Web Crippling Behaviour of Cold-formed Duplex Stainless Steel Tubular Sections at Elevated Temperatures

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OUTLINE OF THE PAPER

- Introduction
- Summary of experimental investigation
- Numerical investigation
- Comparison with design strengths at elevated temperatures
- Proposed design equations and comparison at elevated and room temperatures
- Conclusions

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Introduction

- Significant progress has been made in recent years in the development of design guidance for stainless steel structures in room temperature.
- However, investigation of the structural performance of stainless steel structural members at elevated temperatures is limited.
- The objectives of this paper are to numerically investigate the behaviour of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures.

Introduction

- The current web crippling design rules in most of the specifications for cold-formed stainless steel structures are generally empirical in nature and are based on the test results of cold-formed carbon steel.
- No web crippling design rules are given for stainless steel members at elevated temperatures.
- The web crippling design rules in the current specifications for cold-formed stainless steel square and rectangular hollow sections are examined for the possibility of using the design rules at elevated temperatures.
- A unified web crippling equation is proposed at elevated temperatures by considering the reduced yield strength and stiffness at elevated temperatures.

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Summary of Experimental Investigation

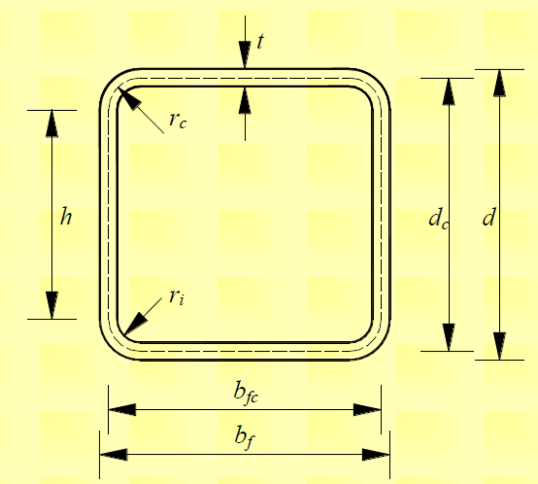
- Zhou and Young [10] reported an experimental investigation of cold-formed high strength stainless steel tubular sections subjected to web crippling at room temperature, which was used to **verify** the finite element model developed in this study.

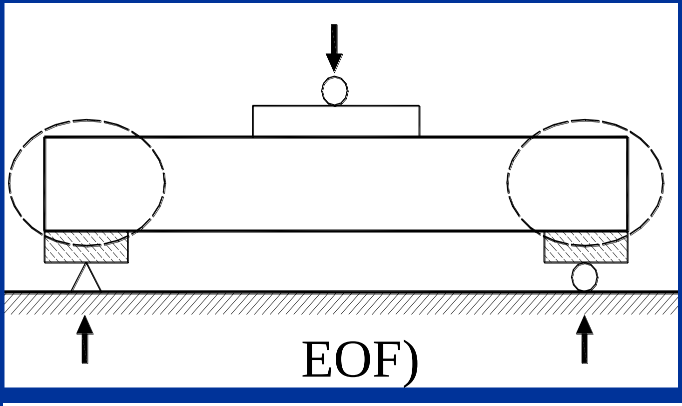
SHS & RHS

d =[40 - 200]

b =[40 - 150]

h/t =[16.5 - 49.7]

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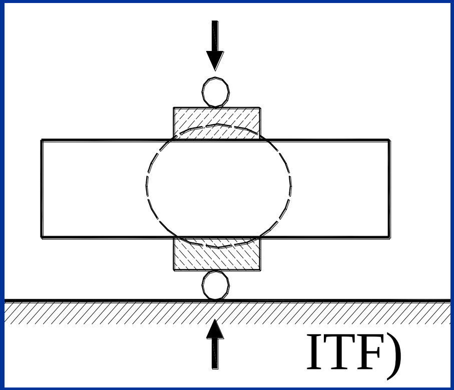
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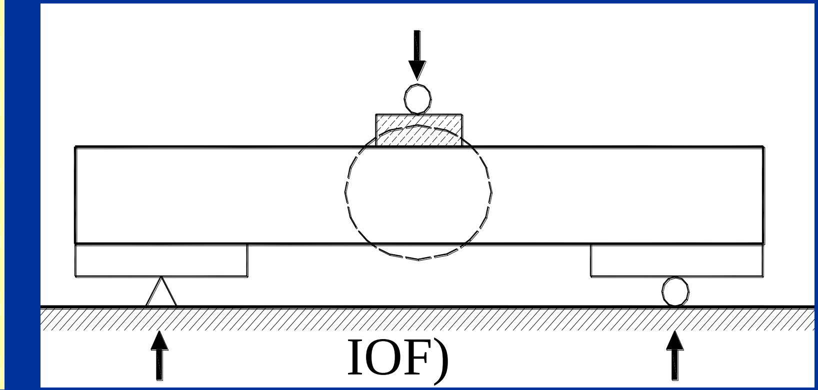
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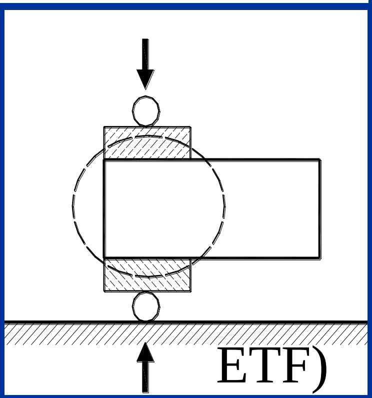
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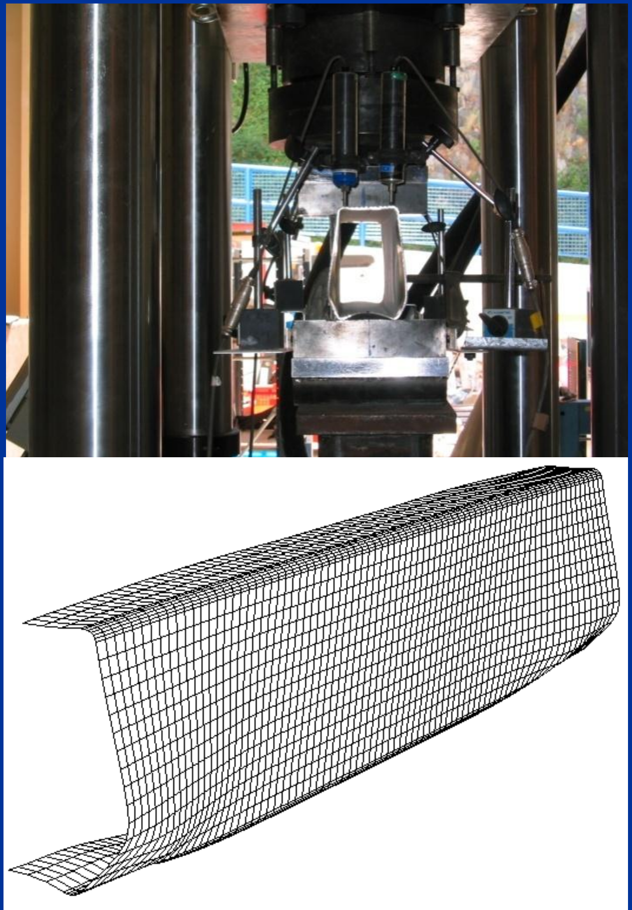
Numerical Investigation

- The finite element program **ABAQUS** [9] was used to simulate the cold-formed stainless steel tubular sections subjected to web crippling. Due to symmetry, only one-half of the cross-section was modelled.



