NANYANG TECHNOLOGICAL UNIVERSITY

A*STAR Research

A Rational Approach to Fire Resistance Analysis of Reinforced Concrete Columns Subjected to Uniaxial / Biaxial Bending and Axial Restraint

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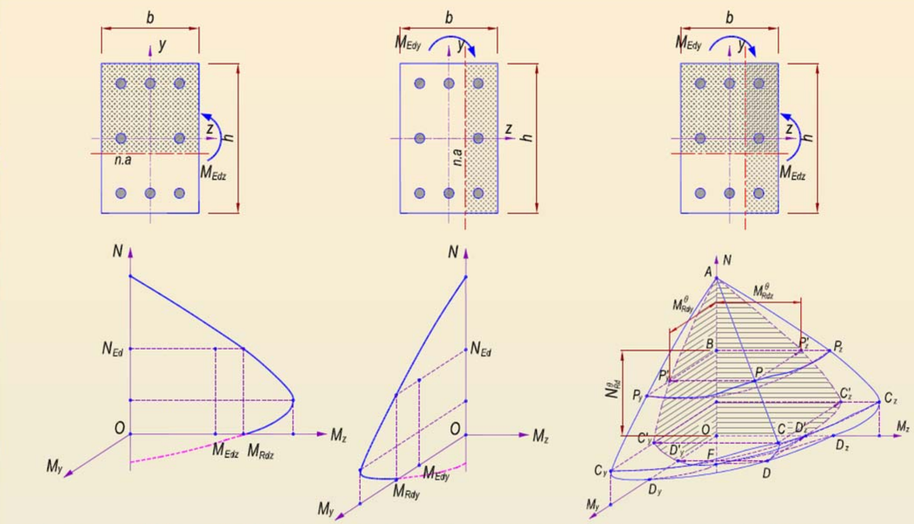
Fire Resistance Analysis of RC Columns Subjected to Uniaxial / Biaxial Bending and Axial Restraint

1. Introduction

1.1. Published Research Works

1. Mostly on columns subjected to axial load and uniaxial bending.
   - An indirect approach using Bresler's formula was proposed by Tan and Yao (2003) for biaxially-loaded columns under fires;
   - EC2 for ambient design specifies an approximate approach;
   - Fire provisions of current codes neglect biaxial bending;
2. Additional axial forces due to axial restraint were rarely considered;
3. Mostly conducted in standard fires. Based on failure time in fire tests to validate ultimate loads predicted by analytical/numerical methods;
4. Limited information of fire tests on biaxially-loaded columns have been used for verification.



(a) Uniaxially-loaded column about z-axis (b) Uniaxially-loaded column about y-axis (c) Biaxially-loaded column

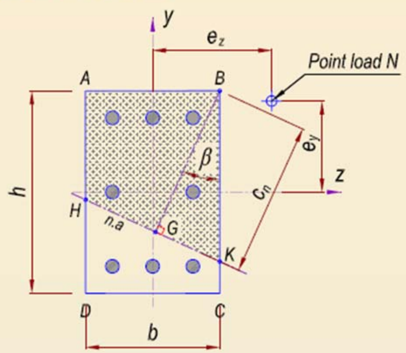
Tan & Yao (2003) $$\frac{1}{P_n(T)} = \frac{1}{P_{nx0}(T)} + \frac{1}{P_{ny0}(T)} - \frac{1}{P_0(T)}$$

BS EN 1992-1-1:2004
EN 1992-1-1:2004 (E) $$\left(\frac{M_{Edz}}{M_{Rdz}}\right)^a + \left(\frac{M_{Edy}}{M_{Rdy}}\right)^a \leq 1{,}0$$

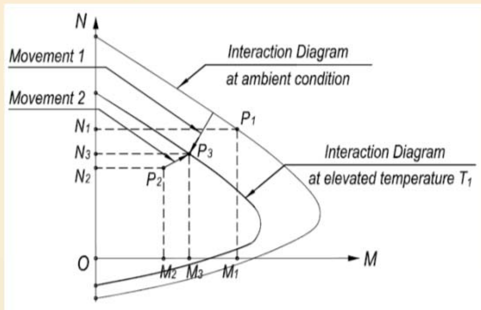
BS EN 1992-1-2:2004 ?

1.2. Proposed Approach

1. Conduct temperature-dependent sectional analysis directly based on inclined neutral axes;
2. Additional thermal-induced forces are considered;
3. Any fire curve can be adopted. Based on both variation of acting loads and deteriorations of strength/stiffness to predict failure time;
4. Fire tests on either uniaxially- or biaxially-loaded columns under either standard or nonstandard fires are used for validation.



