Influence of the Section Factor on Fire-resistance Behaviours of Stainless Steel Beams with Three Faces Exposed to Fire

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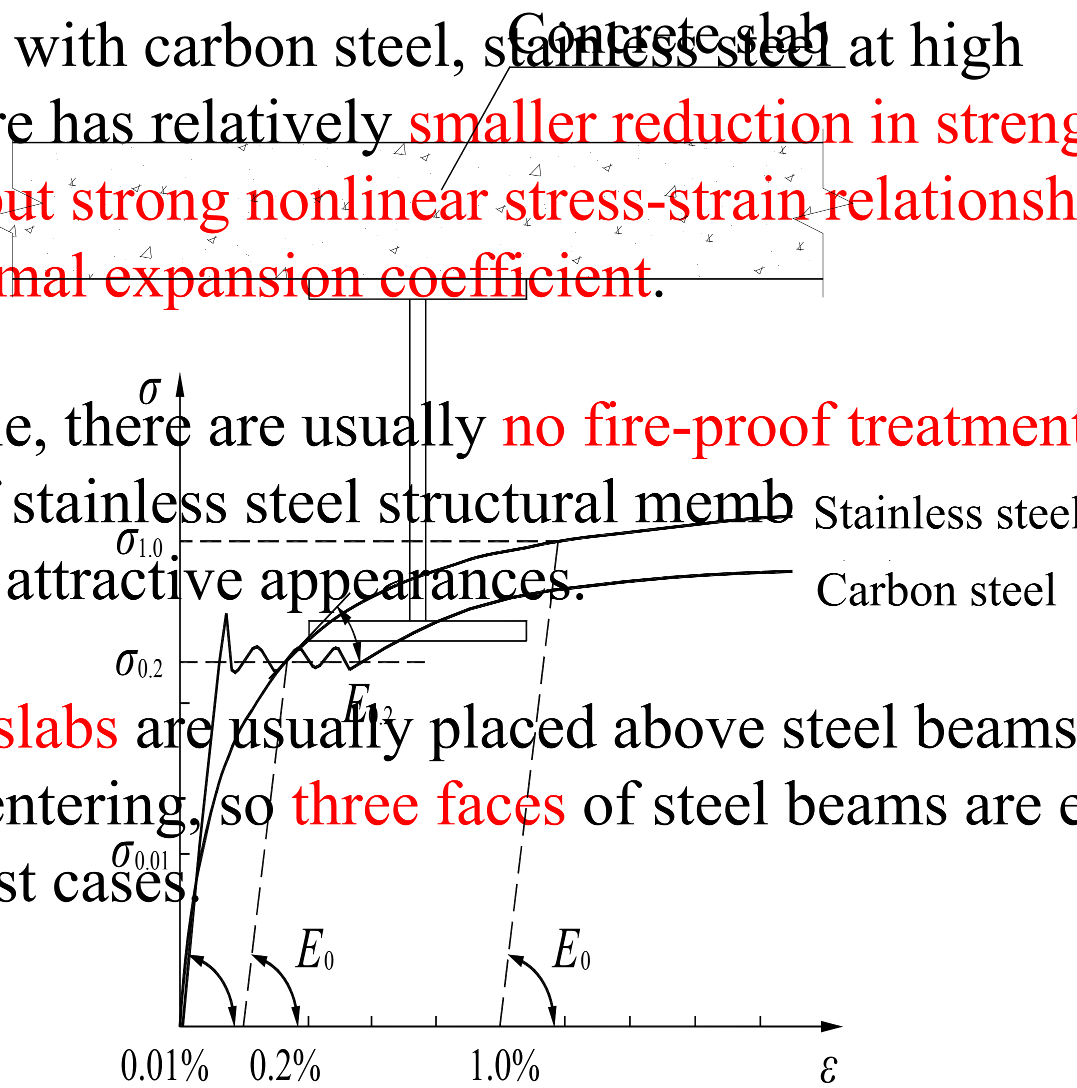
Contents

01 Introduction

◆Compared with carbon steel, stainless steel at high temperature has relatively smaller reduction in strength and stiffness, but strong nonlinear stress-strain relationship and larger thermal expansion coefficient.

◆Meanwhile, there are usually no fire-proof treatments on the surface of stainless steel structural memb[ers] to guarantee attractive appearances.

◆Concrete slabs are usually placed above steel beams in practical entering, so three faces of steel beams are exposed to fire in most cases.