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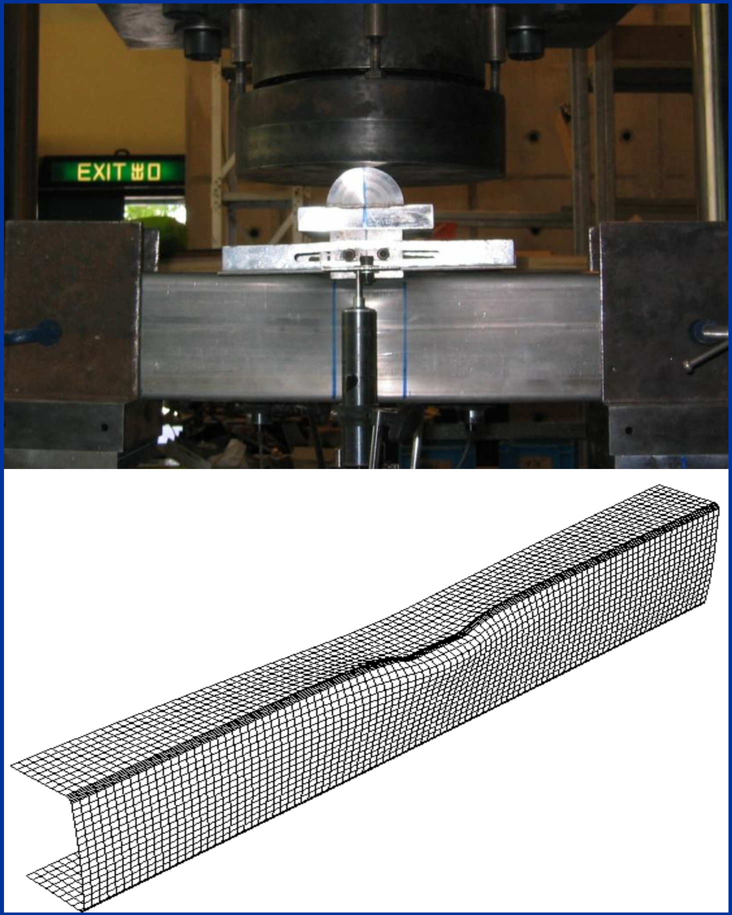

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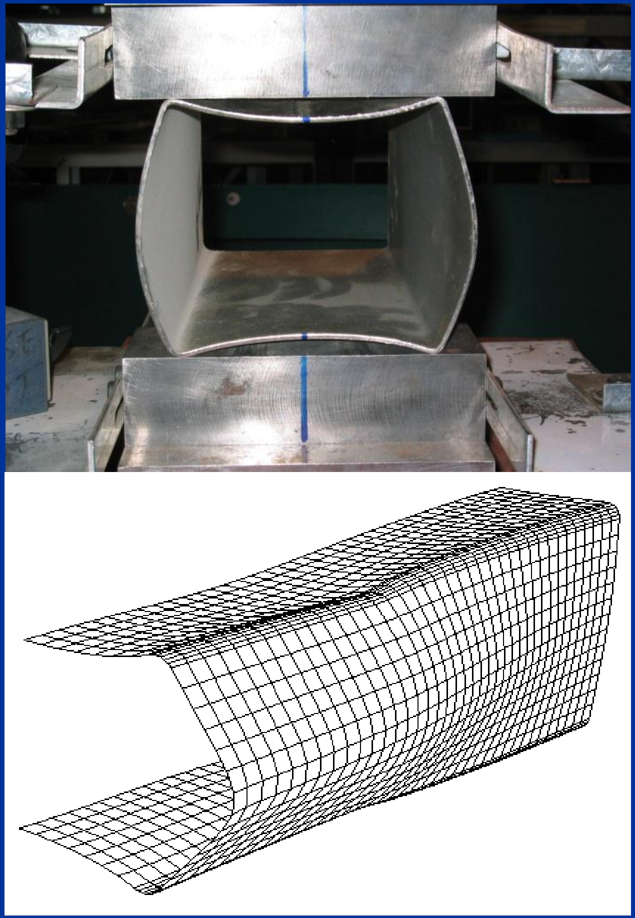
Numerical Investigation

- The measured cross-section dimensions and material properties obtained from the tests were used in the FEM. The model was based on the centreline dimensions of the cross-sections.



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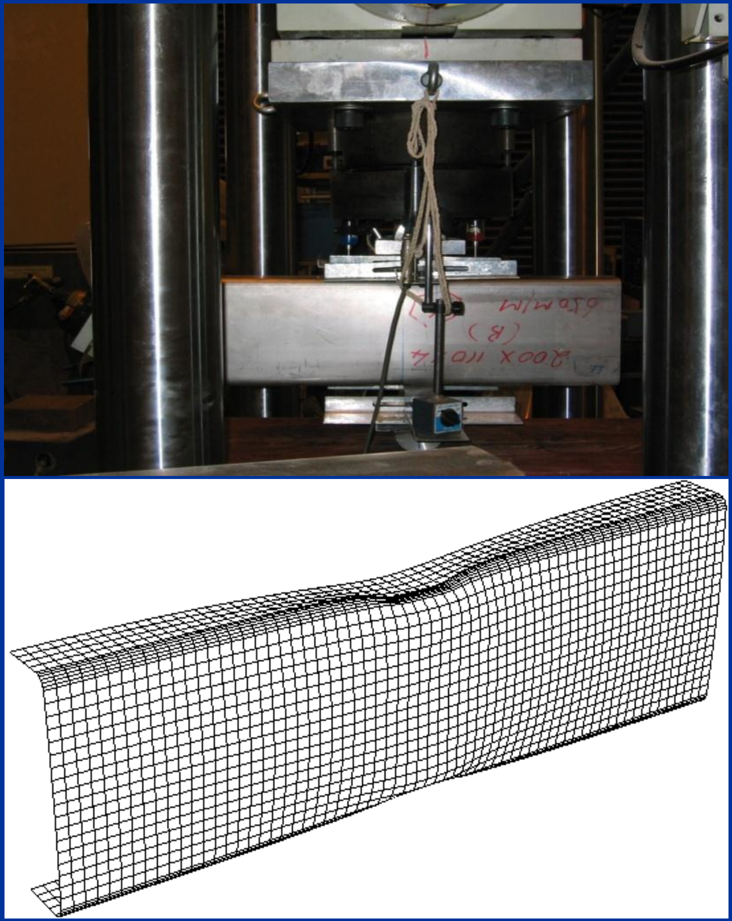