Direct analysis

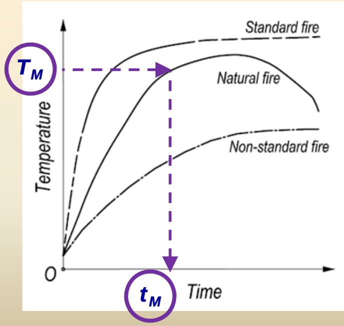


Failure criteria

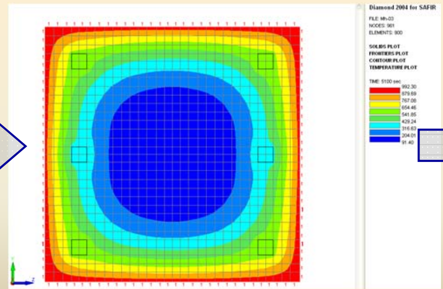
Fire Resistance Analysis of RC Columns Subjected to Uniaxial / Biaxial Bending and Axial Restraint

2. Principle of Analysis

Step 1. Temperature-time Curve

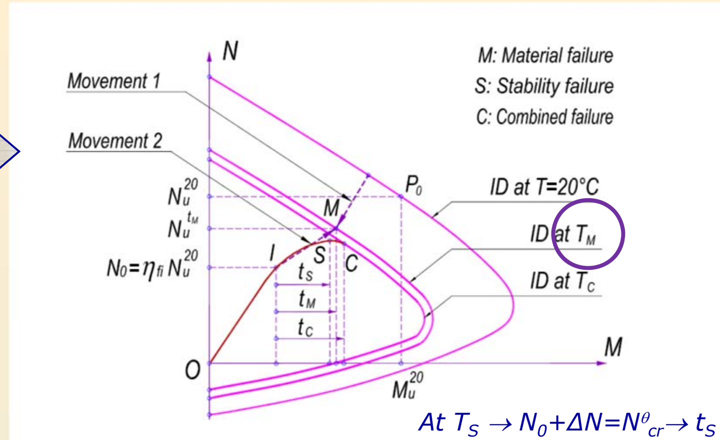


Step 2. Thermal Analysis



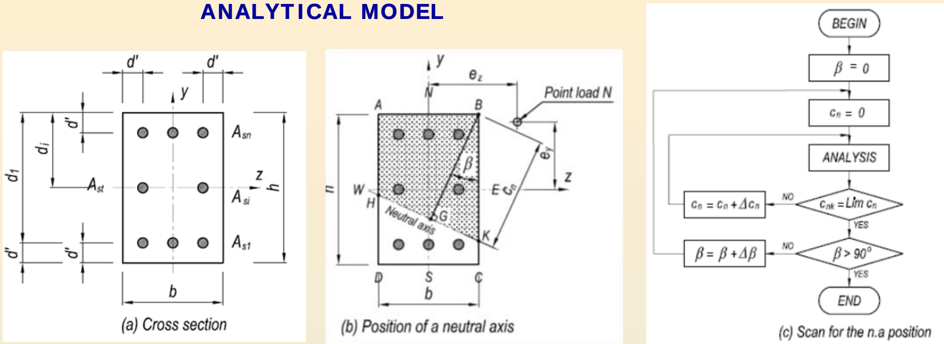
SAFIR software

Step 3. Sectional Analysis

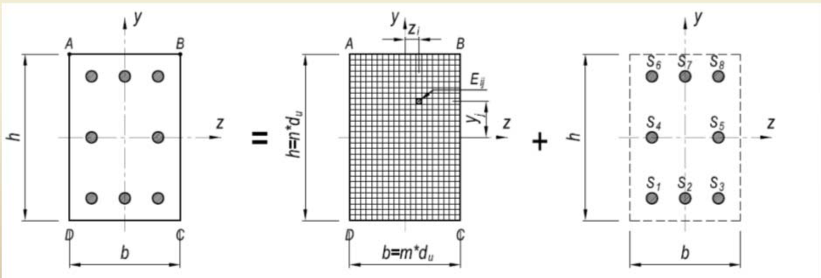


Failure modes

ANALYTICAL MODEL



(a) Cross section (b) Position of a neutral axis (c) Scan for the n.a position



(1) Cross section (2) Analytical model for the concrete (3) Analytical model for the steel bars