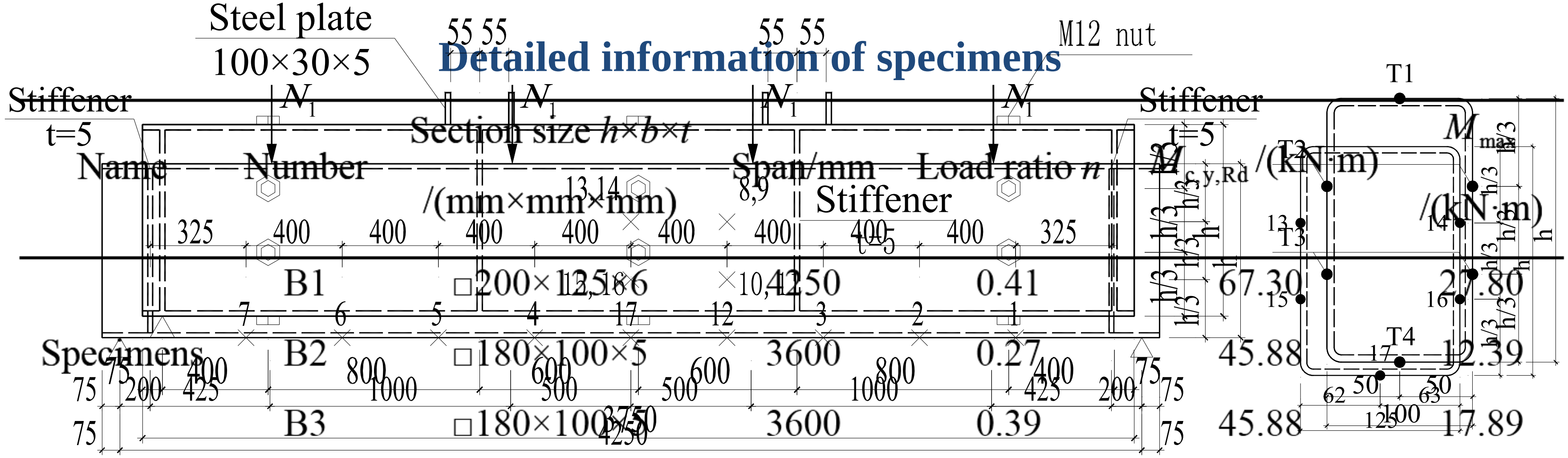


02 Selection of specimens

◆ To study the bearing capacity of rectangular stainless steel beams with three faces exposed to fire, a rectangular stainless steel beam specimen (B1) from Gardner and Baddoo and two rectangular stainless steel beams specimen (B2 and B3) from Xia were selected as the researched objects.

Detailed information of specimens

Name	Number	Section size $h\times b\times t$ /(mm×mm×mm)	Span/mm	Load ratio n	$M_{c,y,Rd}$ /(kN·m)	M_{max} /(kN·m)
Specimens	B1	□200×125×6	4250	0.41	67.30	27.80
	B2	□180×100×5	3600	0.27	45.88	12.39
	B3	□180×100×5	3600	0.39	45.88	17.89



Specimen B2 and B3

FE numerical simulation

Temperature Field

Affecting →

← Not affecting

Stress Field

Sequential coupled analysis method

① Temperature field calculation

② High Temperature Stress Analysis

Heat transfer model

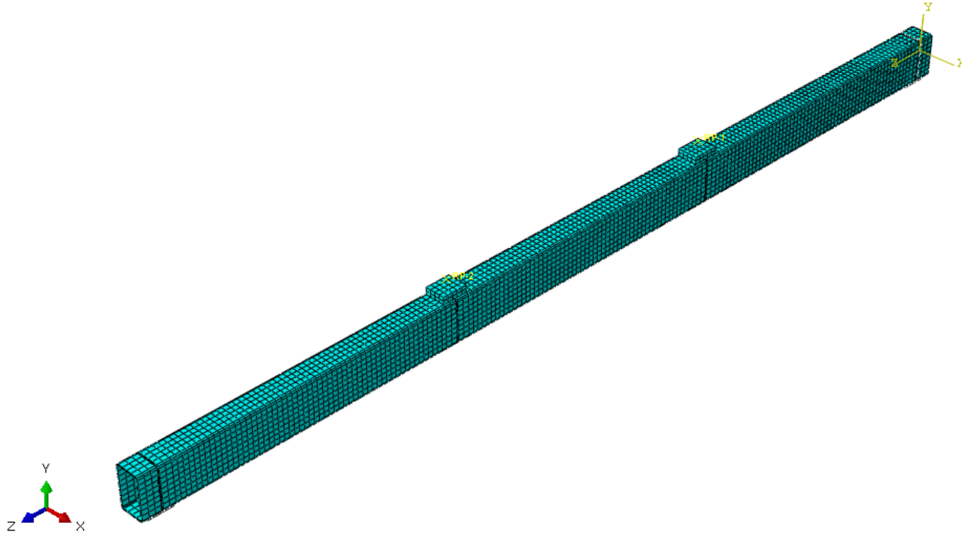
Fire resistance analysis model

FE numerical simulation

Heat transfer model

- Thermal parameters

- Heat convection coefficient
  α_c =25W/(m^2·°C)
- Thermal emissivity
  ε_m =0.4
- Flame radiation coefficient
  ε_f =1.0



