Structure in Fire Forum
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Fire tests of restrained columns and practical design method

PhD student: Peijun Wang

Supervisors: Prof. GQ Li (Tongji University, China)
Dr. YC Wang (The University of Manchester)

Outline

- 1. Background
- 2. Fire test on restrained steel columns
- 3. Practical design method of restrained columns
- 4. Conclusions

1. Background

- Typical beam-column connections in China are rigid connections, which can provide great axial and rotational restraint to the column;
- The existence of axial restraint can reduce the failure temperature of the column. However, both the design codes in China and other countries don't incorporate the effect of restraints;
- At present, there is very little research data on the behavior of restrained columns under the combination of axial load and bending moment.

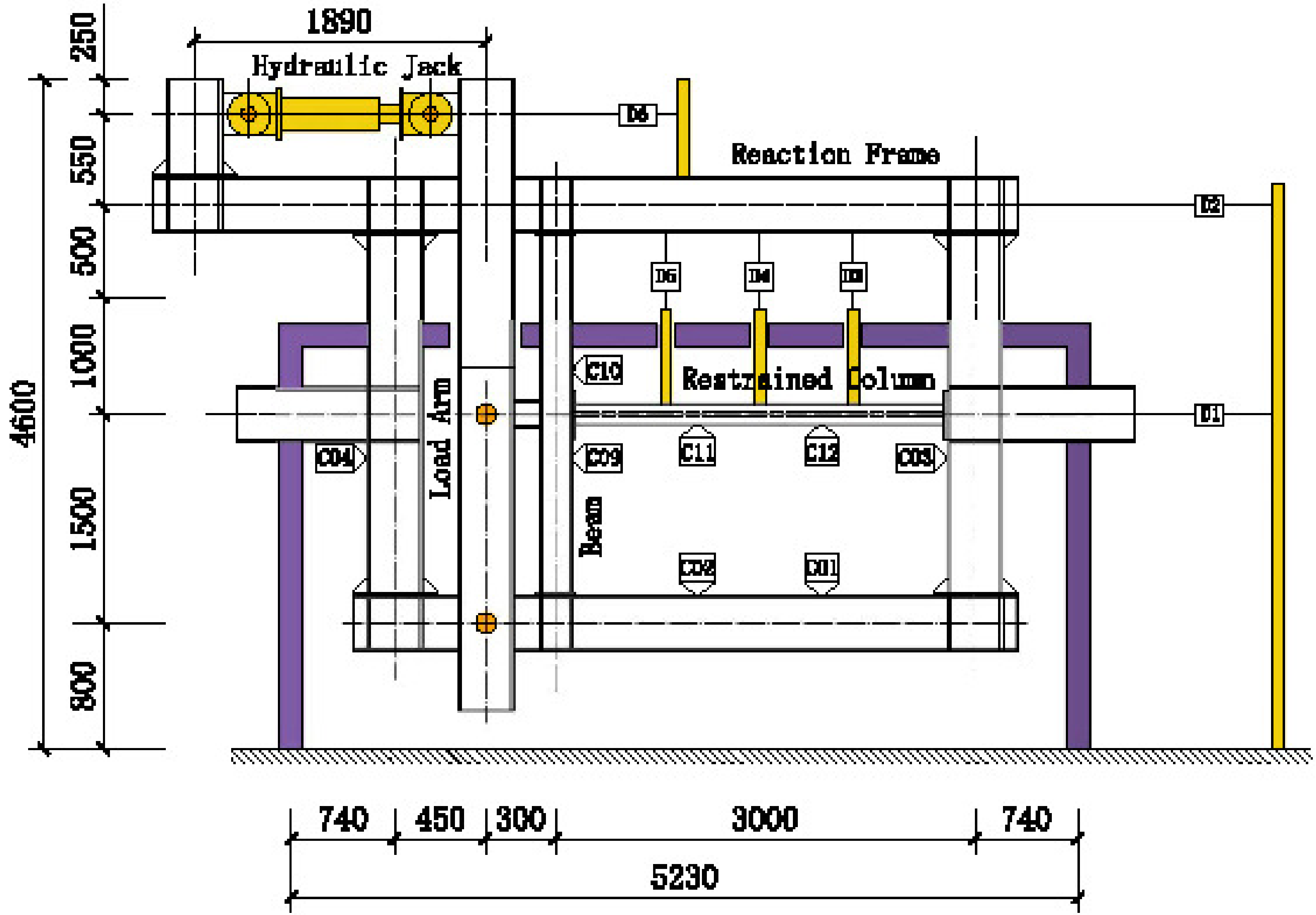
Typical beam-column connection


Typical beam-column connections in China

2. Fire tests on restrained columns

- 2.1 Test set-up
- 2.2 Test specimen
- 2.3 Test results
- 2.4 Failure of the column

2.1 Test set up



2.2 Test specimen

- Test design

test specimen	Axial load (kN)	Axial restraint	Rotational restraint	Maximum temperature	Aim of test
Test-00	233.33	No	No	30°C	To check test set up
Test-01		Yes	Yes	800°C	To obtain behavior of restrained columns
Test-02					

- Test column

Slenderness: 99.8;

Load Ratio: 0.75;