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Numerical Investigation

- The cold-formed stainless steel section was modelled using the S4R shell element.
- The finite element mesh sizes ranged from 2×2mm (length by width) to 10×10mm were used for the flanges and webs depending on the size of the sections, where a finer mesh size of 6 elements at the corners of the sections was used.
- The interfaces between the bearing plates and stainless steel section are modelled using the contact pairs.
- The loading method used in the finite element analysis was identical to that used in the tests.
- The measured stress-strain curves of the specimens at room and elevated temperatures were used in the analysis.

Verification of FEM

- A total of 28 cold-formed high strength stainless steel tubular sections subjected to web crippling tested by Zhou and Young [10] at room temperature were analyzed in the verification of the developed FEM.

- The mean value of the P_{Exp}/P_{FEA} ratio is 0.99 with the corresponding coefficient of variation (COV) of 0.061.

- Generally, both the failure modes and the ultimate web crippling strengths reflect good agreement between the experimental and finite element results.

- It is shown that the FEM can closely predict the behaviour of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling.

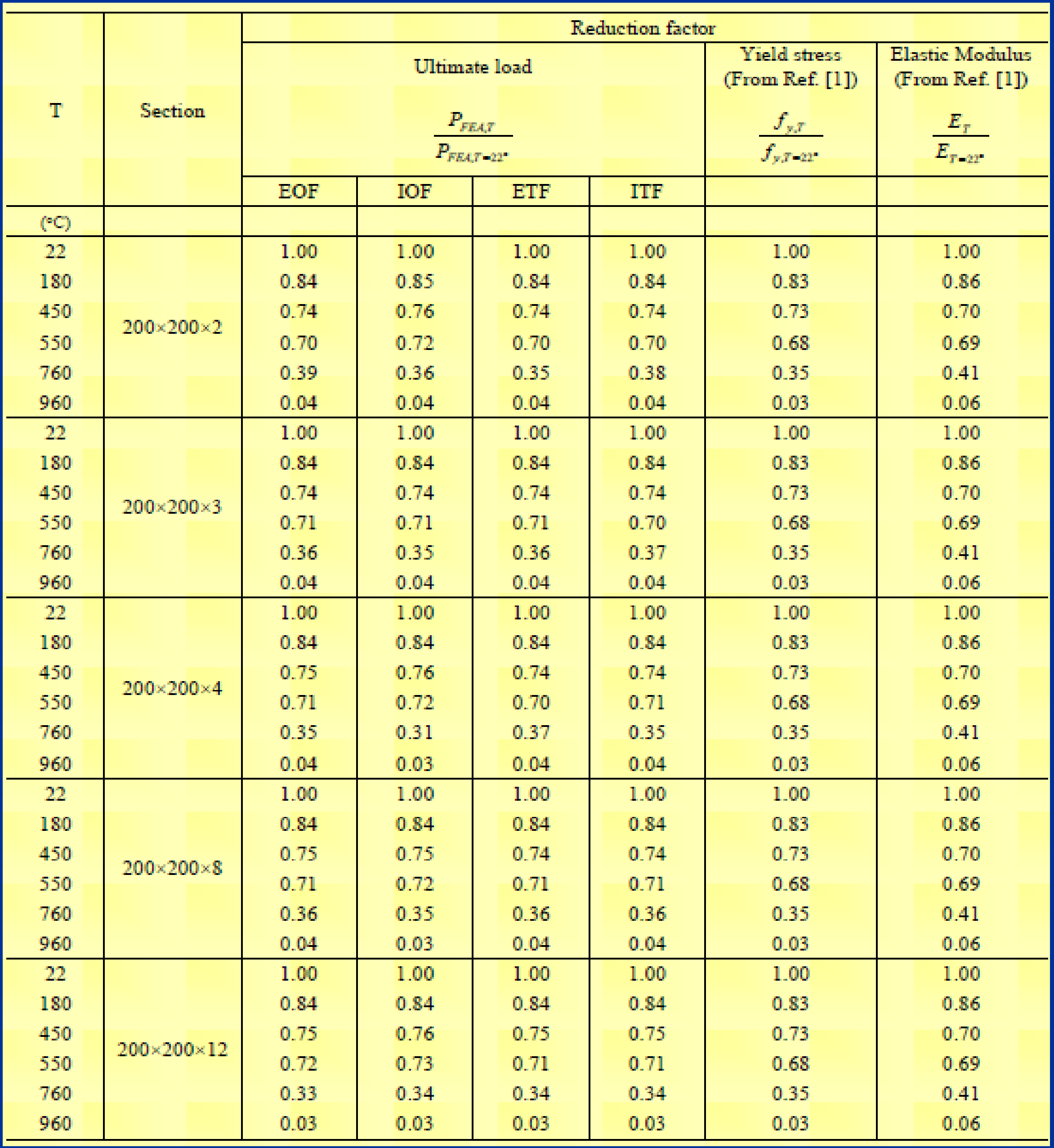
Parametric Study

- A total of 120 specimens for various temperatures were analyzed in the parametric study, and these temperatures are 22, 180, 450, 550, 760 and 960 ºC.

- The specimens consisted of five different section sizes, they are 200×200×2, 200×200×3, 200×200×4, 200×200×8 and 200×200×12.

- The stress-strain curve of the flat portions of cold-formed duplex stainless steel tubular sections at elevated temperatures measured by Chen and Young [1] were used in the parametric study.

