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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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Motivation

In extensive published research works on fire resistance of reinforced concrete (RC) columns: (1) Concentric load and eccentric load with uniaxial bending have been mostly concerned. For biaxially-loaded columns, an indirect approach using Bresler's formula was proposed (Tan and Yao, 2003); (2) Additional axial forces due to axial restraint were rarely considered; (3) Fire resistance was usually validated by comparing the ultimate loads predicted and measured at a given failure time in fire tests following a standard fire curve; and (4) Limited information of fire tests on biaxially-loaded columns have been used for verification.

Proposed Approach

By conducting the temperature-dependent sectional analysis based on inclined neutral axes, fire resistance of axially-restrained RC columns subjected to uniaxial/biaxial bending in either non-standard or standard fires can be determined as the failure time with the most possible failure criterion, i.e when the increased acting load reaches either buckling or ultimate capacity of the column at elevated temperatures. The computer-based approach was well validated by experimental data obtained from both Technical University of Braunschweig (Hass, 1986) and Nanyang Technological University (NTU) in 2010.

Methodology

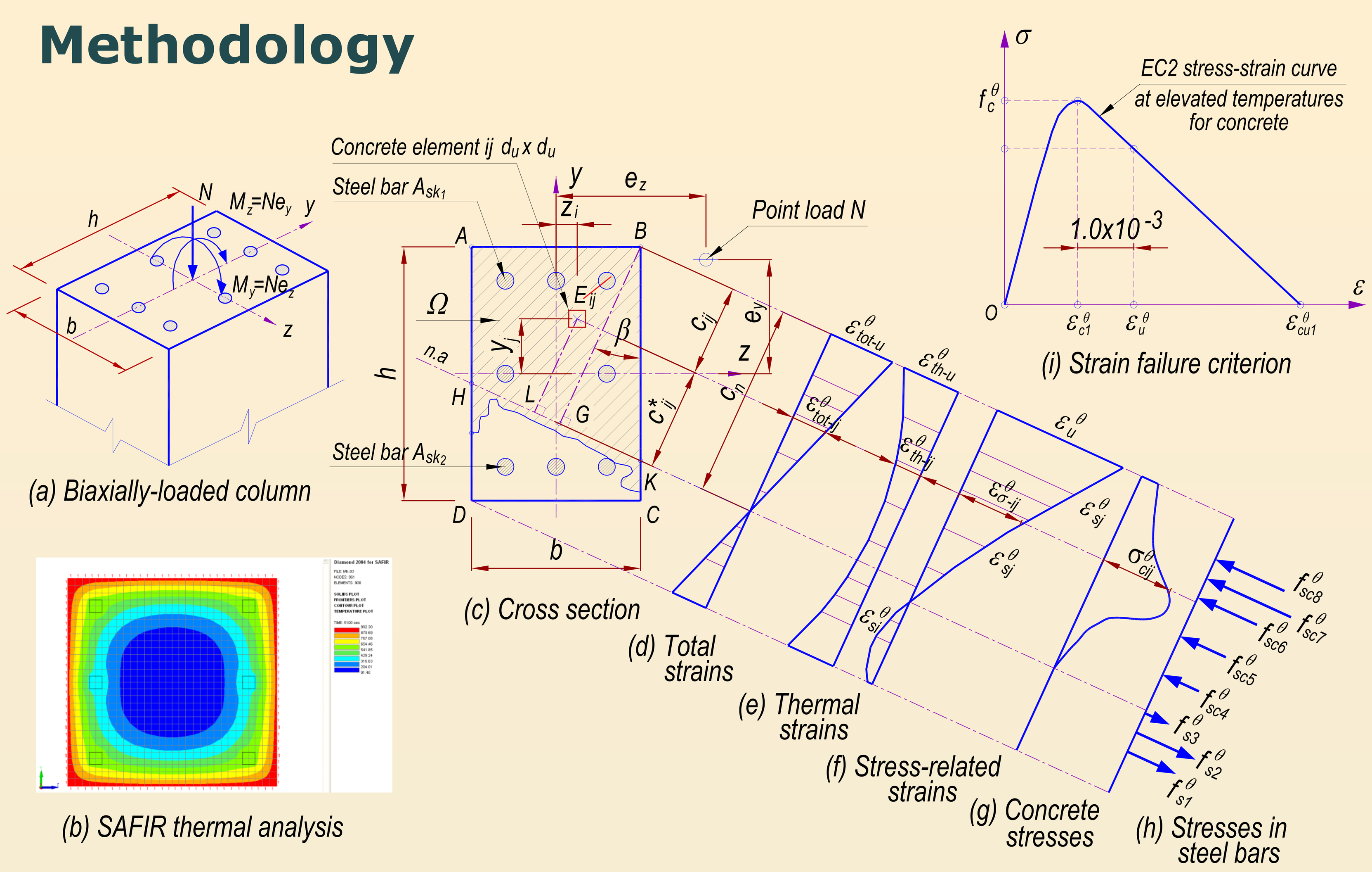

FIG. 1. Direct sectional analysis to determine the column load resistance at elevated temperatures

$$N_{Rd}^{\theta} = \sum_{ij} \sigma_{cij}^{\theta} d_u^2 + \sum_{k_1} A_{sk_1}\left(f_{sck_1}^{\theta} - \sigma_{ck_1}^{\theta}\right) + \sum_{k_2} A_{sk_2} f_{sk_2}^{\theta}$$

$$M_{Rdy}^{\theta} = \sum_{ij} \sigma_{cij}^{\theta} d_u^2 z_i + \sum_{k_1} A_{sk_1}\left(f_{sck_1}^{\theta} - \sigma_{ck_1}^{\theta}\right) z_{k_1} + \sum_{k_2} A_{sk_2} f_{sk_2}^{\theta} z_{k_2}$$

$$M_{Rdz}^{\theta} = \sum_{ij} \sigma_{cij}^{\theta} d_u^2 y_j + \sum_{k_1} A_{sk_1}\left(f_{sck_1}^{\theta} - \sigma_{ck_1}^{\theta}\right) y_{k_1} + \sum_{k_2} A_{sk_2} f_{sk_2}^{\theta} y_{k_2}$$