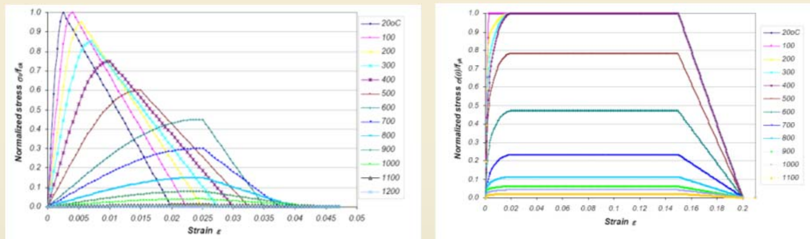
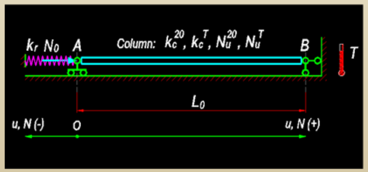


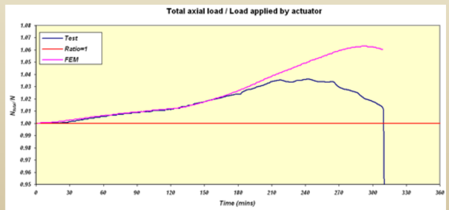
Fig. 2.8 Eurocode stress-strain relationships of siliceous aggregate concrete

Fig. 2.11 Eurocode stress-strain relationships of hot rolled reinforcement

EUROCODE Material Model

$$N = N_0\left[\frac{k_r}{\sum k_{ci}^T + k_r}\left(\frac{\sum\left(k_{ci}^T(-u_{thi})\right)}{N_0}-1\right)+1\right]$$

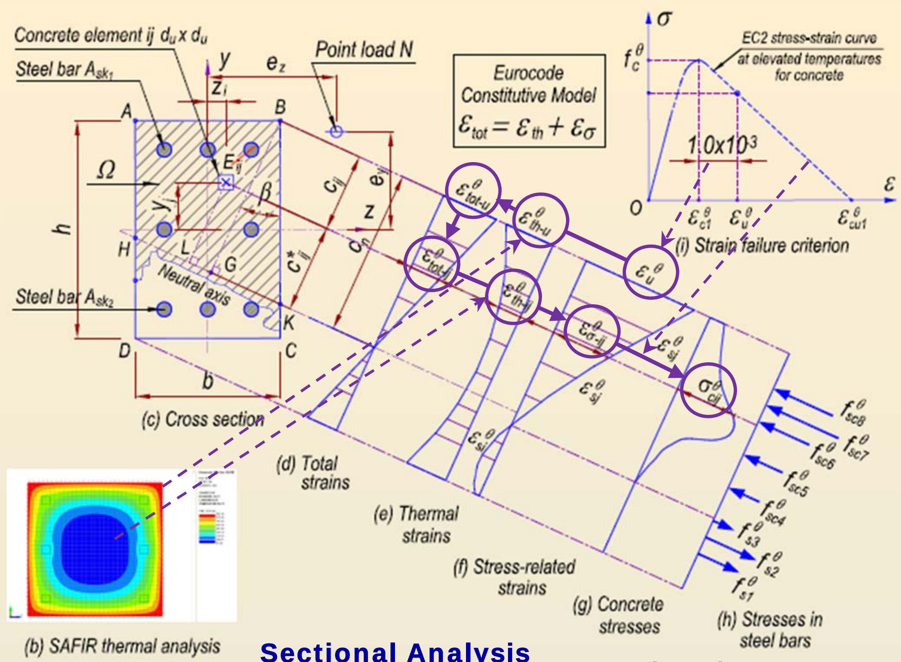




Thermal-induced Axial Force

Fire Resistance Analysis of RC Columns Subjected to Uniaxial / Biaxial Bending and Axial Restraint

3. Analytical Approach and Computer Program



Sectional Analysis

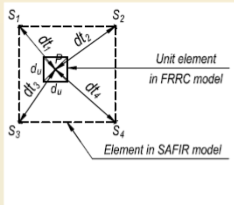
Strain Failure Criterion

Concrete	$\varepsilon^{\theta}_{c1}$	$\varepsilon^{\theta}_{cu1}$	ε^{θ}_{u}	Siliceous aggregates		Calcareous aggregates	
temp. (°C)	x10⁻³	x10⁻³	x10⁻³	$\varepsilon^{\theta}_{th}$x10⁻³	$\varepsilon^{\theta}_{tot-u}$x10⁻³	$\varepsilon^{\theta}_{th}$x10⁻³	$\varepsilon^{\theta}_{tot-u}$x10⁻³
20	2.5	20.0	3.5	-0.000	3.500	-0.000	3.500
100	4.0	22.5	5.0	-0.743	4.257	-0.494	4.506
200	5.5	25.0	6.5	-1.804	4.696	-1.192	5.308
300	7.0	27.5	8.0	-3.141	4.859	-2.058	5.942
400	10.0	30.0	11.0	-4.892	6.108	-3.176	7.824
500	15.0	32.5	16.0	-7.195	8.805	-4.630	11.370
600	25.0	35.0	26.0	-10.188	15.812	-6.504	19.496
700	25.0	37.5	26.0	-14.009	11.991	-8.882	17.118
800	25.0	40.0	26.0	-14.000	12.000	-11.848	14.152
900	25.0	42.5	26.0	-14.000	12.000	-12.000	14.000
1000	25.0	45.0	26.0	-14.000	12.000	-12.000	14.000
≥1100	25.0	47.5	26.0	-14.000	12.000	-12.000	14.000