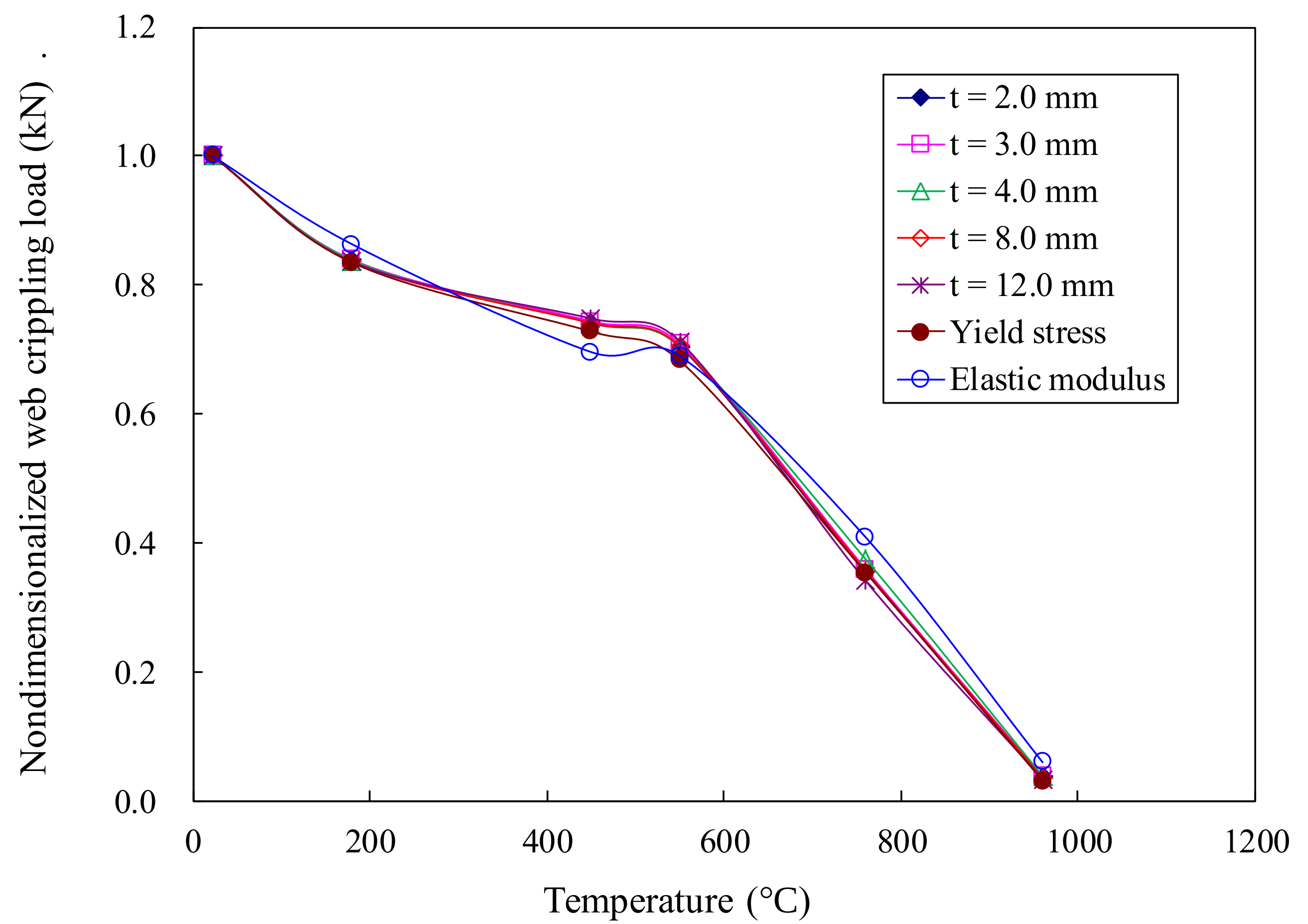
Parametric Study



T	Section	Reduction factor					
		Ultimate load $\frac{P_{FEA,T}}{P_{FEA,T=22^\circ}}$				Yield stress (From Ref. [1]) $\frac{f_{y,T}}{f_{y,T=22^\circ}}$	Elastic Modulus (From Ref. [1]) $\frac{E_T}{E_{T=22^\circ}}$
		EOF	IOF	ETF	ITF		
(°C)							
22	200×200×2	1.00	1.00	1.00	1.00	1.00	1.00
180		0.84	0.85	0.84	0.84	0.83	0.86
450		0.74	0.76	0.74	0.74	0.73	0.70
550		0.70	0.72	0.70	0.70	0.68	0.69
760		0.39	0.36	0.35	0.38	0.35	0.41
960		0.04	0.04	0.04	0.04	0.03	0.06
22	200×200×3	1.00	1.00	1.00	1.00	1.00	1.00
180		0.84	0.84	0.84	0.84	0.83	0.86
450		0.74	0.74	0.74	0.74	0.73	0.70
550		0.71	0.71	0.71	0.70	0.68	0.69
760		0.36	0.35	0.36	0.37	0.35	0.41
960		0.04	0.04	0.04	0.04	0.03	0.06
22	200×200×4	1.00	1.00	1.00	1.00	1.00	1.00
180		0.84	0.84	0.84	0.84	0.83	0.86
450		0.75	0.76	0.74	0.74	0.73	0.70
550		0.71	0.72	0.70	0.71	0.68	0.69
760		0.35	0.31	0.37	0.35	0.35	0.41
960		0.04	0.03	0.04	0.04	0.03	0.06
22	200×200×8	1.00	1.00	1.00	1.00	1.00	1.00
180		0.84	0.84	0.84	0.84	0.83	0.86
450		0.75	0.75	0.74	0.74	0.73	0.70
550		0.71	0.72	0.71	0.71	0.68	0.69
760		0.36	0.35	0.36	0.36	0.35	0.41
960		0.04	0.03	0.04	0.04	0.03	0.06
22	200×200×12	1.00	1.00	1.00	1.00	1.00	1.00
180		0.84	0.84	0.84	0.84	0.83	0.86
450		0.75	0.76	0.75	0.75	0.73	0.70
550		0.72	0.73	0.71	0.71	0.68	0.69
760		0.33	0.34	0.34	0.34	0.35	0.41
960		0.03	0.03	0.03	0.03	0.03	0.06

- The ultimate web crippling capacity decreases as the temperature increases.