FE numerical simulation

□ Heat transfer model

The same geometric shape, meshing and node numbers

□ Fire resistance analysis model

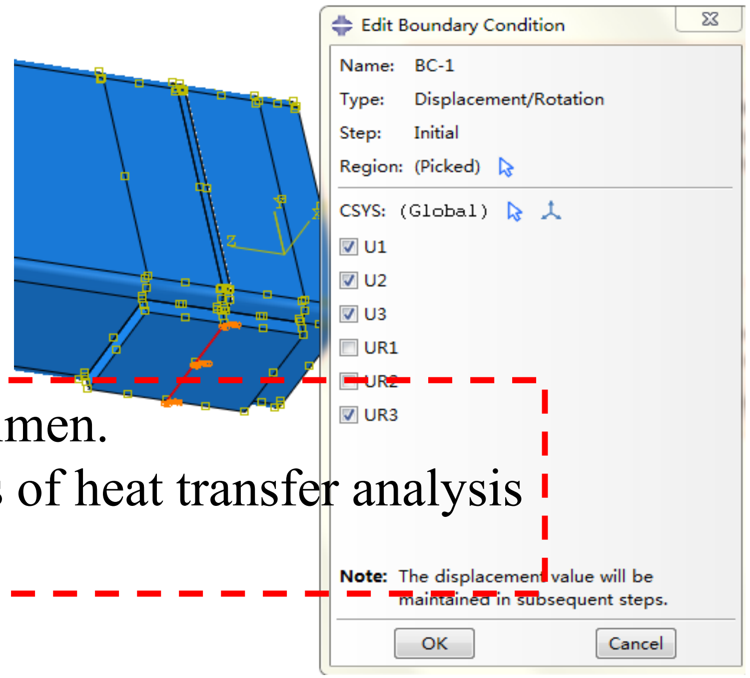
- Mechanical properties
- Boundary conditions
- Step and loading

• Initial elastic modulus

• Stress-strain relationship at high temperature

• Step-load to apply design load to specimen.

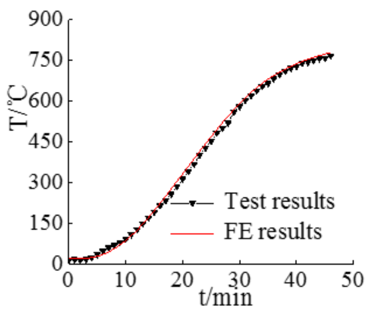
• Step-temp to apply temperature results of heat transfer analysis model to specimen.