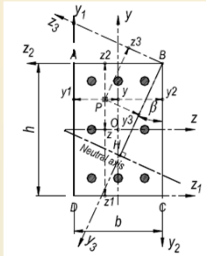
Subroutines of FRRC program

Name	Description
1.IP	Input for geometrical and material properties
2.AL	Determination of applied loads (first-order and second-order)
3.CA	Analysis of coordinate
4.TA	Determination of temperature
5.CM	Material model of concrete at elevated temperatures
6.RM	Material model of reinforcing steel at elevated temperatures
7.FC	Criteria for failure of material at elevated temperatures
8.CC	Computing concrete contribution to the load resistance
9.RC	Computing reinforcing steel contribution to the load resistance
10.FD	Description of failure
11.OP	Output for time, neutral axis and load resistance at failure
12.ID	Determination of interaction diagrams / surface at failure

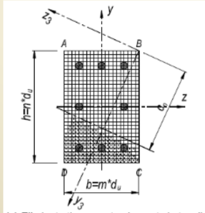
FRRC Model



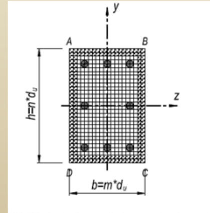
(b) Elements in SAFIR and FRRC models



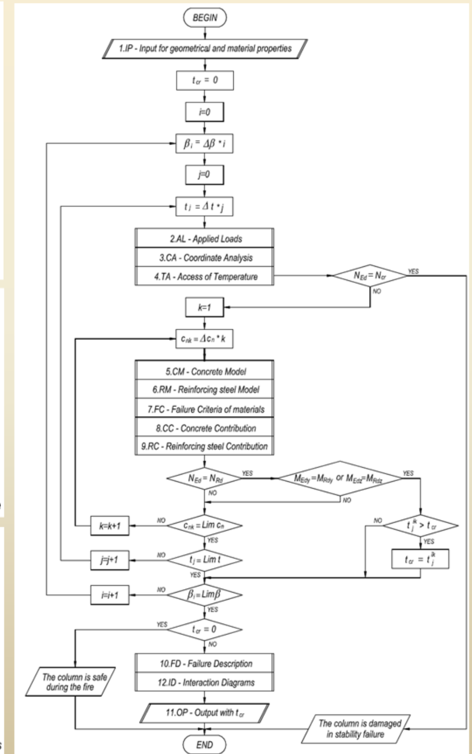
(a) Coordinate systems of the section



(a) Eliminate the conrete elements in tensile



(b) Eliminate the spalled concrete elements

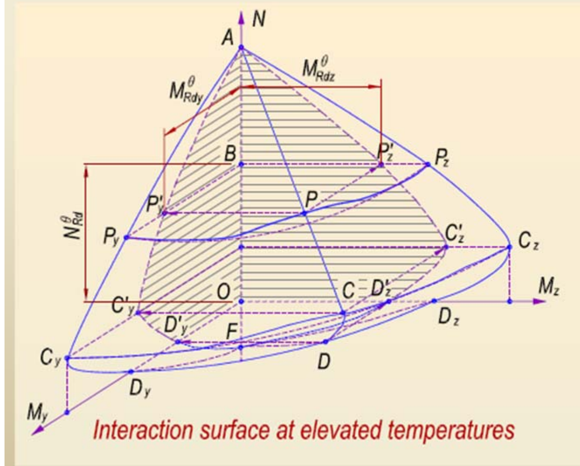


Load Resistance:

$$N^{\theta}_{Rd} = \sum_{ij} \sigma^{\theta}_{cij} d_u^2 + \sum_{k_1} A_{sk_1}(f^{\theta}_{sck_1} - \sigma^{\theta}_{ck_1}) + \sum_{k_2} A_{sk_2} f^{\theta}_{sk_2}$$

$$M^{\theta}_{Rdy} = \sum_{ij} \sigma^{\theta}_{cij} d_u^2 z_i + \sum_{k_1} A_{sk_1}(f^{\theta}_{sck_1} - \sigma^{\theta}_{ck_1}) z_{k_1} + \sum_{k_2} A_{sk_2} f^{\theta}_{sk_2} z_{k_2}$$

$$M^{\theta}_{Rdz} = \sum_{ij} \sigma^{\theta}_{cij} d_u^2 y_j + \sum_{k_1} A_{sk_1}(f^{\theta}_{sck_1} - \sigma^{\theta}_{ck_1}) y_{k_1} + \sum_{k_2} A_{sk_2} f^{\theta}_{sk_2} y_{k_2}$$