Comparison of the reduction factors of web crippling strengths under ETF loading condition



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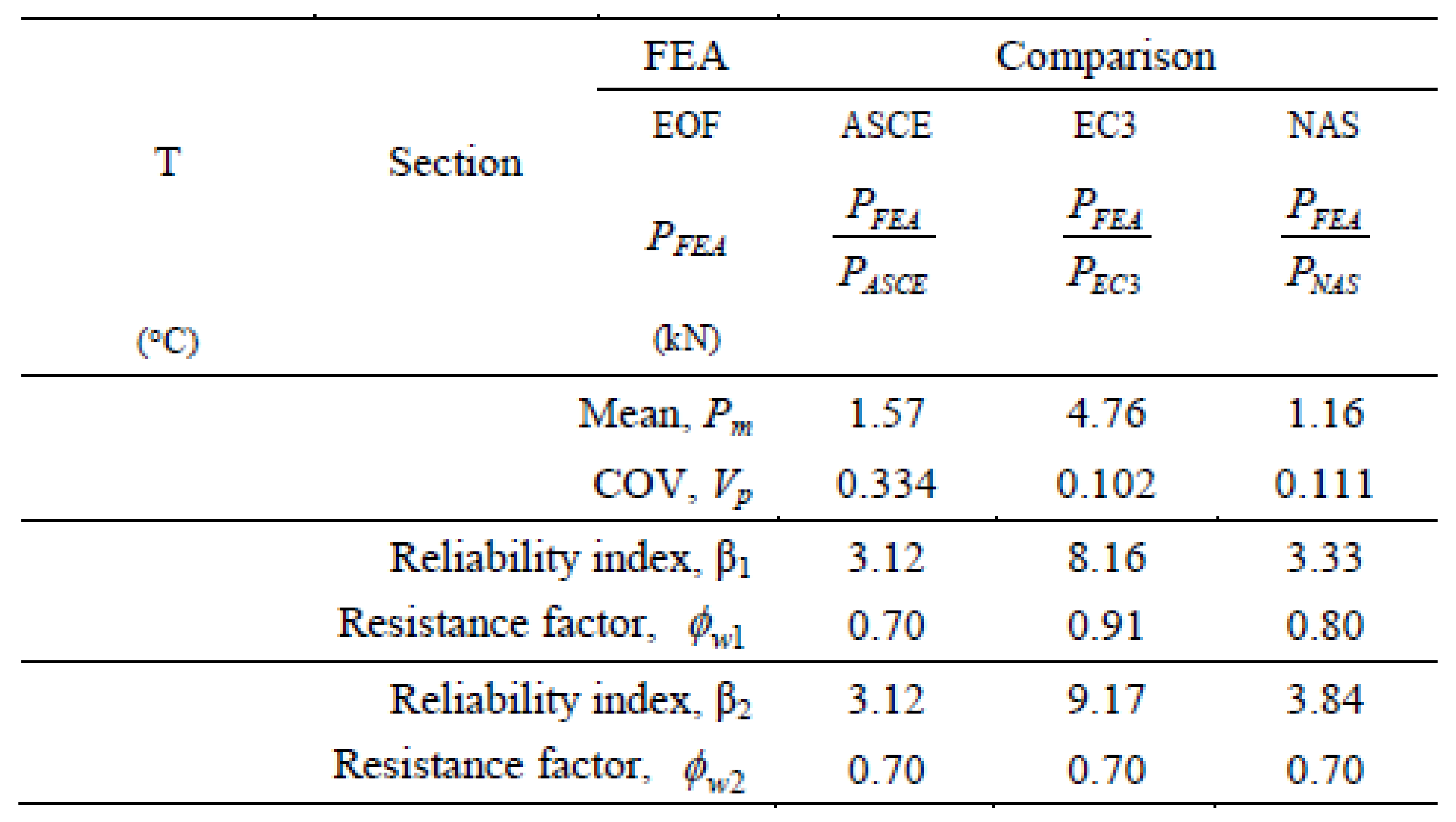
Comparison with Design Strengths

- The web crippling strengths (P_{FEA}) per web predicted from the finite element analysis at elevated temperatures were compared with the nominal web crippling strengths obtained using the ASCE Specification [6], AS/NZS Standard [7] and EC3 Code [8] Part 1.4 by substituting the reduced yield strength ($\sigma_{0.2}$) and elastic modulus into the conventional design rules.

- In addition, the web crippling strengths (P_{FEA}) predicted from the FEA were also compared with the nominal web crippling strengths (P_{NAS}) predicted using the NAS Specification [11] for cold-formed carbon steel structural members.

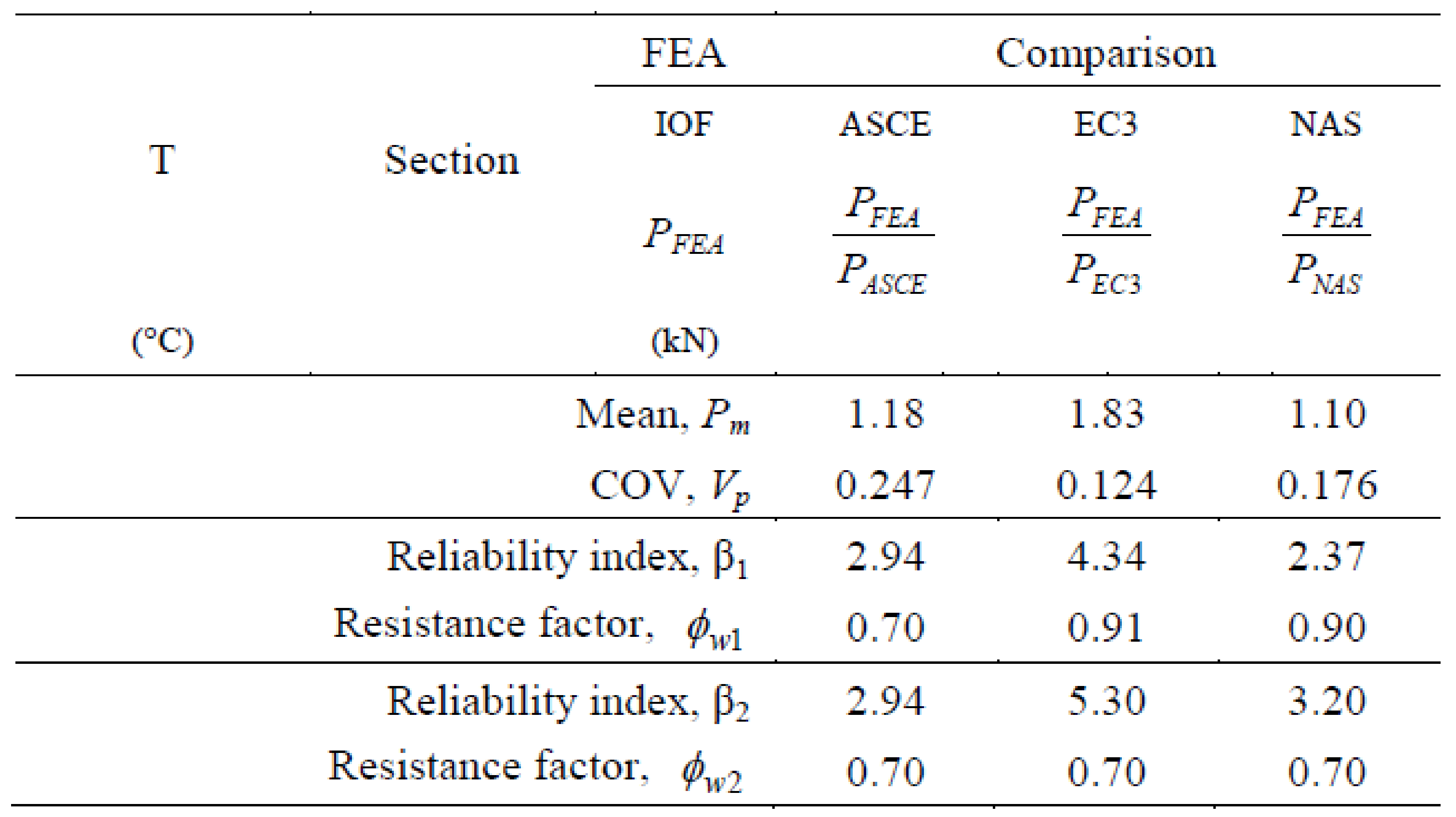
Comparison with design strengths at elevated temperatures