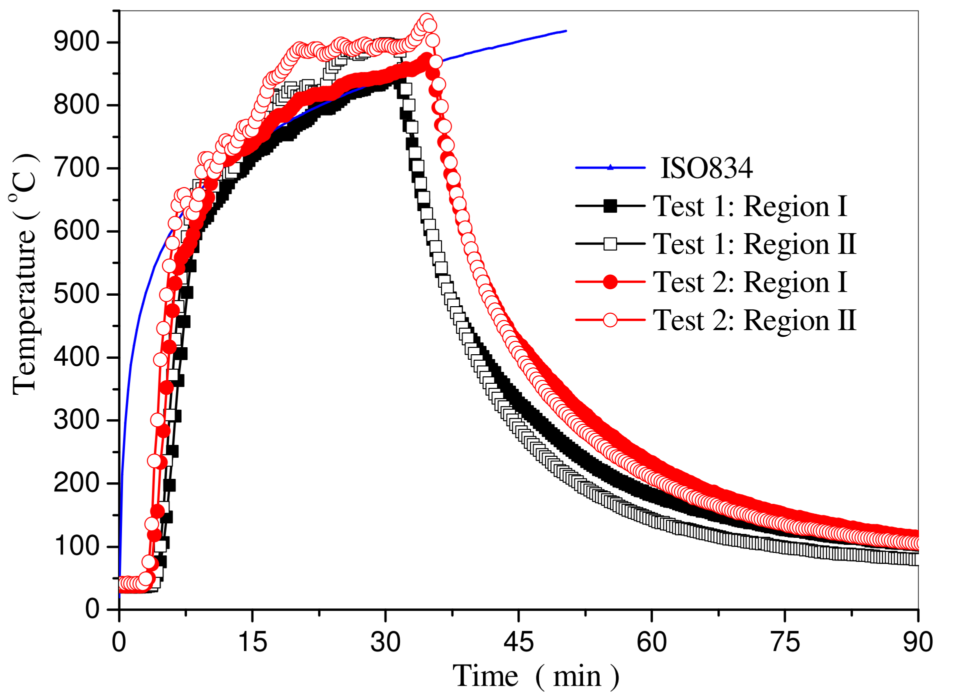
Yield Strength: 235N/mm^2

- Restraint stiffness

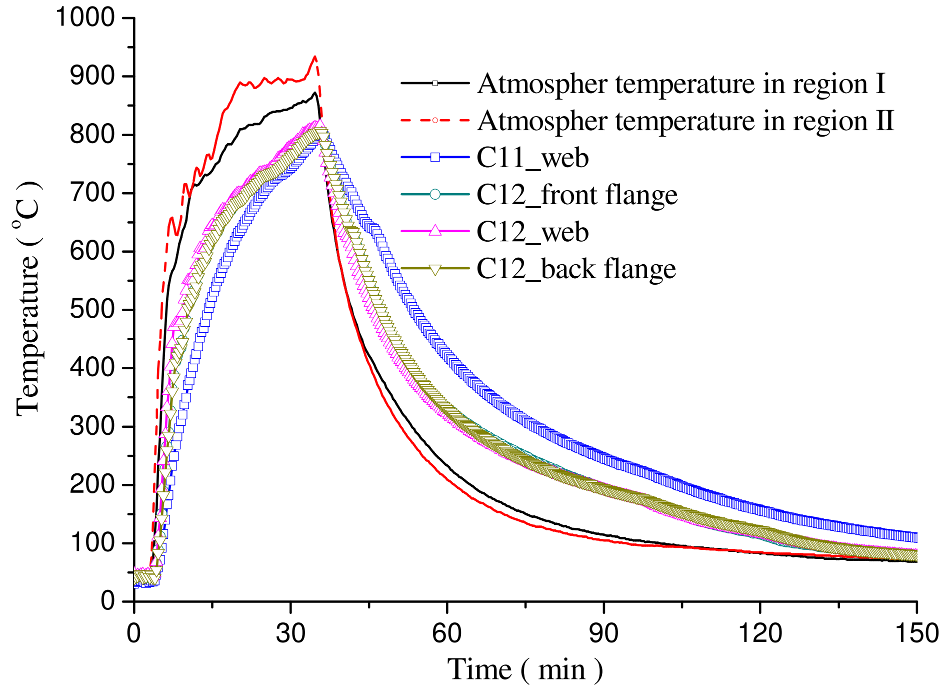
Test No.	Section	Column axial restraint stiffness (10^6 kN/m)	Column axial stiffness (10^6 kN/m)	Axial restraint ratio	Rotational restraint stiffness (kN.m)	Column rotational Stiffness (kN.m)	Rotational restraint ratio
Test-01	H180x12x176x6	14.924	161.27	0.0925	33578.4	311.6	107.8
Test-02	H180x12x216x6	22.316		0.1384	50211.4		161.1