Direct Approach:

$$\text{If } N^{\theta}_{Ed} = N^{\theta}_{Rd} \text{ then } M^{\theta}_{Edy} \leq \overline{M}^{\theta}_{Rdy} \text{ and } M^{\theta}_{Edz} \leq \overline{M}^{\theta}_{Rdz}$$

Indirect Approach:

$$\text{If } N^{\theta}_{Ed} = N^{\theta}_{Rd} \text{ then } \left(\frac{M^{\theta}_{Edy}}{M^{\theta}_{Rdy}}\right)^a + \left(\frac{M^{\theta}_{Edz}}{M^{\theta}_{Rdz}}\right)^a \leq 1$$

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4. Experimental Verification

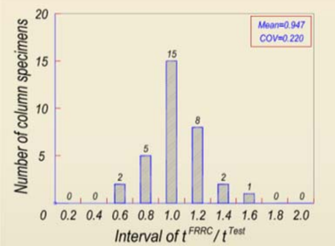


FIG. 7. Validation used Hass's tests (1986)

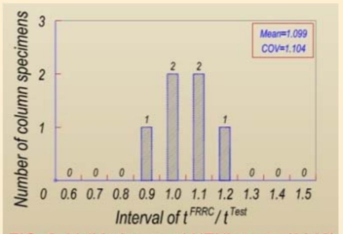
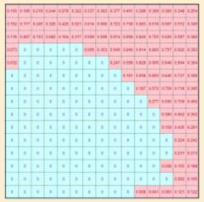


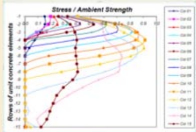
FIG. 8. Validation used NTU's tests (2010)