– EOF loading condition



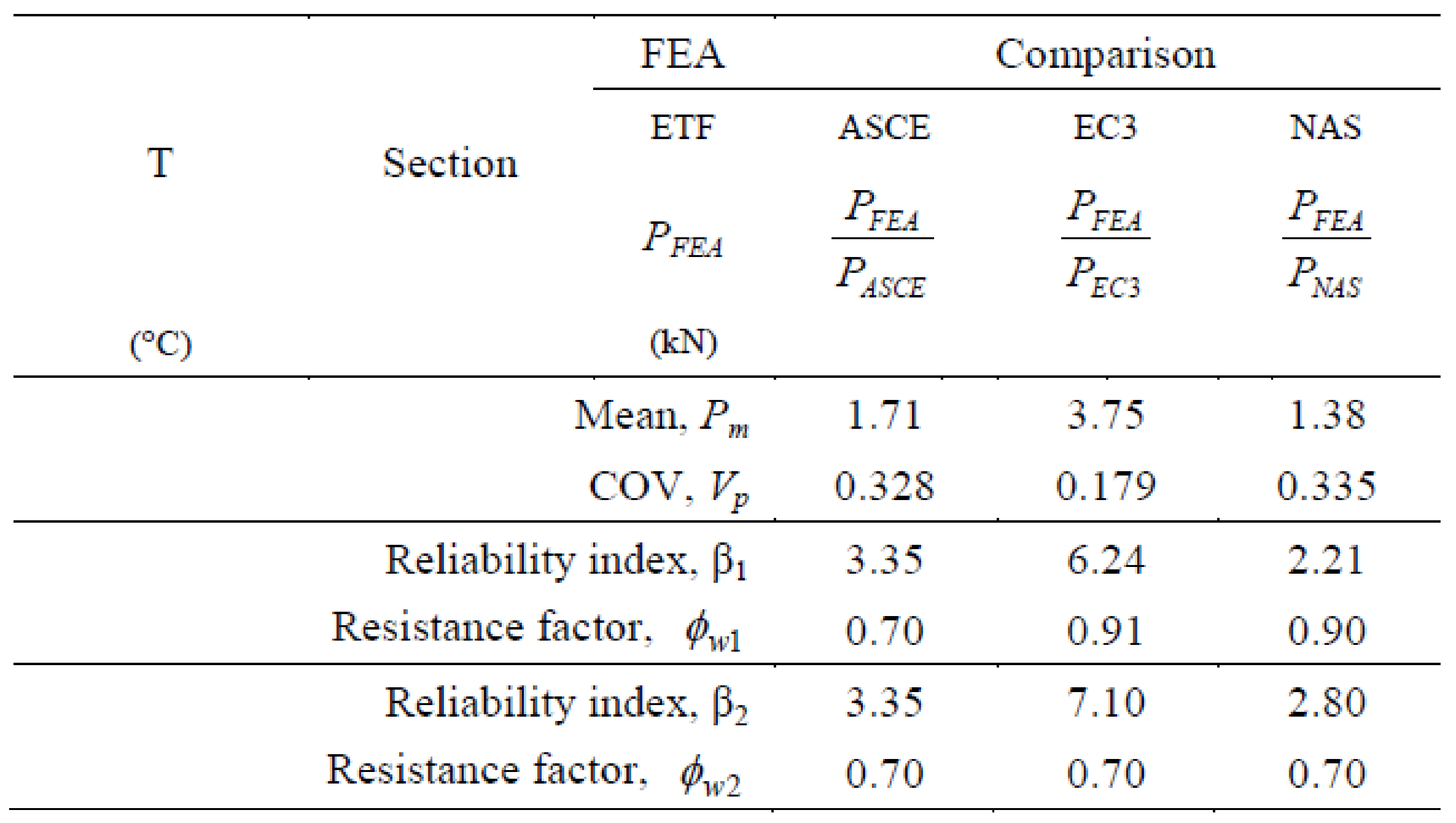
T	Section	FEA	Comparison		
		EOF	ASCE	EC3	NAS
(°C)		P_{FEA} (kN)	$\frac{P_{FEA}}{P_{ASCE}}$	$\frac{P_{FEA}}{P_{EC3}}$	$\frac{P_{FEA}}{P_{NAS}}$
Mean, P_m			1.57	4.76	1.16
COV, V_p			0.334	0.102	0.111
Reliability index, β_1			3.12	8.16	3.33
Resistance factor, ϕ_{w1}			0.70	0.91	0.80
Reliability index, β_2			3.12	9.17	3.84
Resistance factor, ϕ_{w2}			0.70	0.70	0.70

Comparison with design strengths at elevated temperatures – IOF loading condition