2.3 Test results

Furnace Temperature

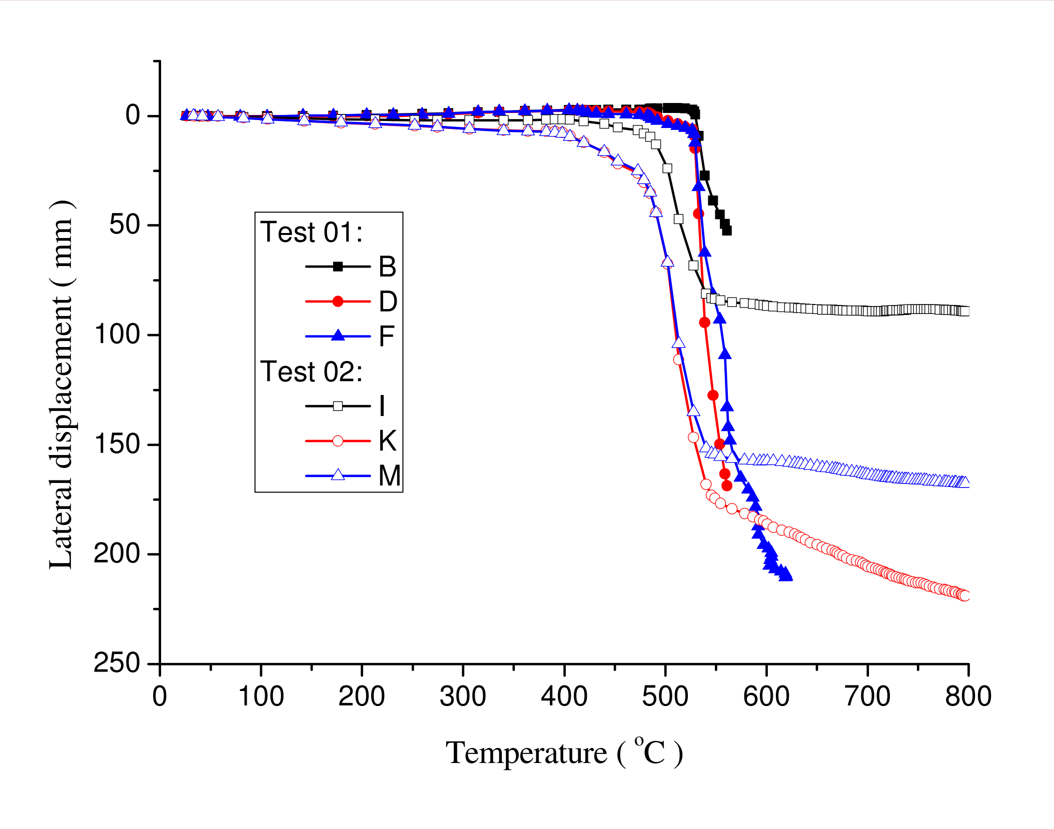


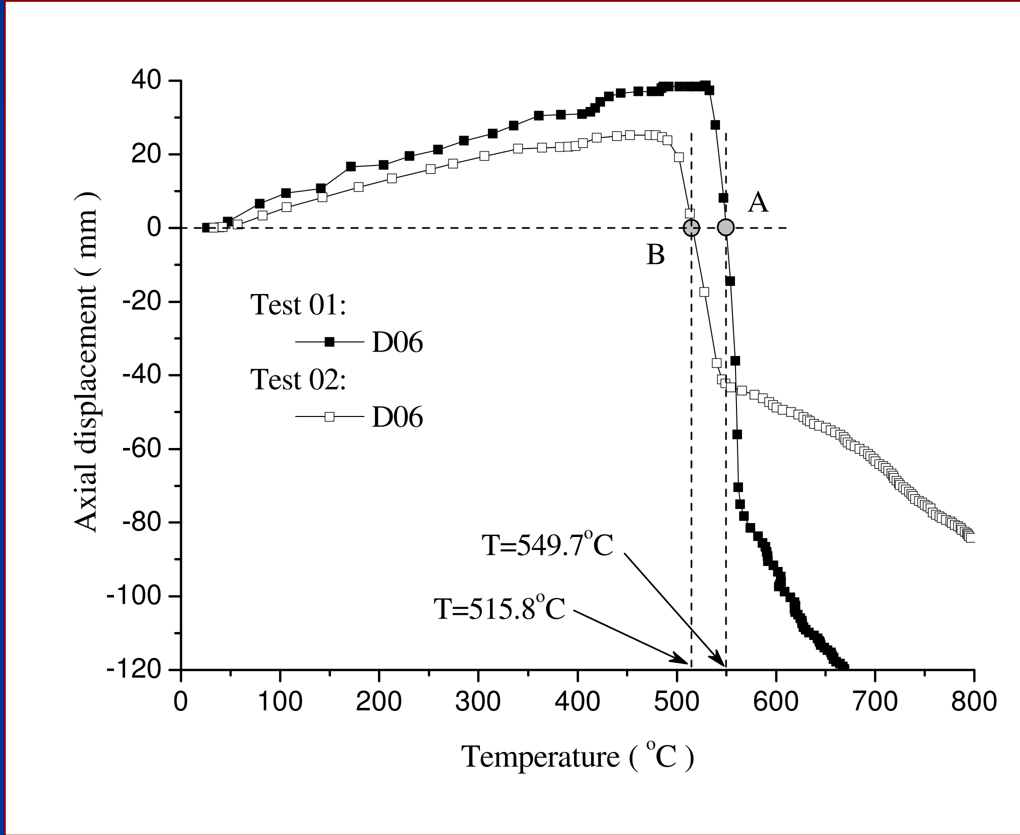
Column Temperature



2.3 Test results

- Lateral deflection of the restrained column





2.4 Failure of the column

- Global buckling of the column in Test-01

- Global buckling of the column in Test-02

3. Practical design methods

- 3.1 Restrained column under axial load
- 3.2 Restrained column under the combination of axial and bending moment (under development)

3.1 Restrained column under axial load

Parameters:

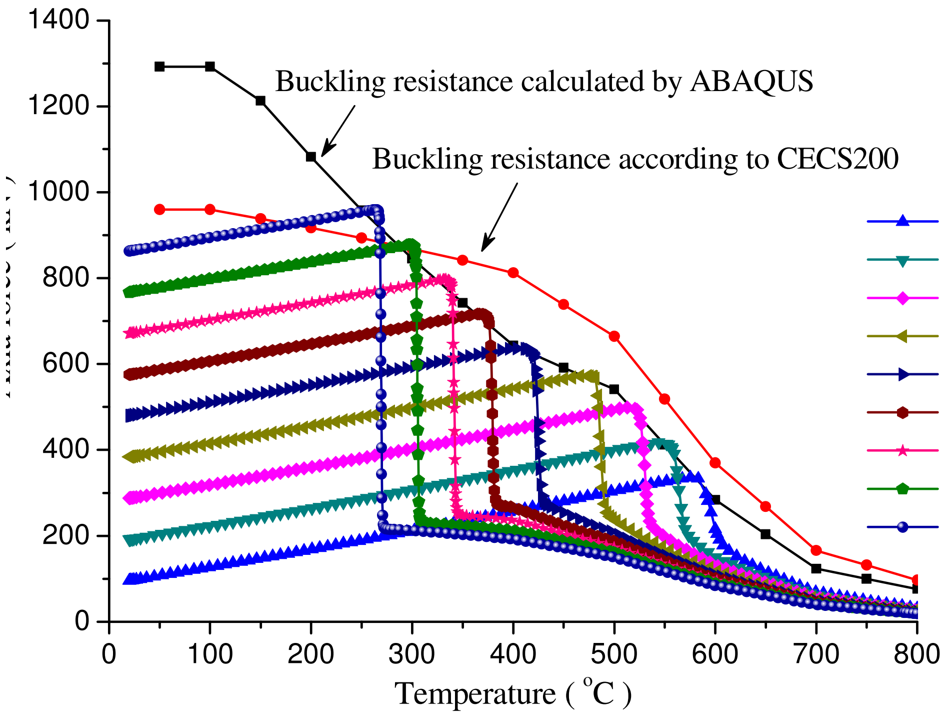
- Load ratio
- Slenderness
- Axial restraint ratio
- Rotational restraint ratio

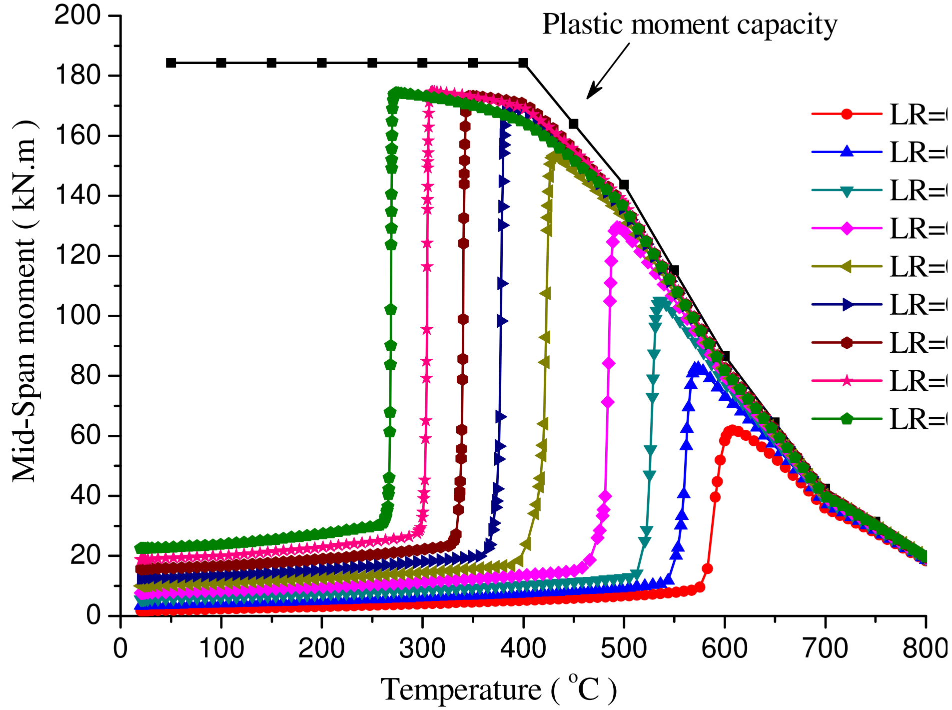
Effective length factor

Parameters:

- Load ratio
- Slenderness
- Axial restraint ratio

3.1.1 Axially restrained column under different load ratios

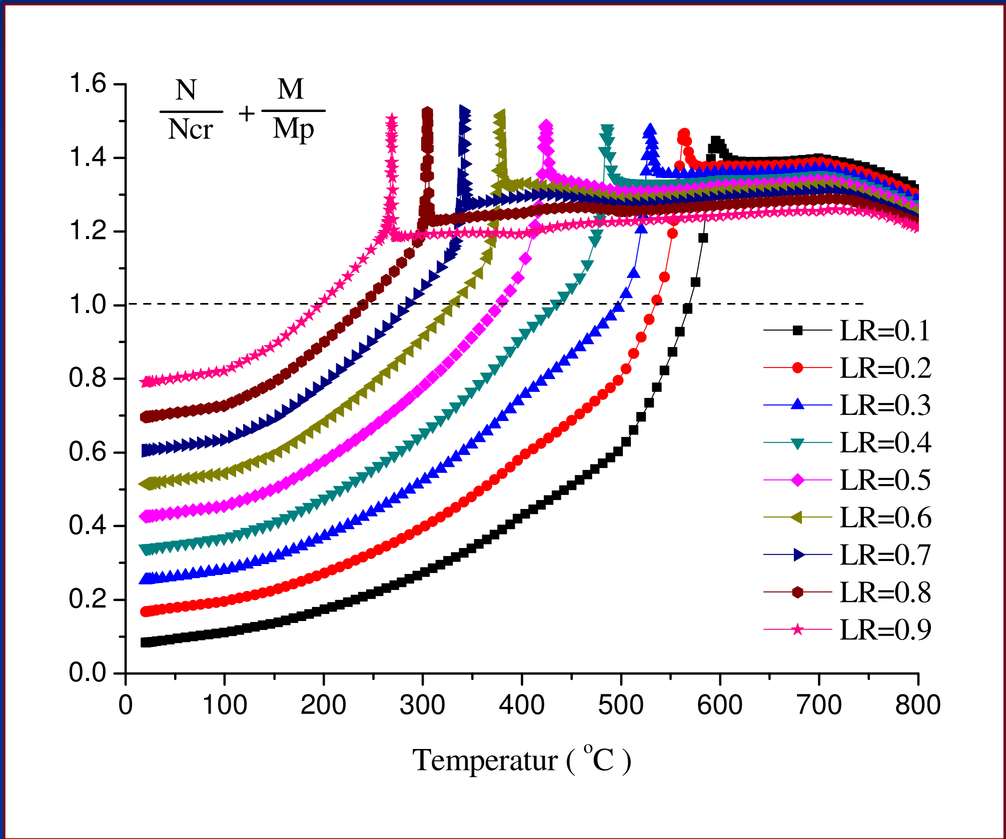


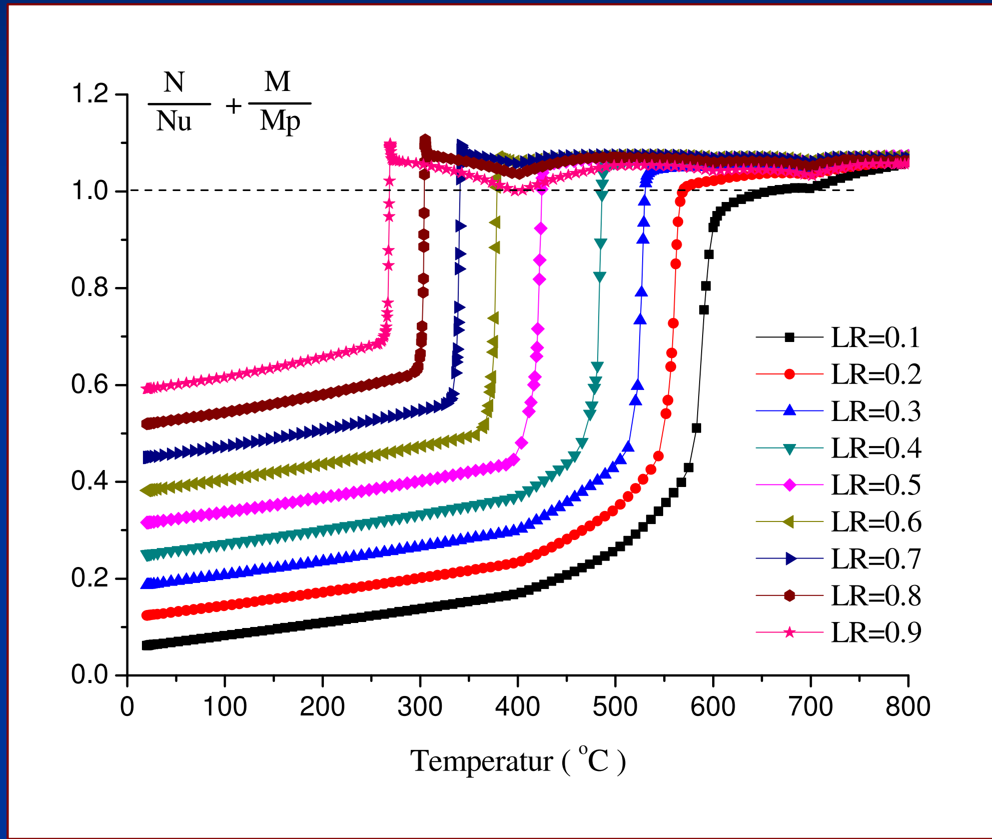


Axial force

Mid-span moment

3.1.1 Axially restrained column under different load ratio





$$\frac{N}{N_{cr,T}} + \frac{M}{M_{p,T}}$$

$$\frac{N}{N_{u,T}} + \frac{M}{M_{p,T}}$$

3.1.2 Simplified design method -- before buckling

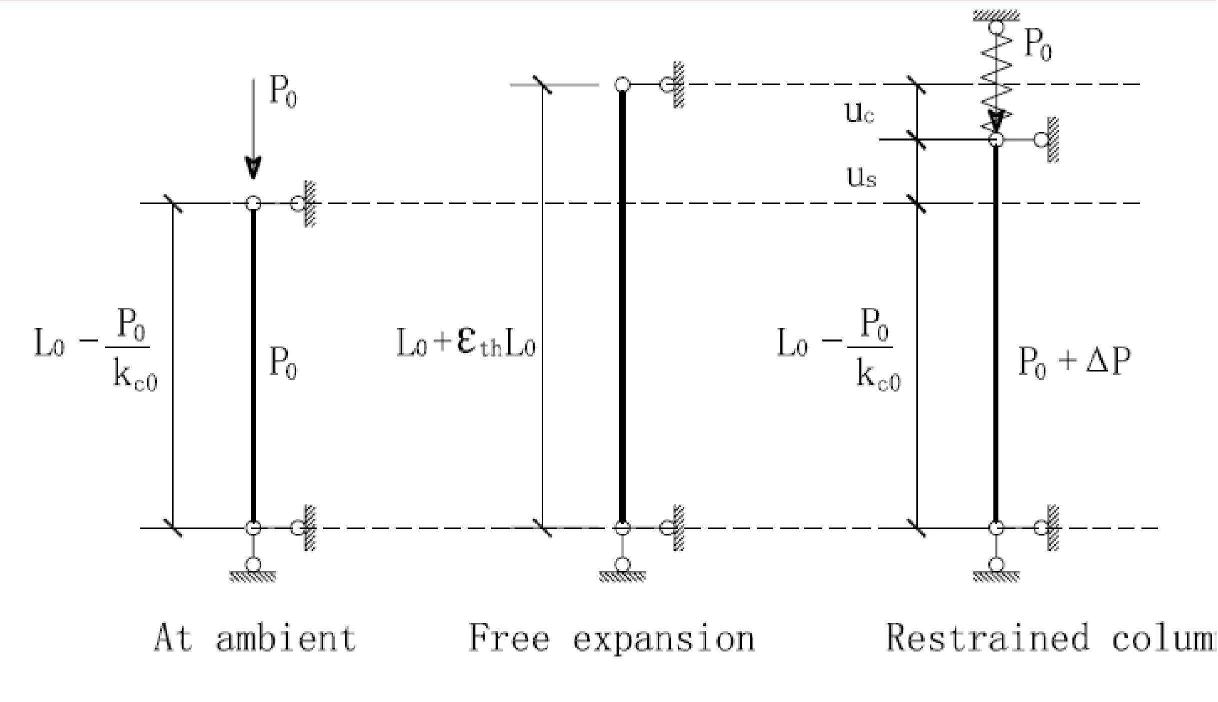
