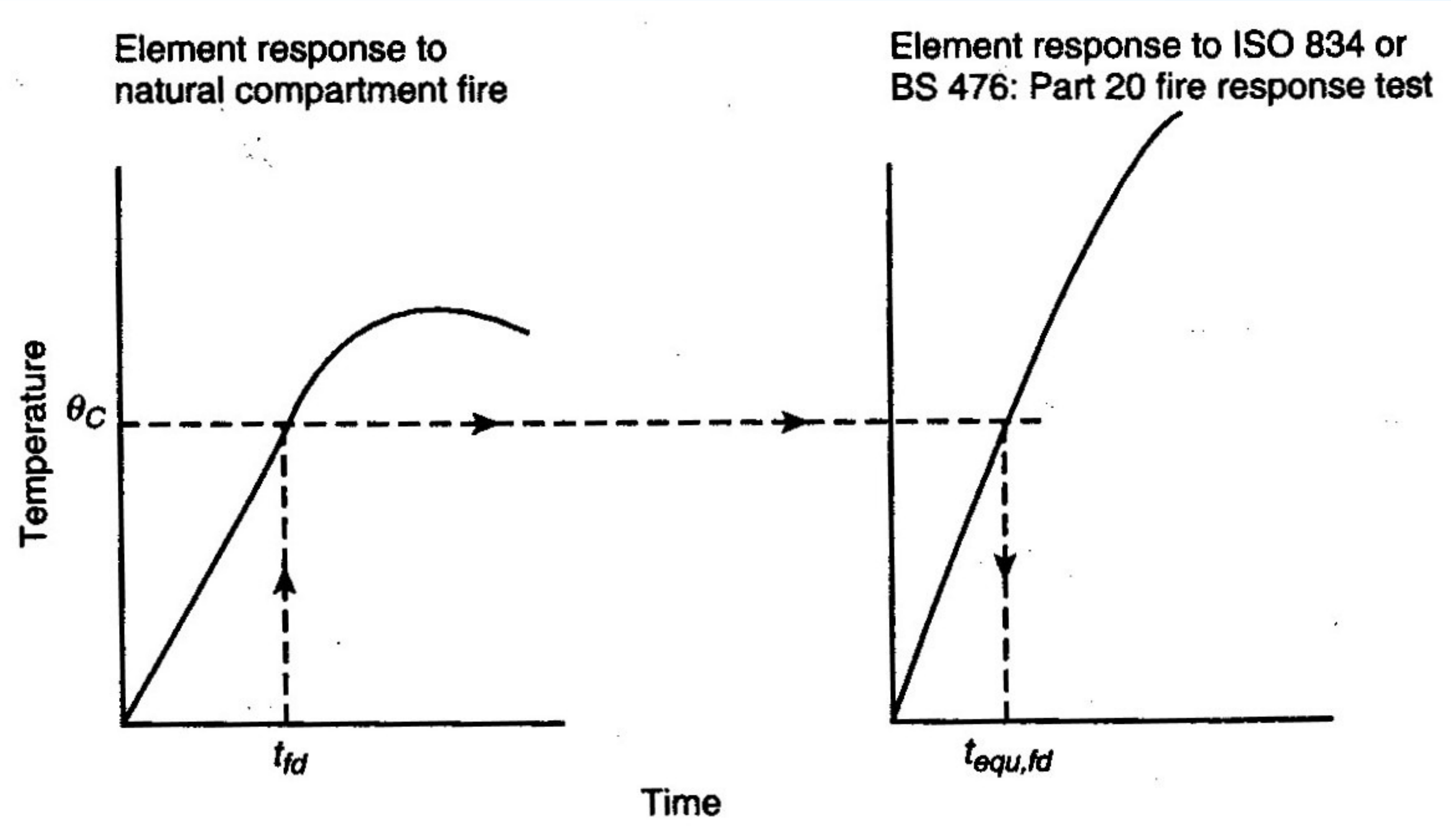
(4) Where no detailed assessment of the thermal properties of the enclosure is made, the conversion factor k_b may be taken as:

$$k_b = 0{,}07 \quad [\text{min} \cdot \text{m}^2/\text{MJ}] \quad \text{when } q_d \text{ is given in } [\text{MJ/m}^2] \qquad \text{(F.2)}$$

otherwise k_b may be related to the thermal property $b = \sqrt{(\rho c \lambda)}$ of the enclosure according to Table F.2. For determining b for multiple layers of material or different materials in walls, floor, ceiling, see annex A (5) and (6).

EN 1991-1-2: 2004 Equivalent Time of Fire Exposure

This approach may be used where the design of members is based on tabulated data or other simplified rules, related to the standard fire exposure.



Fire Safety Engineering by J.A. Purkiss

Fire Engineering Approach

The capacity of a structural member under fire can then be calculated from the first principles or the required concrete cover can be determined from the tabulated data in the deemed-to-comply approach once the equivalent FRR is established.

Conclusions

Deem-to-Comply design approach has been proved to offer reliable solutions for fire resisting design of conventional buildings, provided issues of concrete cover spalling have been properly considered.

PolyU fire research and So Uk Fire Test provided some local reference information and practical solutions to suppress concrete spalling of high strength concrete under fire.

Fire limit states and fire resistance design of reinforced concrete, including prevention of spalling in high strength concrete, are incorporated in the new Code of Practice: Standard Use of Concrete 2013.

If fire engineering design approach is adopted, the capacity of a structural member under fire can then be calculated from the first principles or the required concrete cover can be determined from the tabulated data in the deemed-to-comply approach once the equivalent FRR is established.

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End of Presentation

Thank you

Ir Dr Y.L. Wong
RPE, RI
ceylwong@polyu.edu.hk
mobile no. 64969170