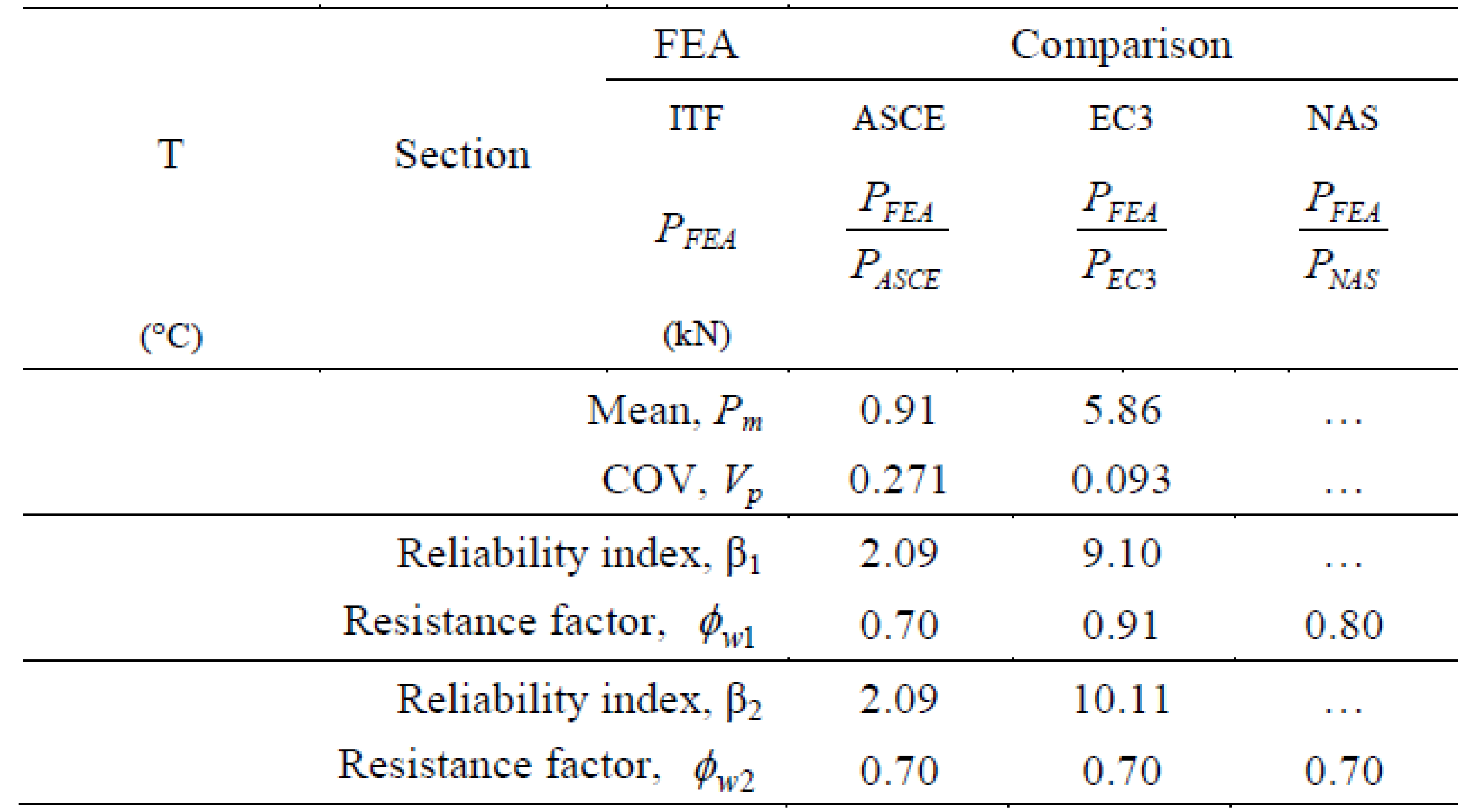
T	Section	FEA	Comparison		
		IOF	ASCE	EC3	NAS
(°C)		P_{FEA} (kN)	$\frac{P_{FEA}}{P_{ASCE}}$	$\frac{P_{FEA}}{P_{EC3}}$	$\frac{P_{FEA}}{P_{NAS}}$
		Mean, P_m	1.18	1.83	1.10
		COV, V_p	0.247	0.124	0.176
		Reliability index, β_1	2.94	4.34	2.37
		Resistance factor, ϕ_{w1}	0.70	0.91	0.90
		Reliability index, β_2	2.94	5.30	3.20
		Resistance factor, ϕ_{w2}	0.70	0.70	0.70

Comparison with design strengths at elevated temperatures – ETF loading condition



T (°C)	Section	FEA ETF P_{FEA} (kN)	Comparison ASCE $\frac{P_{FEA}}{P_{ASCE}}$	 EC3 $\frac{P_{FEA}}{P_{EC3}}$	 NAS $\frac{P_{FEA}}{P_{NAS}}$
		Mean, P_m	1.71	3.75	1.38
		COV, V_p	0.328	0.179	0.335
		Reliability index, β_1	3.35	6.24	2.21
		Resistance factor, ϕ_{w1}	0.70	0.91	0.90
		Reliability index, β_2	3.35	7.10	2.80
		Resistance factor, ϕ_{w2}	0.70	0.70	0.70

Comparison with design strengths at elevated temperatures – ITF loading condition



T	Section	FEA	Comparison		
		ITF	ASCE	EC3	NAS
		P_{FEA}	$\frac{P_{FEA}}{P_{ASCE}}$	$\frac{P_{FEA}}{P_{EC3}}$	$\frac{P_{FEA}}{P_{NAS}}$
(°C)		(kN)			
Mean, P_m			0.91	5.86	…
COV, V_p			0.271	0.093	…
Reliability index, β_1			2.09	9.10	…
Resistance factor, ϕ_{w1}			0.70	0.91	0.80
Reliability index, β_2			2.09	10.11	…
Resistance factor, ϕ_{w2}			0.70	0.70	0.70

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Proposed Design Equations

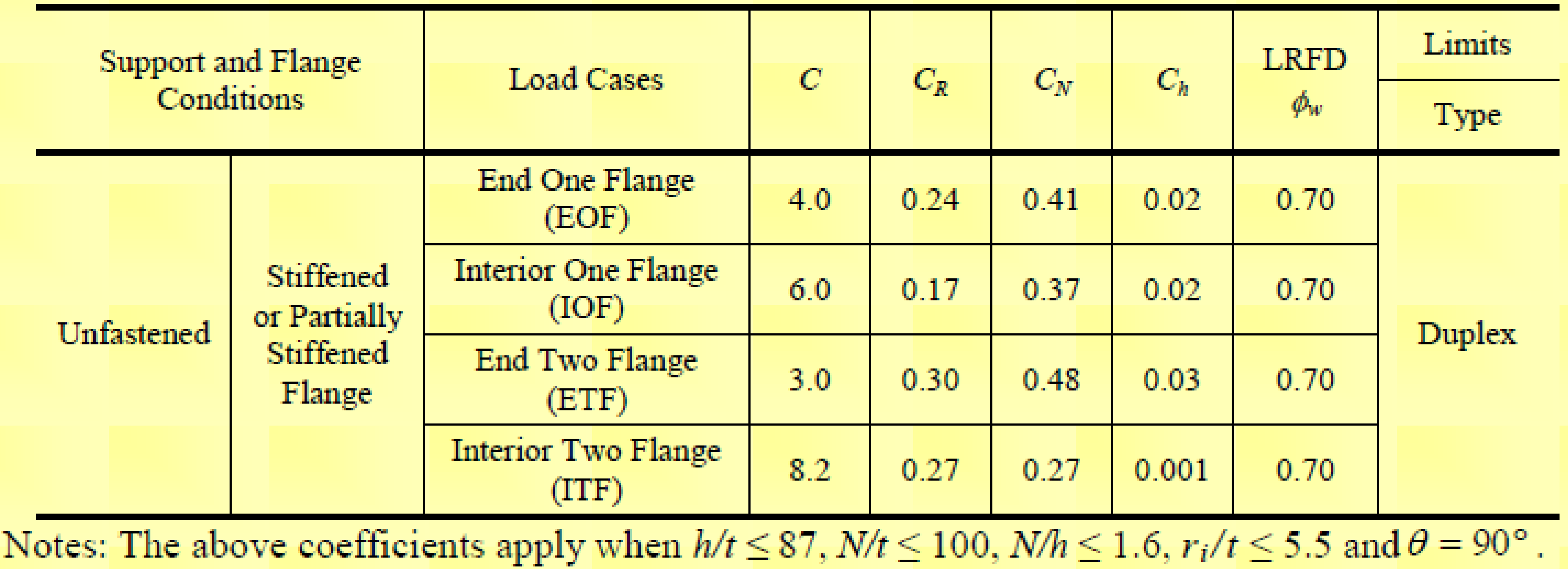
- No web crippling design rules are given for stainless steel members at elevated temperatures.
- In this study, a unified web crippling equation for cold-formed high strength stainless steel square and rectangular hollow sections at elevated temperatures is proposed.