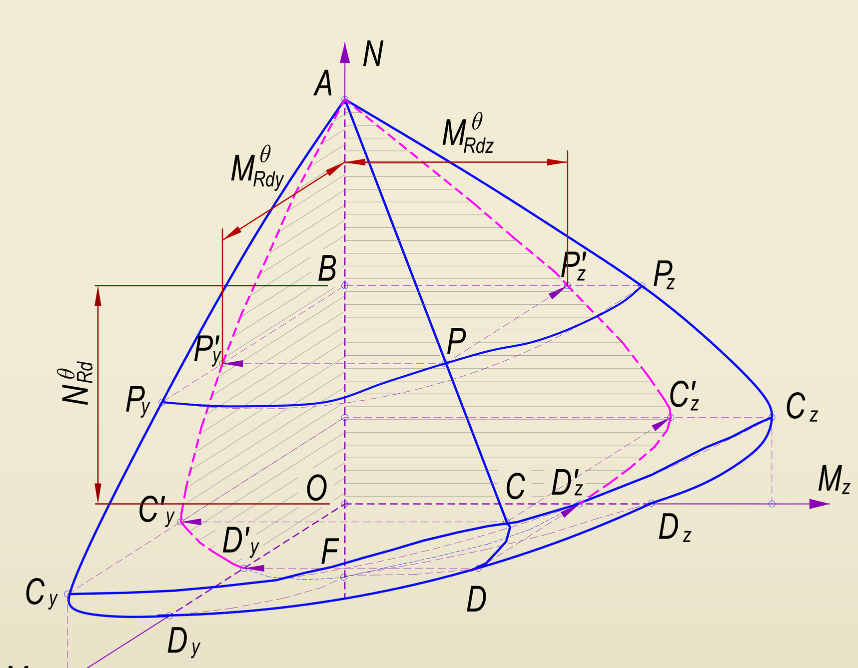

FIG. 2. Interaction surface at elevated temperatures

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

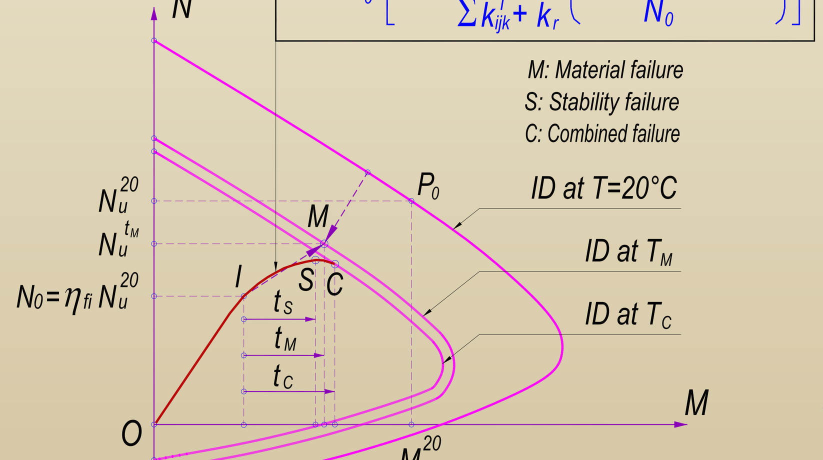

FIG. 3. Failure criteria

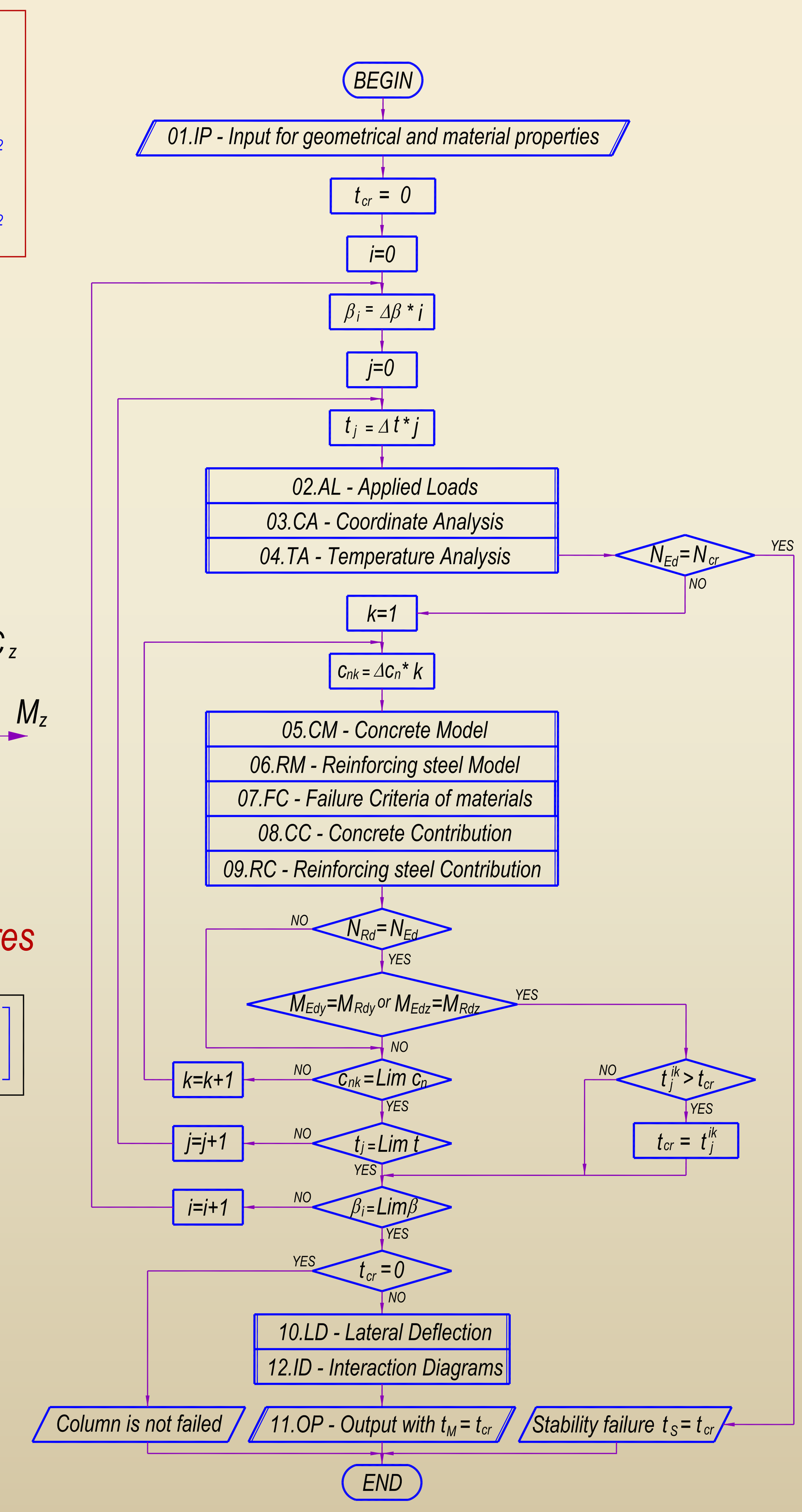

FIG. 4. Flowchart of FRRC program

Experimental Verification

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	930	84	0	150	82	0.976
	10	10	200	200	4Φ20	4.76	24.1	487	p-p	38	0	0	0	340	48	0	100	39	0.813
	20	20	300	300	6Φ20	3.8	33.2	458	p-f	38	30	0	0	845	111	0	130	94	0.847
	27	30	300	300	6Φ20	4.76	38.2	404	p-p	38	5	0	0	1224	48	0	150	55	1.146
	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
	33	41	300	300	6Φ20	4.70	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