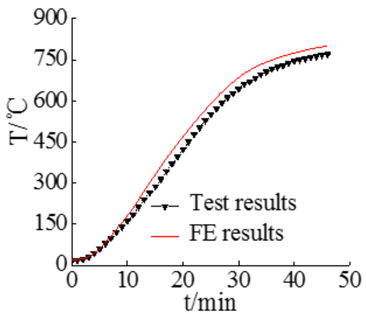
FE numerical simulation

◻ Comparison between FE results and test results

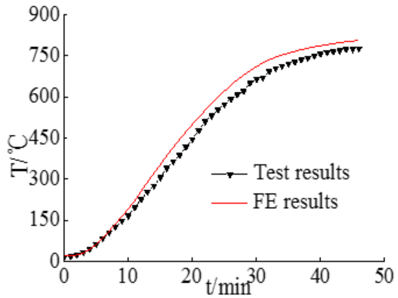
◆ Temperature-time curve



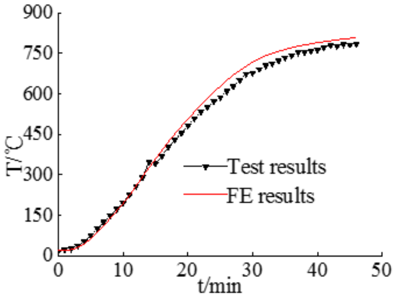
(a) T1



(b) T2

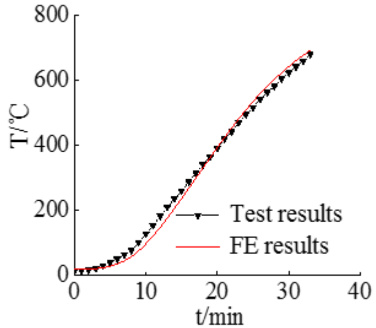


(c) T3

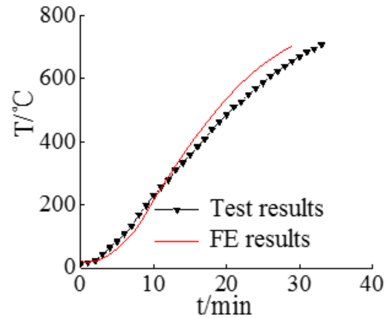


(d) T4

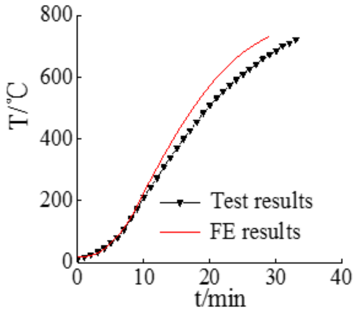
Specimen B2



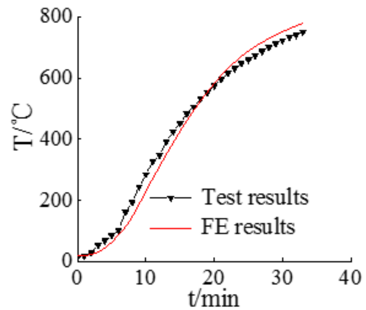
(a) T1



(b) T2



(c) T3



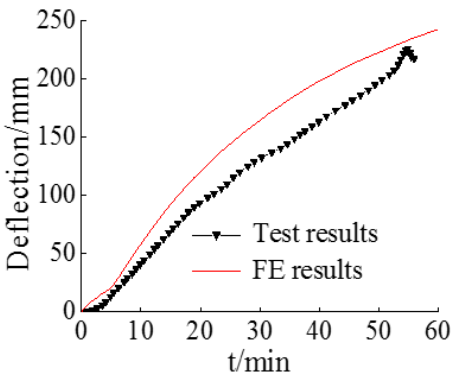
(d) T4

Specimen B3

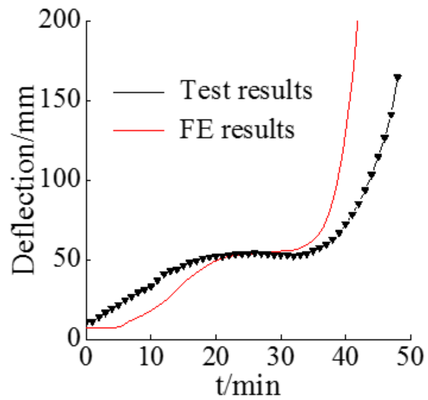
03 FE numerical simulation

□ Comparison between FE results and test results

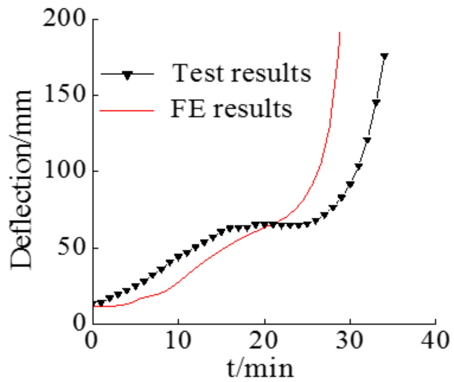
◆ Mid-span deflection-time curve



(a) B1

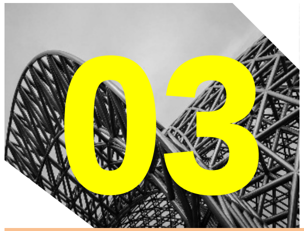


(b) B2



(c) B3

- For specimen B1, ISO-834 heating curve, which rose faster than actual heating curve which was used in the finite element model.
- For specimens B2 and B3, obvious thermal elongation occurred in late stage, which produced frictions between hinge bearings as well as loading devices and specimens.



FE numerical simulation

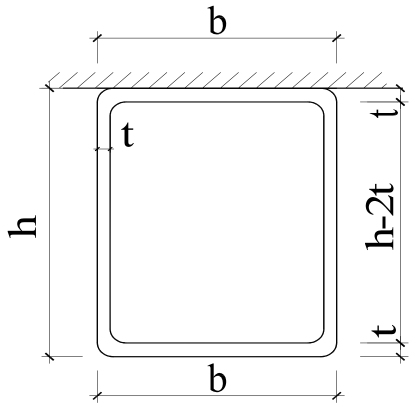
□ Comparison between FE results and test results

◆ Critical temperature

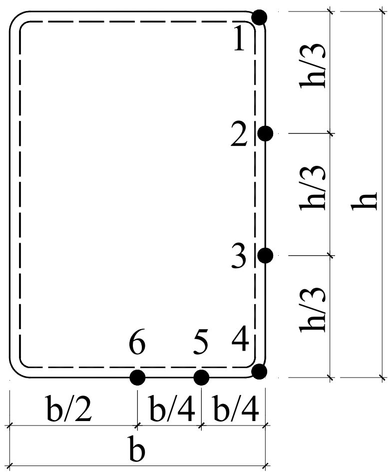
Number	Section size $h \times b \times t$ /(mm×mm×mm)	Load ratio n	T_{Test} /°C	T_{FEM} /°C	T_{FEM} / T_{Test}
B1	□200×125×6	0.41	884	859	0.97
B2	□180×100×5	0.27	783	792	1.01
B3	□180×100×5	0.39	740	725	0.98

- FE results and test results are closed, proving that the fire resistance model can well simulate the bearing capacity of stainless steel beams under fire.

Parametric analysis



Section parameters



Temperature measuring points at mid-span

Based on finite element models

Adopting ISO-834 standard fire curve

Parametric analysis

Load ratio n

Section factor A_m/V

$$A_m/V = \frac{h + b/2}{t(h + b - 2t)}$$

n, h, b, t

Parametric analysis

□ Section height

Group	Number	Section size $h \times b \times t$ /(mm×mm×mm)	Section factor A_m/V /(m^{-1})	Load ratio n	Ultimate flexural capacity/(kN·m)
1	C1-1~ C1-6	□200×300×14	53	Corresponding to 0.2~0.7	273.66
2	C2-1~ C2-6	□250×300×14	55	Corresponding to 0.2~0.7	369.99
3	C3-1~ C3-6	□300×300×14	56	Corresponding to 0.2~0.7	476.02
4	C4-1~ C4-6	□350×300×14	57	Corresponding to 0.2~0.7	591.73
5	C5-1~ C5-6	□400×300×14	58	Corresponding to 0.2~0.7	717.14
6	C6-1~ C6-6	□450×300×14	59	Corresponding to 0.2~0.7	852.24
7	C7-1~ C7-6	□500×300×14	60	Corresponding to 0.2~0.7	997.03