- Design equation:

$$\frac{N}{N_{cr,T}} = 1$$

$$N = P_0 + k_s u_s$$

$$u_s = \frac{k_c}{k_s + k_c}\left(\varepsilon_{th} L - \frac{P_0}{k_c} + \frac{P_0}{k_{c,0}}\right)$$

- Model for calculate u_s:



3.1.2 Simplified design method -- after buckling

- Design equation

$$N = P_0$$

$$\frac{N}{N_{u,T}} + \frac{N \cdot w}{M_{p,T}} = 1$$

- Calculate w?

$$u_s = \alpha \frac{w^2}{L}$$

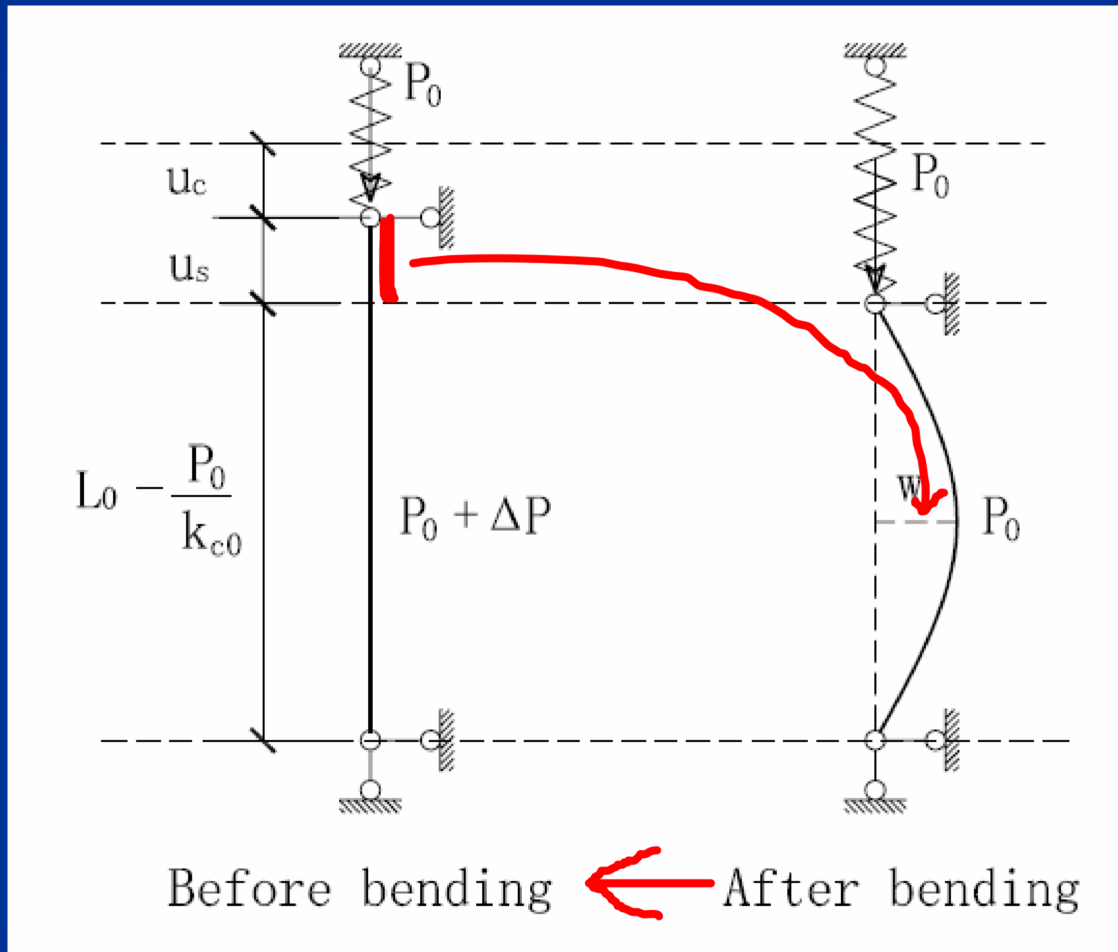
$$\alpha = \alpha(\lambda, \beta, \rho)$$