TAB. 1. Experimental verification

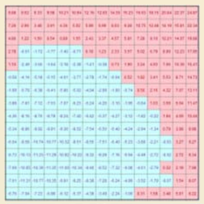
Test	No.	Ref.	Experimental Data													Proposed Approach			Ratio
			b (mm)	h (mm)	Rebar (mm)	L (m)	f'_c (MPa)	f_y (MPa)	End Cond.	d' (mm)	e_y (mm)	e_z (mm)	k_r (kN/mm)	N_{app} (kN)	t^{Test} (min)	β (rad)	c_n (mm)	t^{FRRC} (min)	t^{FRRC}/t^{Test}
Hass (1986)	1	1	300	300	6φ20	3.76	24.1	487	p-p	38	30	0	0	710	86	0	126	85	0.988
	2	2	300	300	6φ20	3.76	24.1	487	p-p	38	0	0	0	710	86	0	150	82	0.953
	3	3	300	300	6φ20	3.76	24.1	487	p-p	38	0	0	0	650	63	0	150	82	1.302
	4	4	300	300	6φ20	4.76	24.1	487	p-p	38	30	0	0	880	108	0	120	74	0.685
	5	5	300	300	6φ20	4.76	34.1	487	p-p	38	0	0	0	600	61	0	130	77	1.262
	6	6	300	300	6φ20	5.76	24.1	487	p-p	38	30	0	0	800	58	0	120	65	1.121
	7	7	300	300	6φ20	5.76	24.1	487	p-p	38	0	0	0	420	58	0	140	58	1.000
	8	8	200	200	4φ20	3.76	24.1	487	p-p	38	0	0	0	420	66	0	100	47	0.712
	9	9	200	200	4φ20	3.76	24.1	487	p-p	38	0	0	0	340	48	0	100	47	0.979
	10	10	200	200	4φ20	4.76	24.1	487	p-p	38	0	0	0	650	80	0	100	39	0.488
	11	11	300	300	6φ20	4.76	30.7	462	p-p	38	30	0	0	650	69	0	120	75	1.087
	12	12	300	300	6φ20	4.76	30.7	462	p-p	38	30	0	0	740	85	0	120	75	0.882
	13	13	300	300	6φ20	4.76	30.7	462	p-p	38	15	0	0	280	49	0	120	80	1.633
	14	14	200	200	4φ20	4.76	30.7	462	p-p	38	10	0	0	240	36	0	80	41	1.139
	15	15	200	200	4φ20	4.76	30.7	462	p-p	38	20	0	0	460	75	0	80	47	0.627
	16	16	300	300	6φ20	4.76	30.7	462	p-p	38	90	0	0	362	65	0	110	67	1.031
	17	17	300	300	6φ20	4.76	30.7	462	p-p	38	150	0	0	170	49	0	110	63	1.286
	18	18	200	200	4φ20	4.76	30.7	462	p-p	38	60	0	0	130	53	0	70	55	1.038
	19	19	200	200	4φ20	4.76	30.7	462	p-p	38	100	0	0	845	111	0	60	53	0.477
	20	20	300	300	6φ20	3.8	33.2	458	p-f	38	30	0	0	780	125	0	130	94	0.752
	21	21	300	300	6φ20	3.8	33.2	418	p-f	38	50	0	0	208	40	0	120	82	2.050
	22	25	200	200	4φ20	5.76	32.4	443	p-p	38	10	0	0	735	160	0	70	33	0.206
	23	26	300	300	6φ20	4.76	30.7	433	p-f	38	15	0	0	355	89	0	130	96	1.079
	24	27	300	300	6φ20	4.76	43.2	544	p-f	38	150	0	0	735	93	0	100	80	0.860
	25	28	300	300	6φ20	4.76	31.5	499	p-p	38	±15*	0	0	645	135	0	120	73	0.541
	26	29	300	300	6φ20	4.76	38.2	499	p-p	38	±30*	0	0	1224	48	0	110	71	1.479
	27	30	300	300	6φ20	4.76	38.2	404	p-p	38	5	0	0	1695	57	0	150	55	0.965
	28	31	300	300	6φ20	3.76	42.3	452	p-p	38	5	0	0	1548	38	0	170	65	1.711
	29	37	300	300	6φ20	4.7	34.9	505	p-p	38	5	0	0	970	55	0	180	42	0.764
	30	38	300	300	6φ20	4.7	31.5	503	p-p	38	10	0	0	1308	57	0	140	75	1.316
	31	39	300	300	6φ20	4.7	31.5	526	p-p	38	10	0	0	280	49	0	160	56	1.143
	32	40	300	300	6φ20	4.7	31.5	503	p-p	38	150	0	0	465	50	0	100	75	1.500
	33	41	300	300	6φ20	4.7	31.5	526	p-p	38	150	0	0	465	50	0	120	45	0.900
NTU (2010)	1	C1-3	300	300	6φ20	3.54	55.3	550.2	p-p	40	25	0	31.43	1700	166	0	150	190	1.145
	2	C1-4	300	300	6φ20	3.54	55.3	550.2	p-p	40	40	0	31.43	1400	211	0	130	190	0.900
	3	C1-5	300	300	6φ20	3.54	55.3	550.2	p-p	40	60	0	31.43	1100	159	0	120	196	1.233
	4	C2-1	300	300	6φ20	3.54	55.3	550.2	p-p	40	25	25	30.40	1150	182	0.733	170	194	1.066
	5	C2-2	300	300	6φ20	3.54	55.3	550.2	p-p	40	40	40	30.40	920	189	0.733	160	202	1.069
	6	C2-3	300	300	6φ20	3.54	55.3	550.2	p-p	40	60	60	30.40	650	176	0.733	150	208	1.182