***h* changes**

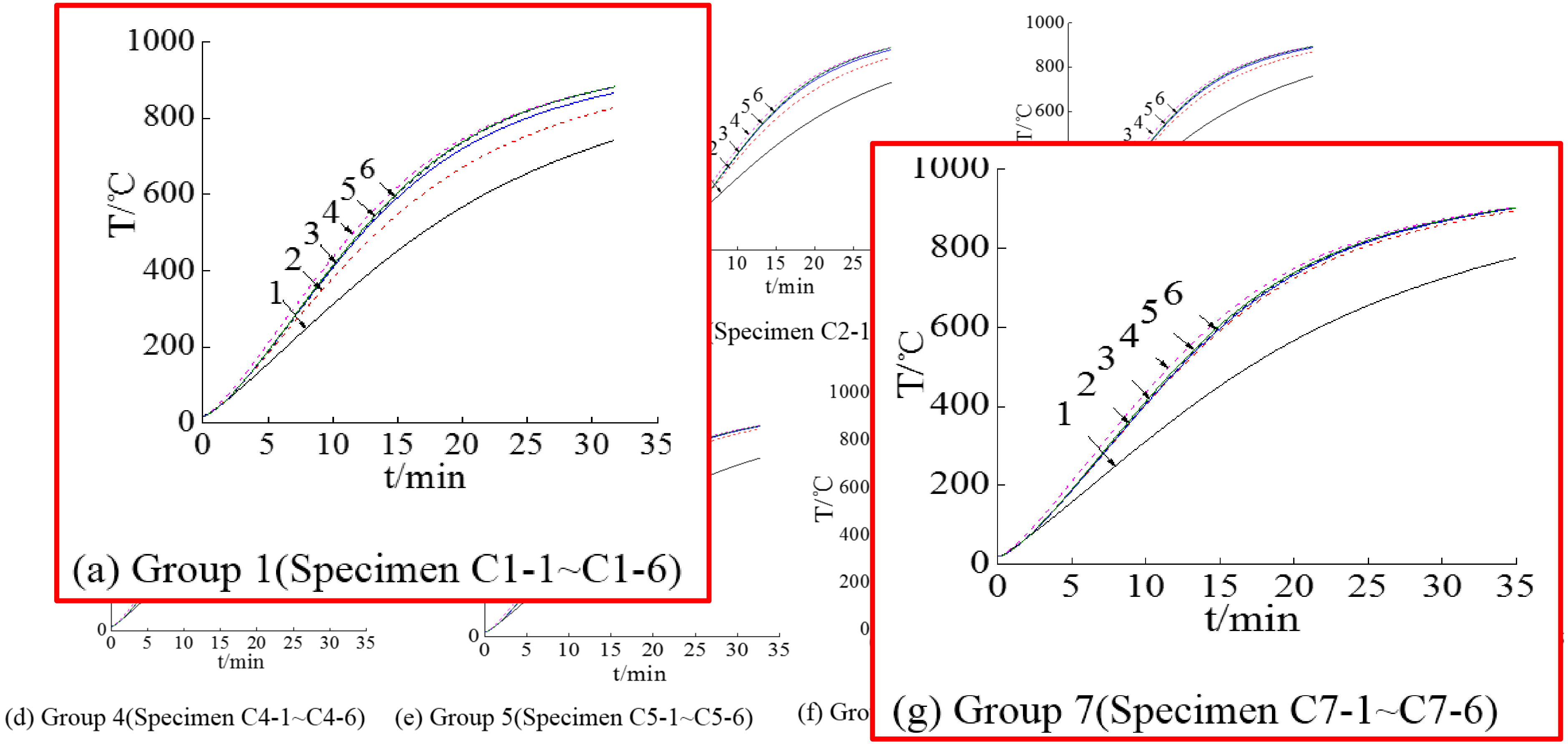
b --300mm
t --14mm

n -- 0.2, 0.3, 0.4, 0.5, 0.6 ,0.7

Parametric analysis

Section height

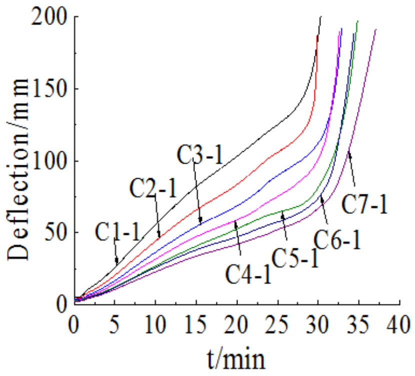
- Temperature-time curve



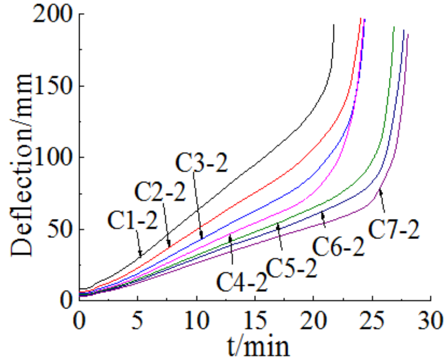
Parametric analysis

□ Section height

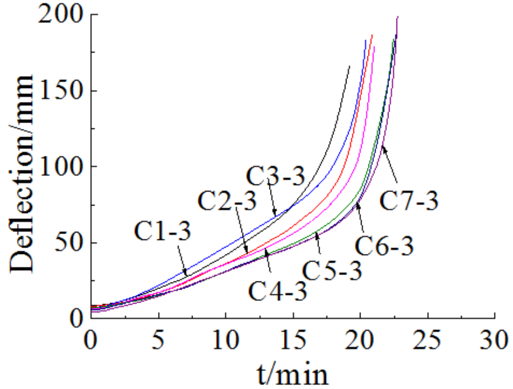
◆ Mid-span deflection-time curve



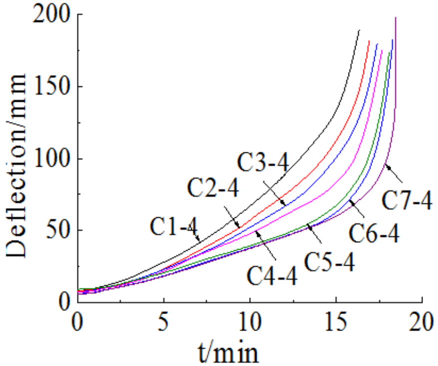
(a) Load ratio n=0.2



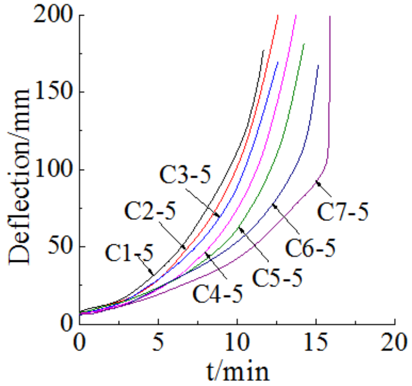
(b) Load ratio n=0.3



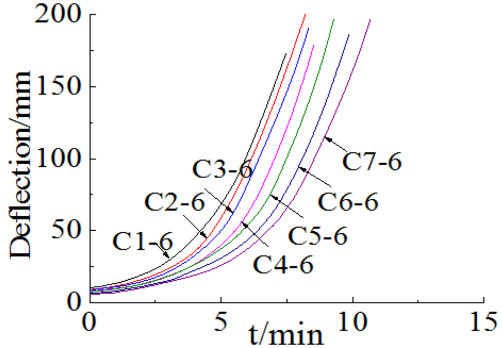
(c) Load ratio n=0.4



(d) Load ratio n=0.5



(e) Load ratio n=0.6



(f) Load ratio n=0.7

Parametric analysis

□ Section width