λ is the slenderness ratio

β is the axial restraint stiffness ratio

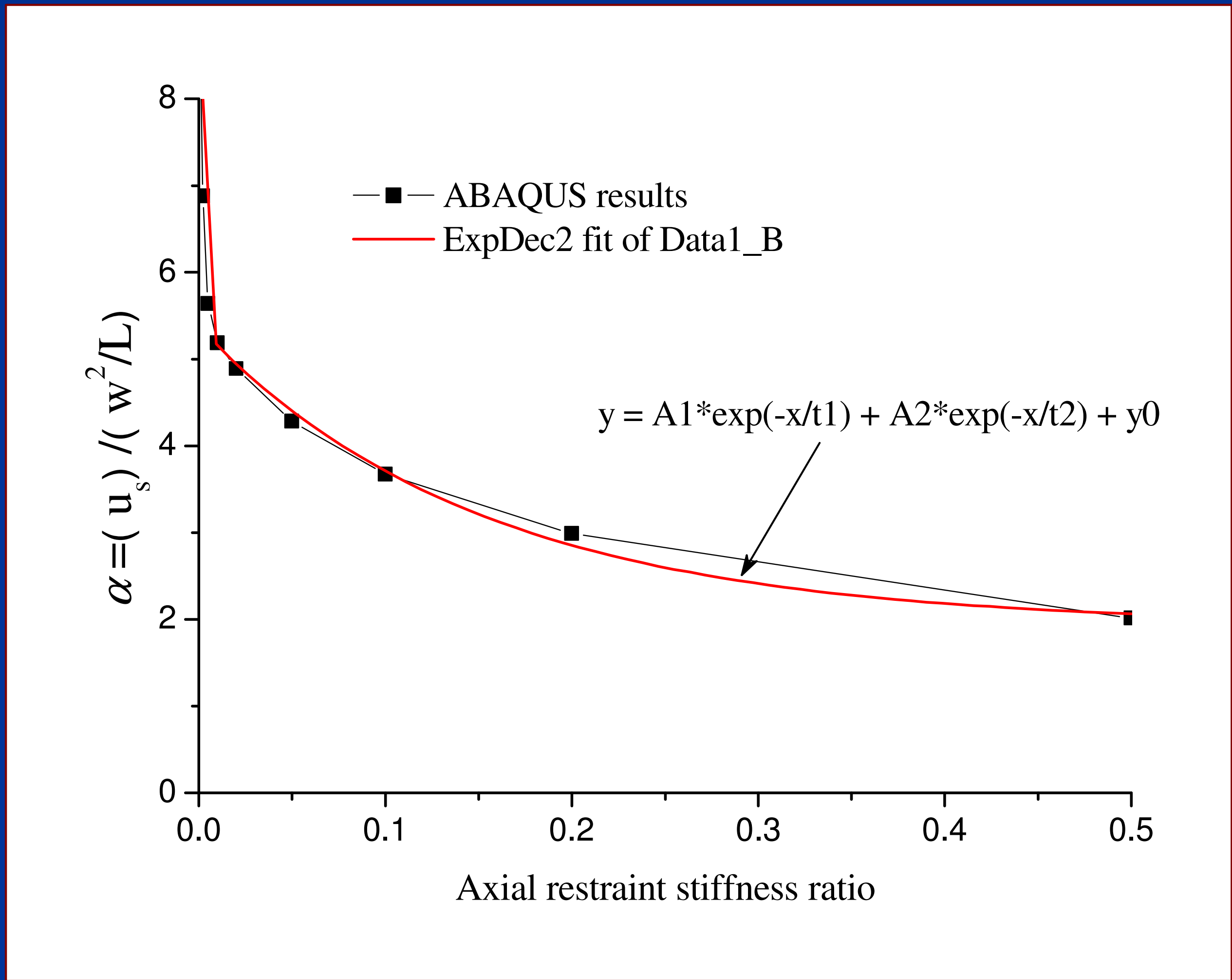
ρ is the axial load ratio

- Model for calculating w



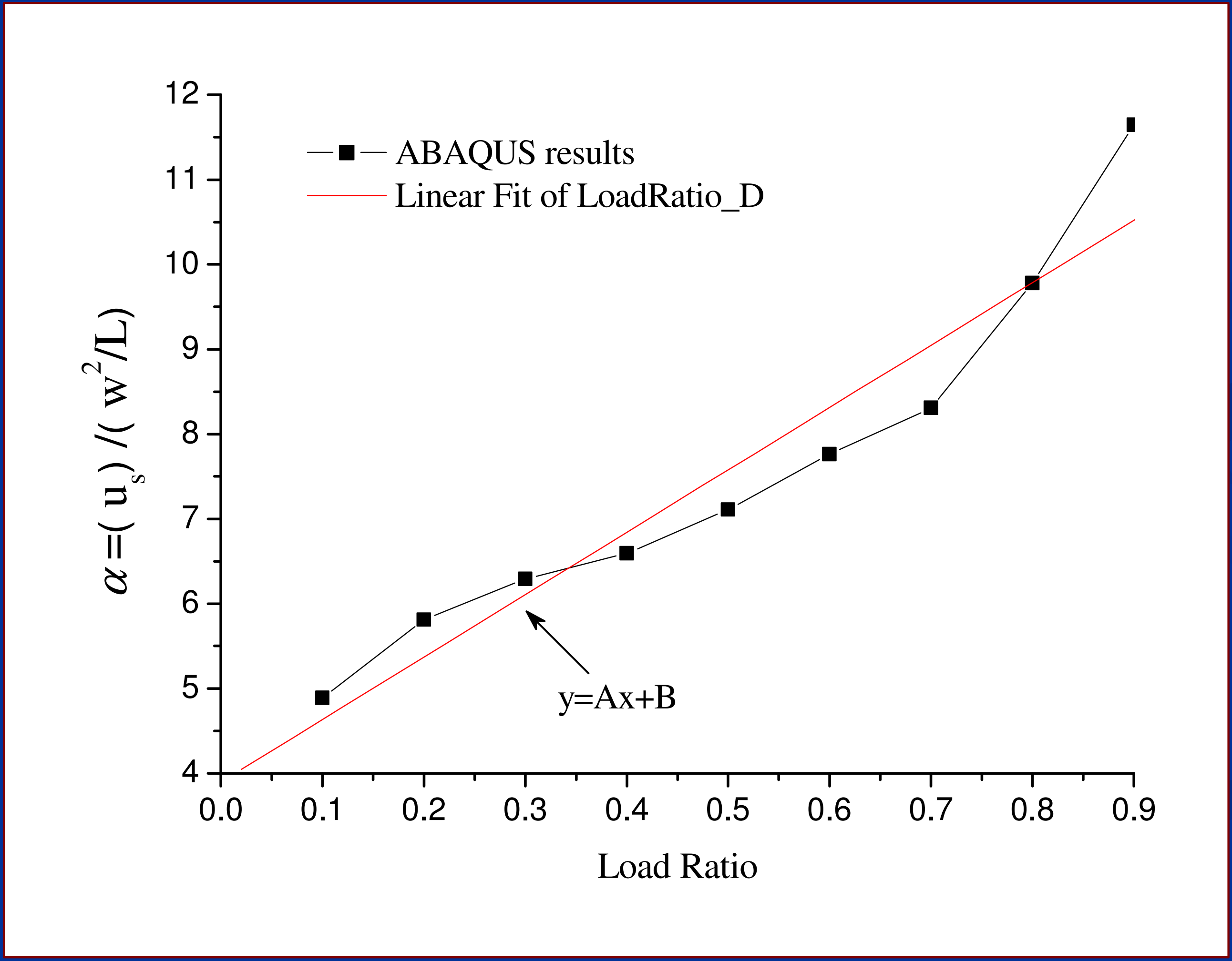
3.1.3 Relationship between u_s and w^2/L