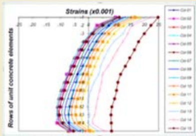
Strain Distribution



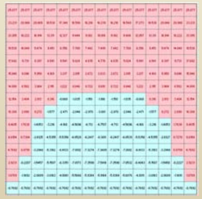


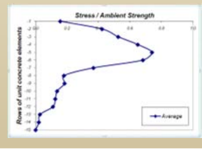
Stress Distribution

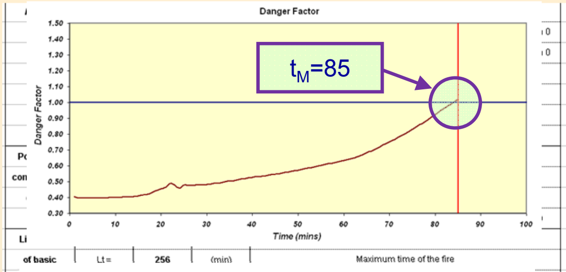




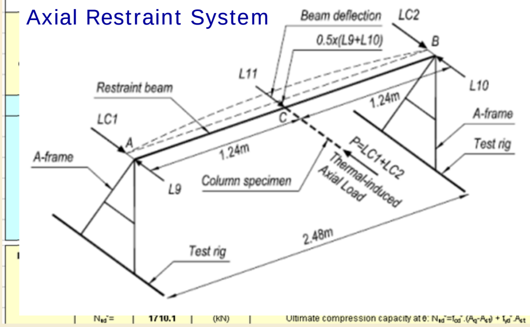
Stress Distribution *Uniaxial Bending*



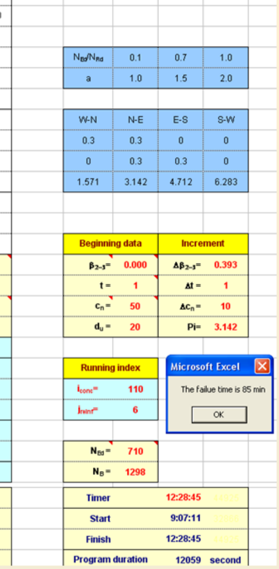




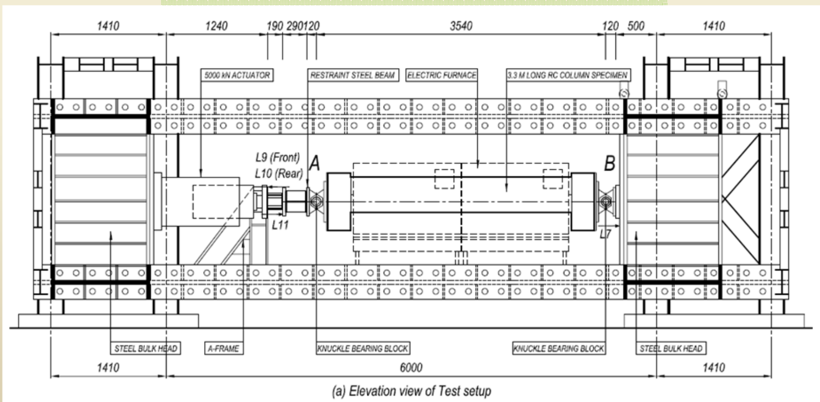
Axial Restraint System



FRRC Program

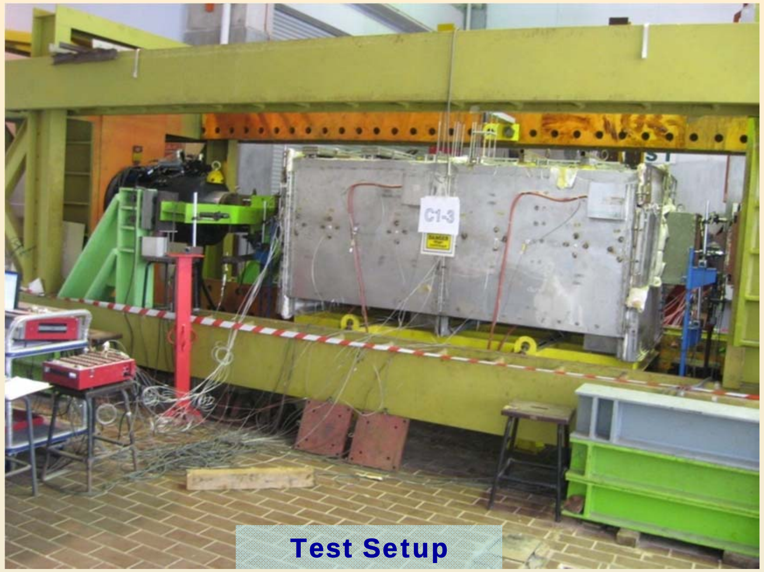


Fire tests conducted in NTU (2010)