Group	Number	Section size $h \times b \times t$ /(mm×mm×mm)	Section factor A_m/V /(m^{-1})	Load ratio n	Ultimate flexural capacity/(kN·m)
1	D1-1~ D1-6	□400×150×14	65	Corresponding to 0.2~0.7	492.68
2	D2-1~ D2-6	□400×200×14	62	Corresponding to 0.2~0.7	567.50
3	D3-1~ D3-6	□400×250×14	60	Corresponding to 0.2~0.7	642.32
4	D4-1~ D4-6	□400×300×14	58	Corresponding to 0.2~0.7	717.14
5	D5-1~ D5-6	□400×350×14	57	Corresponding to 0.2~0.7	791.96
6	D6-1~ D6-6	□400×400×14	56	Corresponding to 0.2~0.7	866.78

***b* changes**

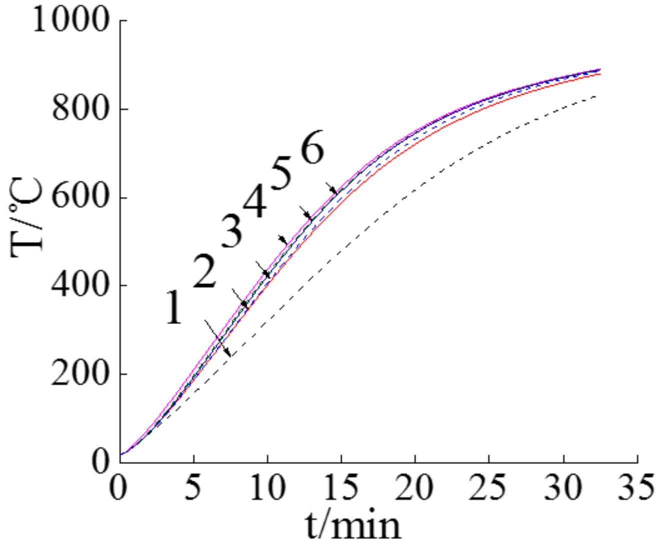
h --400mm
t --14mm

n -- 0.2, 0.3, 0.4
0.5, 0.6 ,0.7

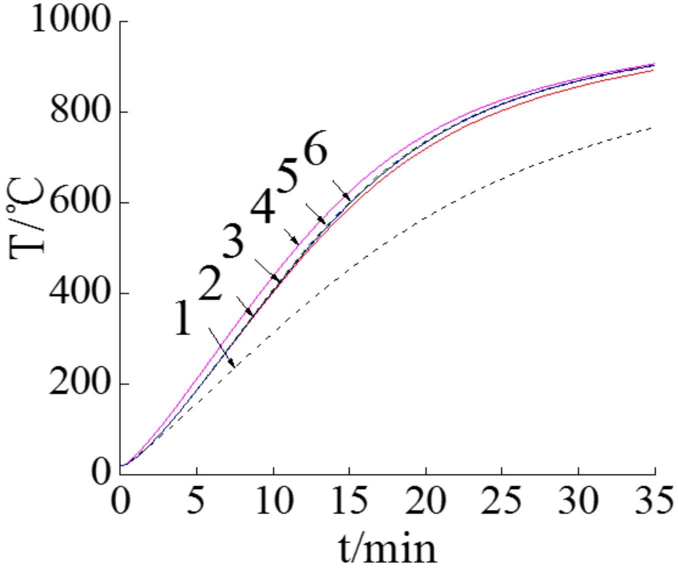
Parametric analysis

☐ Section width

◆ Temperature-time curve



(a) Group 1(Specimen D1-1~D1-6)