- Effect of restraint stiffness



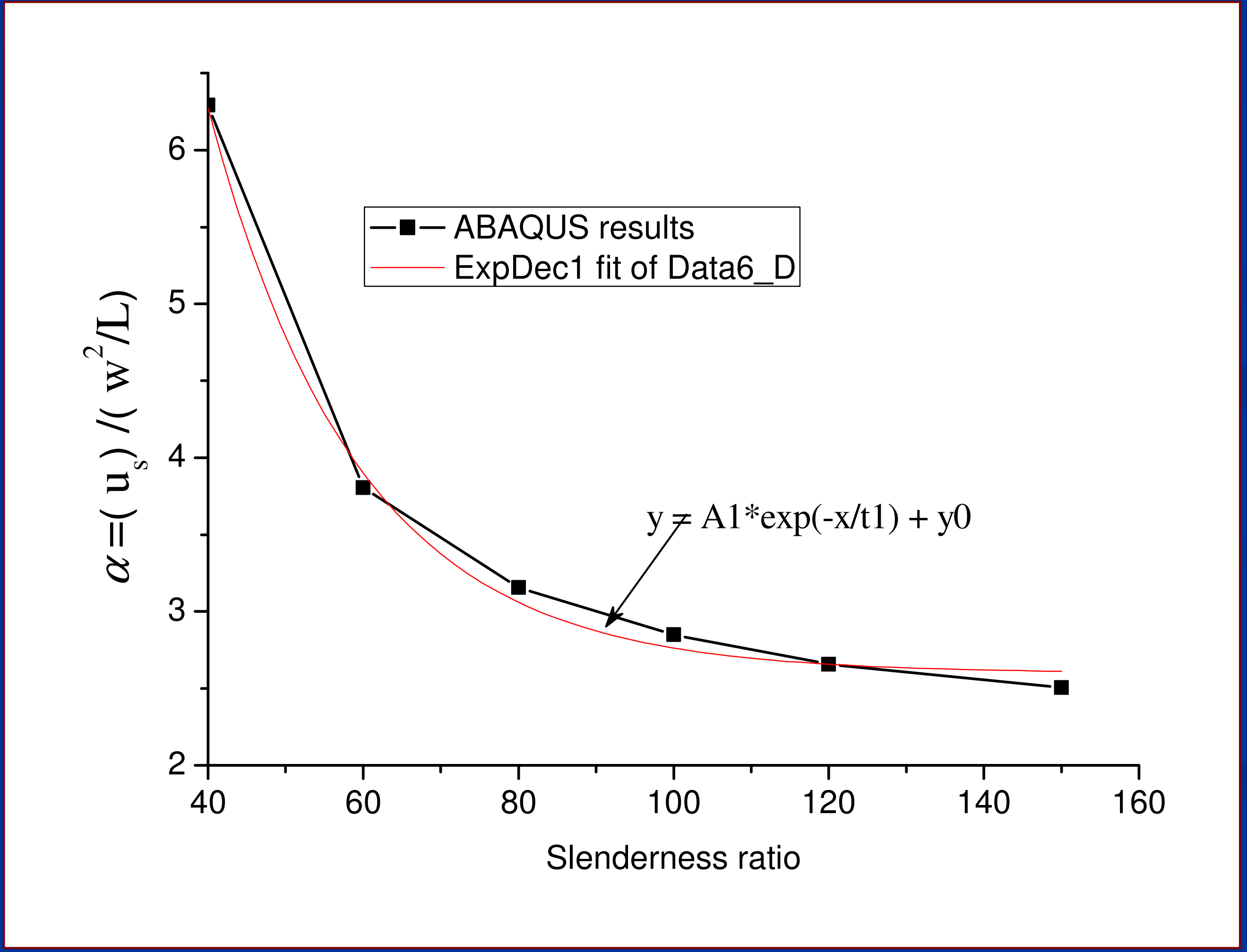
3.1.3 Relationship between u_s and w^2/L

- Effect of load ratio



3.1.3 Relationship between u_s and w^2/L

- Effect of slenderness



3.1.3 Relationship between u_s and w^2/L

- Parameters:
  - Load ratio (9):
    0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9;
  - Slenderness ratio (6):
    40, 60, 80, 100, 120, 150;
  - Restraint stiffness ratio (9):
    0.001, 0.002, 0.005, 0.01, 0.02, 0.05, 0.1, 0.2, 0.5.
- Total: 9 x 6 x 9 = 486
- Results of curve fit :

$$\alpha = c_\lambda c_\beta c_\rho \geq 2.5$$

$$c_\lambda = 18.42e^{-\lambda/30.36} + 2.11$$

$$c_\rho = 1.18\rho + 0.54$$

$$c_\beta = 45.96e^{-\beta/23.07} - 5.77e^{-\beta/25.21} - 38.85$$

3.1.4 Design Procedure

- (1) Calculate the buckling temperature of the column without any restraint, $T_{cr,free}$;

$$\frac{N}{N_{cr,T}} = 1$$

$$N = P_0$$

3.1.4 Design procedure

- (2) Calculate the buckling temperature of the restrained column, $T_{res,buckle}$;

$$\frac{N}{N_{cr,T}} = 1$$

$$N = P_0 + k_s u_s$$

$$u_s = \frac{k_c}{k_s + k_c}\left(\varepsilon_{th} L - \frac{P_0}{k_c} + \frac{P_0}{k_{c,0}}\right)$$