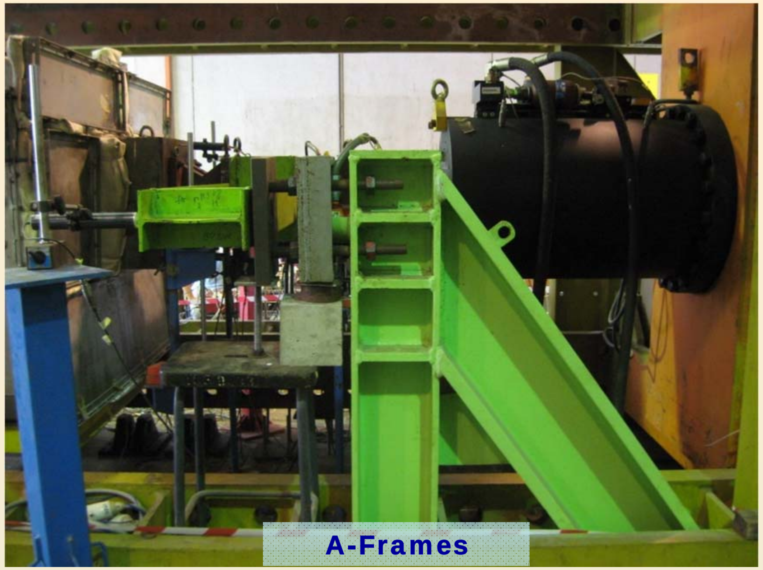


(a) Elevation view of Test setup

5. Fire Tests Conducted in NTU (2010)



Test Setup

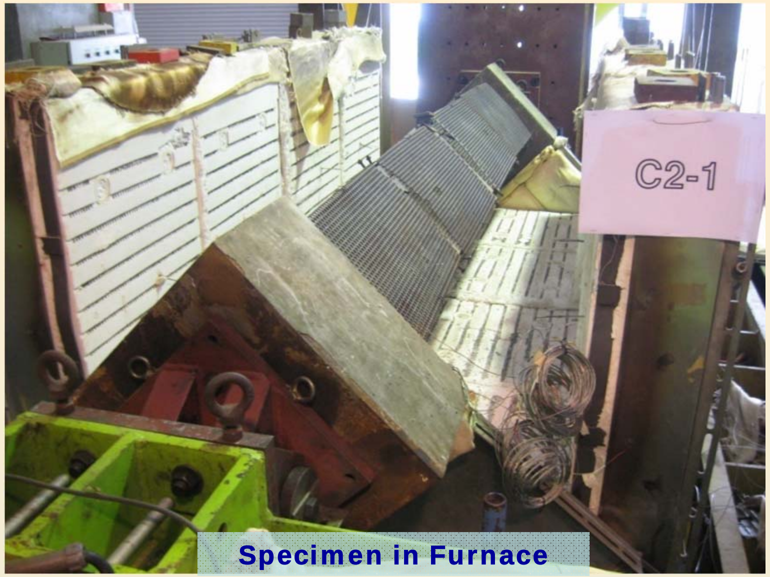

A-Frames


Uniaxially-loaded column

Failed Specimen

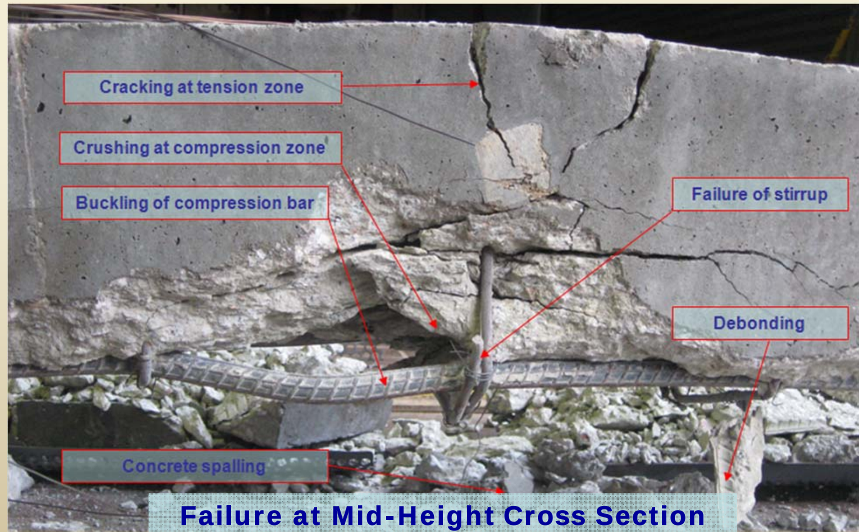
5. Fire Tests Conducted in NTU (2010)


Biaxially-loaded column



Specimen in Furnace

Concrete Spalling



Failure at Mid-Height Cross Section

6. Summary

6.1. Proposed Approach

1. Can be used for columns under either uniaxial bending (β=0 and $\beta=\pi/2$) or biaxial bending ($0< \beta<\pi/2$);
2. Considers additional thermal-induced axial forces due to axial restraint;
3. Incorporates any type of fire curve, time-dependent temperature at any point inside the column can be assessed;
4. Can directly predict failure time of the most possible failure mode and describe stress/strain distributions at failure.

6.2. Experimental Validation

1. Good agreement between the proposed approach and experimental data can be obtained;
2. Fire tests by Hass (1986): Only for uniaxially-loaded columns, no axial restraint , standard fire → $(t^{FRRC}/t^{Test})_{mean}=0.947$;
   Fire tests in NTU (2010): For both uniaxially- and biaxially-loaded columns with axial restraint → $(t^{FRRC}/t^{Test})_{mean}=1.099$;
3. Less conservative results of tests on axially-restrained columns may be due to transient strain / concrete spalling.

6.3. Future Works

1. Incorporate the effects of transient strain into the approach;
2. Conduct parametric study to propose a practical equation for the prediction of column fire resistance.

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Thank You !

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