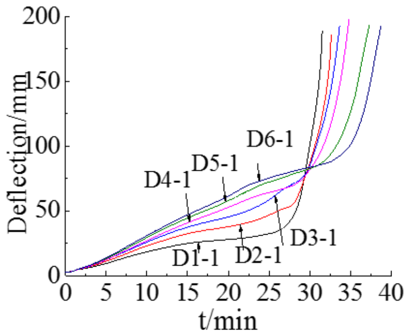


(f) Group 6(Specimen D6-1~D6-6)

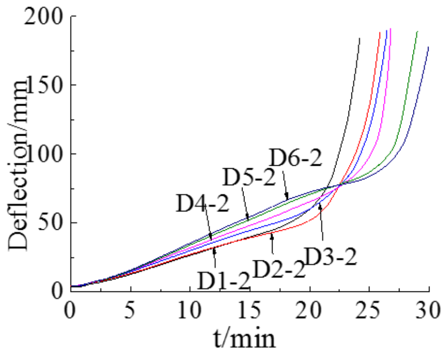
Parametric analysis

□ Section width

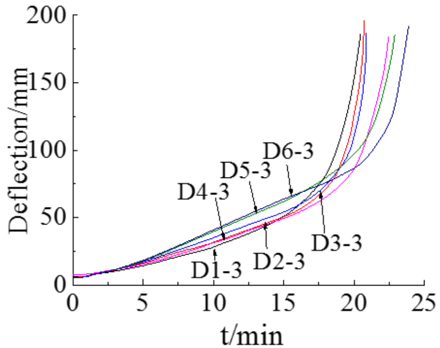
◆ Mid-span deflection-time curve



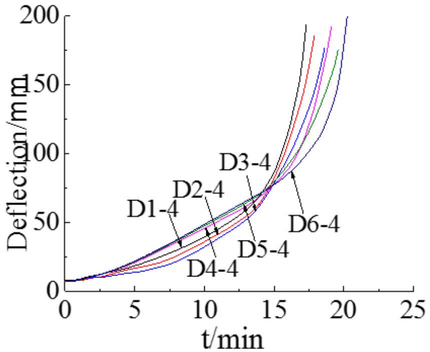
(a) Load ration n=0.2



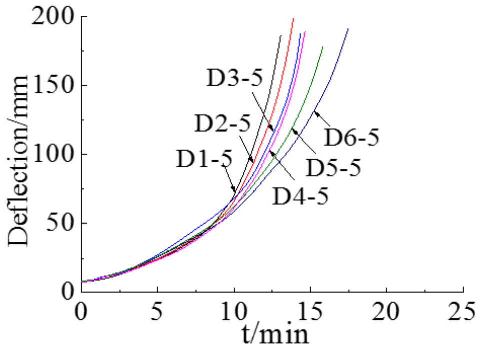
(b) Load ration n=0.3



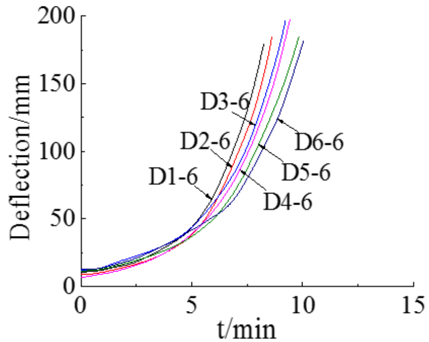
(c) Load ration n=0.4



(d) Load ration n=0.5



(e) Load ration n=0.6



(f) Load ration n=0.7

Bearing capacity formula

□ Formula in Eurocode

◆ Uniformly distributed temperature θ

$$M_{\mathrm{fi},\theta,\mathrm{Rd}} = k_{\mathrm{y},\theta}[\gamma_{\mathrm{M0}}/\gamma_{\mathrm{M,fi}}]M_{\mathrm{Rd}}$$

M_{Rd} is the design plastic moment resistance of the gross cross-section for Class 1 or 2 cross-sections for normal temperature design

$k_{\mathrm{y},\theta}$ is the reduction factor for the yield strength at temperature θ

γ_{M0} is the partial factor of yield bearing capacity , taken as 1.0

$\gamma_{\mathrm{M,fi}}$ is the partial factor of material properties under fire, taken as 1.0.

◆ Non-uniformly distributed temperature at time t

$$M_{\mathrm{fi,t,Rd}} = M_{\mathrm{fi},\theta,\mathrm{Rd}}/(\kappa_1\kappa_2)$$

κ_1 is an adaptation factor for non-uniform temperature across the cross-section, taken as 0.7 for beams with three faces exposed to fire without any protective measures

κ_2 is an adaptation factor for non-uniform temperature along the beam, taken as 0.85 for statically indeterminate beams and 1.0 for the rest.