3.1.4 Design procedure

- (3) Calculate the failure temperature of the restrained column, $T_{res,failure}$;

$$N = P_0$$

$$\frac{N}{N_{u,T}} + \frac{N \cdot w}{M_{p,T}} = 1$$

$$u_s = \alpha \frac{w^2}{L}$$

$$u_s = \frac{k_c}{k_s + k_c}\left(\varepsilon_{th} L - \frac{P_0}{k_c} + \frac{P_0}{k_{c,0}}\right)$$

$$\alpha = c_\lambda c_\beta c_\rho \geq 2.5$$

$$c_\lambda = 18.42 e^{-\lambda/30.36} + 2.11$$

$$c_\rho = 1.18\rho + 0.54$$

$$c_\beta = 45.96 e^{-\beta/23.07} - 5.77 e^{-\beta/25.21} - 38.85$$

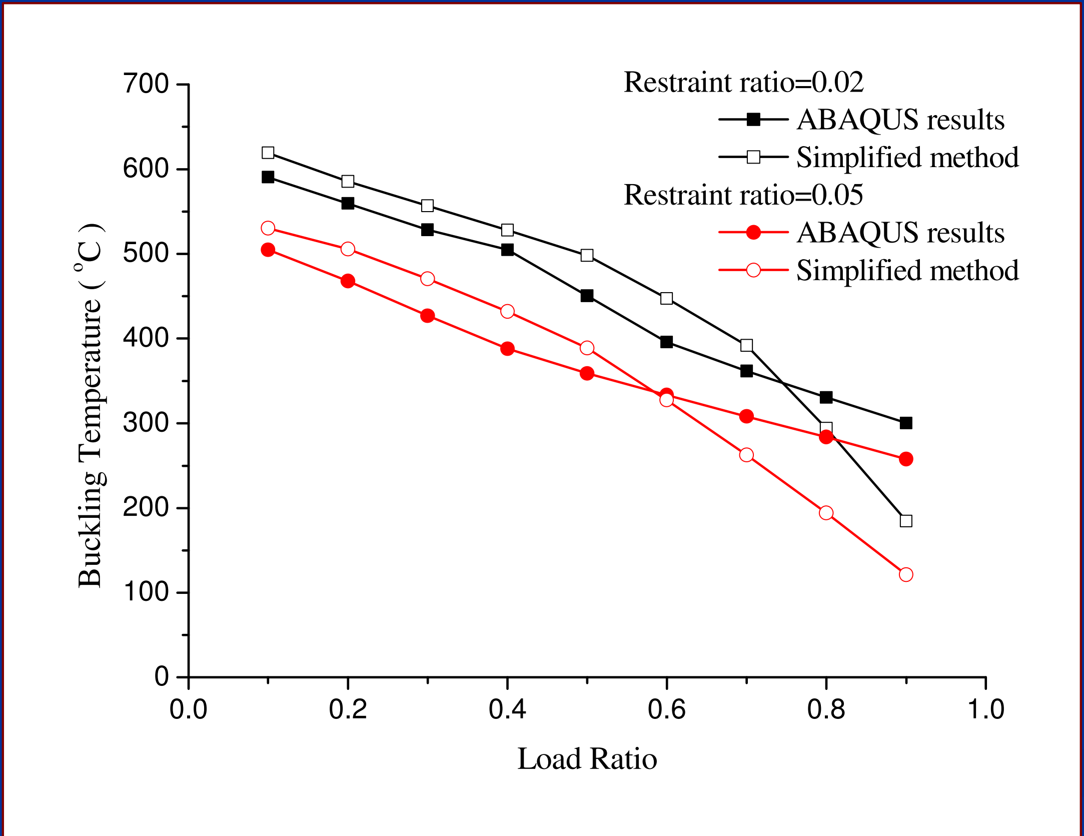
3.1.4 Design procedure

- (4) Failure temperature of the restrained column should satisfy:

$$T_{res,buckle} < T_{res,failure} < T_{free,\ buckle}$$

3.1.5 Verification of the simplified method

- Comparison of buckling temperature of restrained column



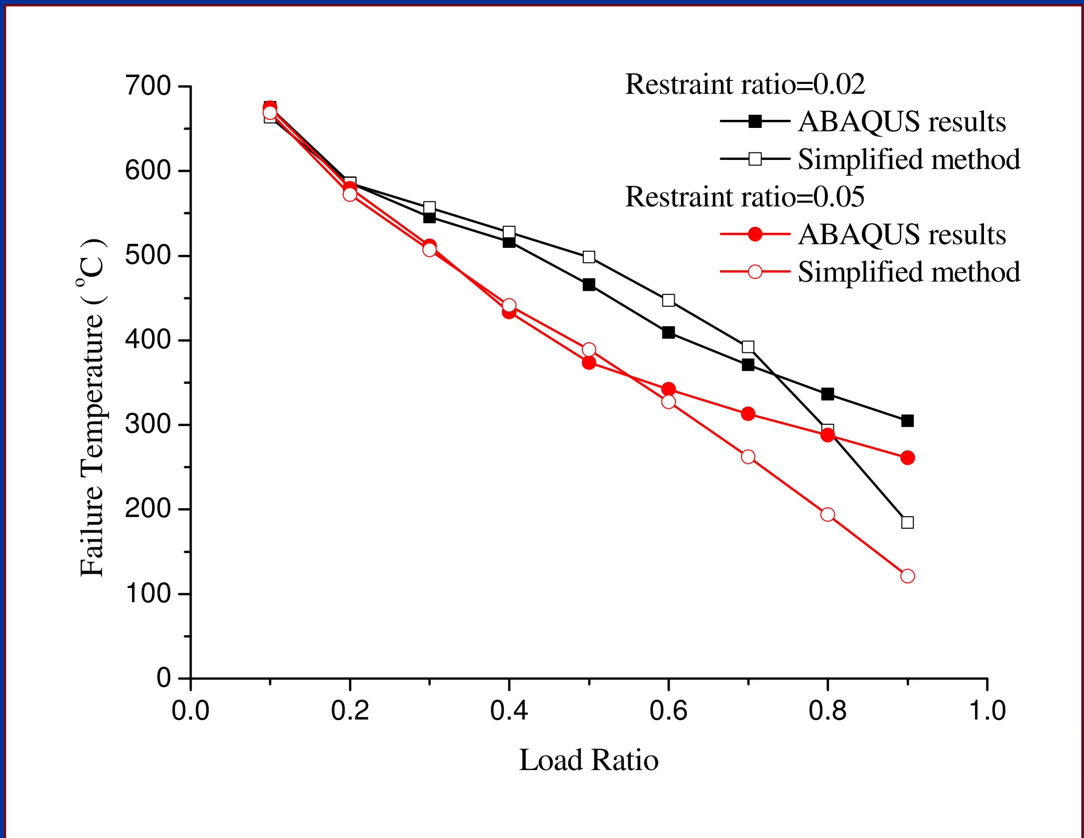
- Parameters:

Slenderness: 80

Restrained Stiffness Ratio :0.02

3.1.5 Verification of the simplified method

- Comparison of failure temperature of restrained column



- Parameters:

Slenderness: 80

Restrained Stiffness Ratio :0.02

Conclusions

- Two both axially and rotationally restrained columns are tested by the authors to study the behaviors of the column under the combination of axial load and bending moment.
- A simplified design method is proposed for calculating the buckling and failure temperatures of restrained column.