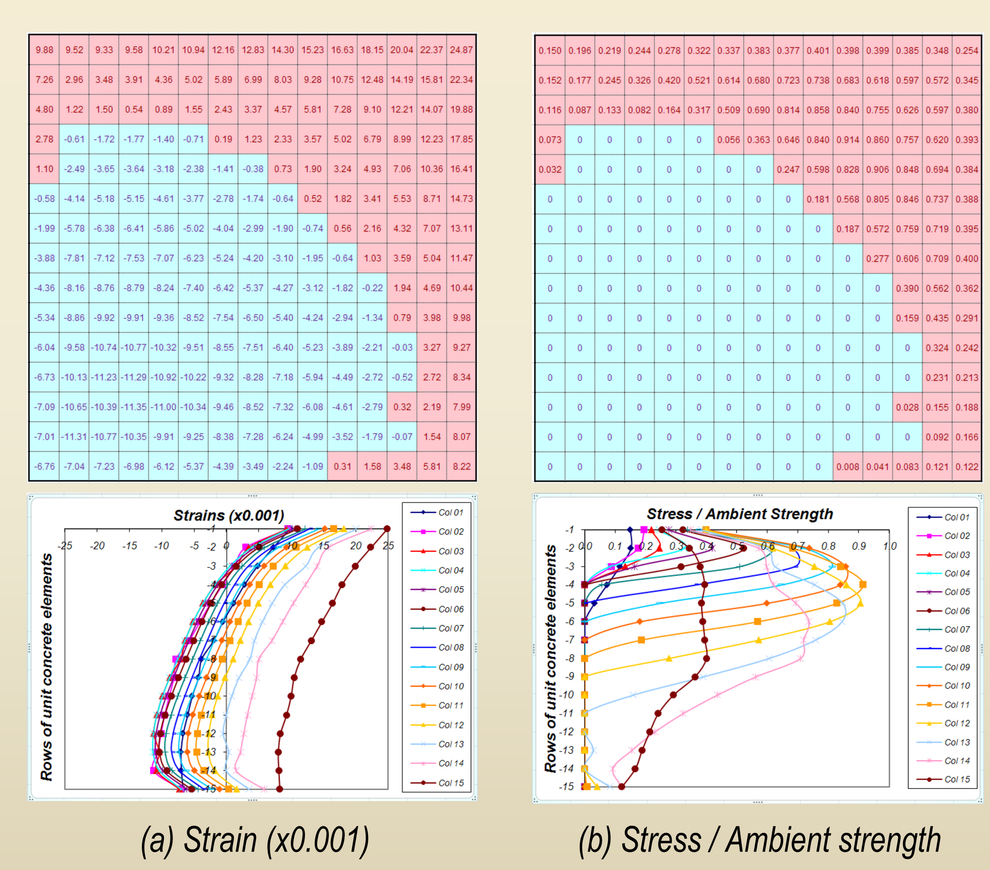

FIG. 5. Strain and stress distributions in concrete at failure

FIG. 6. Fire tests conducted in NTU (2010)

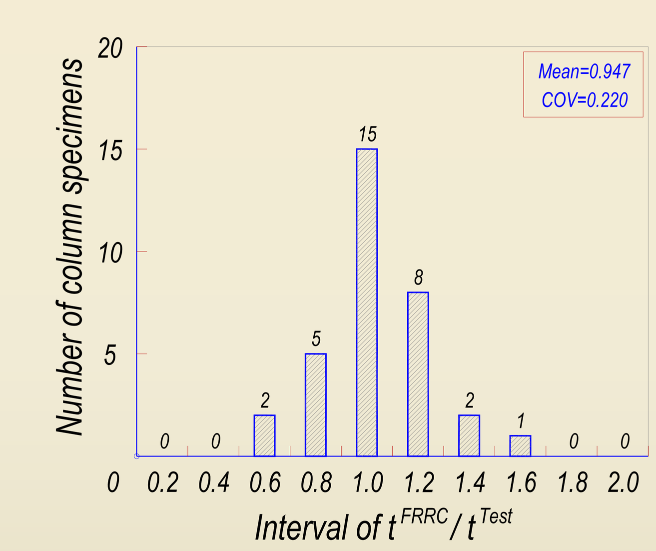

FIG. 7. Validation used Hass's tests (1986)

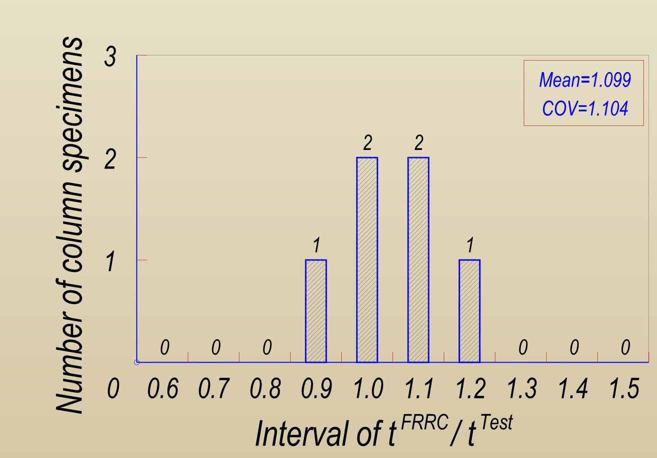

FIG. 8. Validation used NTU's tests (2010)

Summary and Acknowledgement

Good agreement in failure times predicted by the proposed approach and measured in fire tests can be obtained. More conservative results were observed from the case of columns without axial restraint. Transient strain in concrete at elevated temperatures shall be considered in future reseacrh works.

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References

Tan, K. H., Yao, Y., Fire Resistance of Four-Face Heated Reinforced Concrete Columns, Journal of Structural Engineering, 129(9), 1220-1229, 2003; Hass, R., Practical Rules for the Design of Reinforced Concrete and Composite Columns Submitted to Fire, Institute fur Baustoffe, Massivbau und brandschutz der Technichen Universita Braunschweigo, 1986; Frassen, J. M., SAFIR. A Thermal/Structural Program Modelling Structures under Fire, Engineering Journal, A.I.S.C., 42, 3: 143-158, 2005; Eurocode EN 1991-1-2:2004, Design of Concrete Structures – Part 1-2: General Rules, Structural Fire Design, 2004b.