Bearing capacity formula

☐ Bearing capacity formula at high temperature

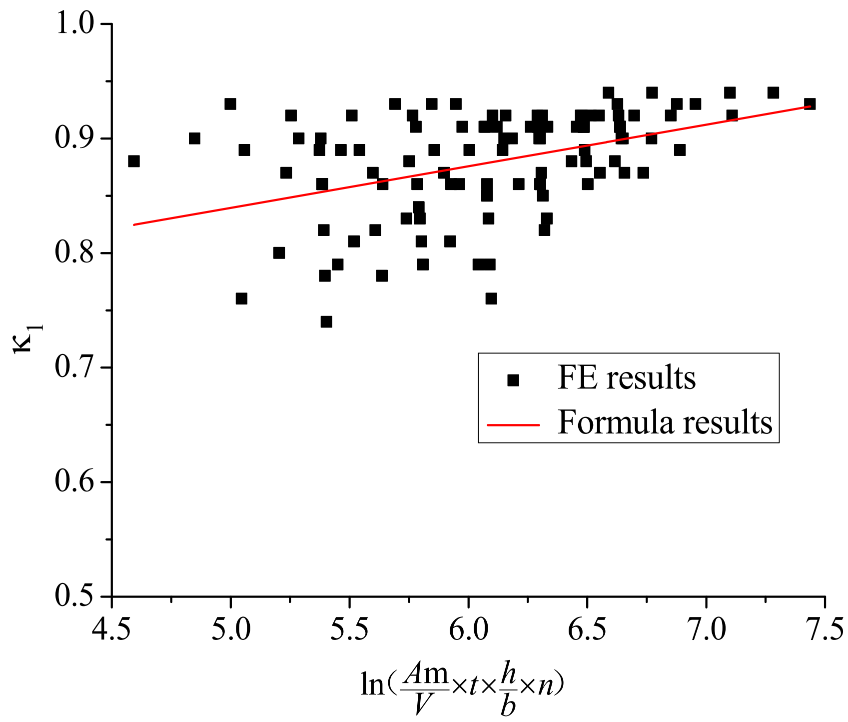
Group	Number	Section size $h \times b \times t$ /mm×mm× mm	Section factor A_m/V(m^{-1})	Load ratio					
				0.2	0.3	0.4	0.5	0.6	0.7
Section height	C1-1~C1-6	□200×300×14	53	0.88	0.93	0.90	0.92	0.93	0.93
	C2-1~C2-6	□250×300×14	55	0.90	0.92	0.89	0.92	0.93	0.92
	C3-1~C3-6	□300×300×14	56	0.89	0.89	0.88	0.91	0.92	0.92
Section width	D1-1~D1-6	□400×150×14	65	0.90	0.94	0.93	0.94	0.94	0.93
	D2-1~D2-6	□400×200×14	62	0.89	0.91	0.92	0.94	0.93	0.92
	D3-1~D3-6	□400×250×14	60	0.87	0.89	0.91	0.92	0.92	0.92
Section thickness	E1-1~E1-6	□400×300×10	81	0.89	0.91	0.91	0.92	0.92	0.93
	E2-1~E2-6	□400×300×12	68	0.90	0.86	0.91	0.91	0.92	0.92
	E6-1~E6-6	□400×300×20	42	0.74	0.79	0.76	0.82	0.86	0.87

- κ_1 is higher than 0.7.
- κ_1 increases with the rising of load ratio.

Bearing capacity formula

□ Bearing capacity formula at high temperature

$$\kappa_1 = 0.0363 \ln\left(\frac{A_{\mathrm{m}}}{V} \times t \times \frac{h}{b} \times n\right) + 0.6578$$



Bearing capacity formula

Verifying formula

◆ Another three specimens with three faces exposed to fire from Xia

Number	Section size $h \times b \times t$ (mm×mm×mm)	Load ratio n	Test results $\kappa_{1,\mathrm{T}}$	Formula result $\kappa_{1,\mathrm{eq}}$	Eurocode κ_1	$\kappa_{1,\mathrm{eq}} / \kappa_{1,\mathrm{T}}$	$\kappa_1 / \kappa_{1,\mathrm{T}}$
B4	□140×100×5	0.39	0.97	0.88	0.70	0.91	0.72
B5	□180×100×5	0.51	0.85	0.90	0.70	1.06	0.82
B6	□220×100×5	0.39	0.82	0.90	0.70	1.10	0.85

Modifying formula

$$\kappa_1 = 0.0352 \ln\left(\frac{A_\mathrm{m}}{V} \times t \times \frac{h}{b} \times n\right) + 0.7199$$

$$M_{\mathrm{fi,t,Rd}} = M_{\mathrm{fi,\theta,Rd}} / [\,0.0352 \ln\left(\frac{A_\mathrm{m}}{V} \times t \times \frac{h}{b} \times n\right) + 0.7199]$$

Conclusions

- For rectangular stainless steel beams with three faces exposed to fire, the value of κ_1 from Eurocode and Design manual for structural stainless steel is unsafe and the actual bearing capacity differs much from the results calculated with codes.

- Section size and load ratio have great impact on the bearing capacity of stainless steel beams with three faces exposed to fire. And the corresponding reduction faction κ_1 is variable.

- The fitting formula can well predict fire resistance of rectangular stainless steel beams with three faces exposed to fire.

Acknowledgments

Thank you for your attention！

Shenggang Fan, Li Du, Liyuan Zhang, Ganping Shu