$$P_P = Ct^2 f_{y,T} \sin\theta \left(1 - C_R \sqrt{\frac{r_i}{t}}\right)\left(1 + C_N \sqrt{\frac{N}{t}}\right)\left(1 - C_h \left(\frac{f_{y,T}}{E_T}\right)\sqrt{\frac{h}{t}}\right)$$

- The proposed web crippling design equation considers the reduced yield strength as well as stiffness at elevated temperatures.

Proposed Design Equations

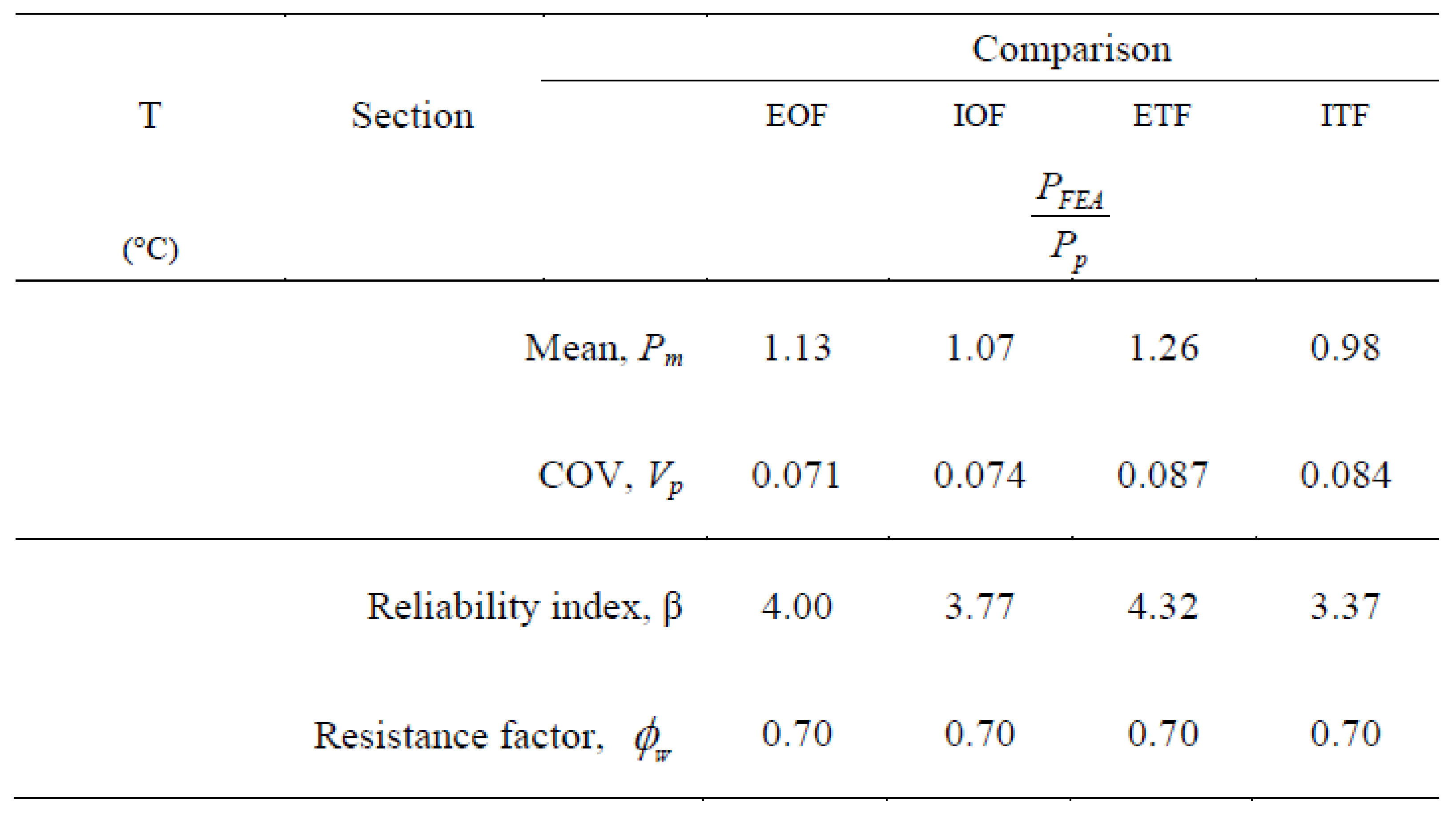
$$P_P = Ct^2 f_{y,T} \sin\theta \left(1 - C_R\sqrt{\frac{r_i}{t}}\right)\left(1 + C_N\sqrt{\frac{N}{t}}\right)\left(1 - C_h\left(\frac{f_{y,T}}{E_T}\right)\sqrt{\frac{h}{t}}\right)$$



Support and Flange Conditions		Load Cases	C	C_R	C_N	C_h	LRFD ϕ_w	Limits Type
Unfastened	Stiffened or Partially Stiffened Flange	End One Flange (EOF)	4.0	0.24	0.41	0.02	0.70	Duplex
		Interior One Flange (IOF)	6.0	0.17	0.37	0.02	0.70	
		End Two Flange (ETF)	3.0	0.30	0.48	0.03	0.70	
		Interior Two Flange (ITF)	8.2	0.27	0.27	0.001	0.70	

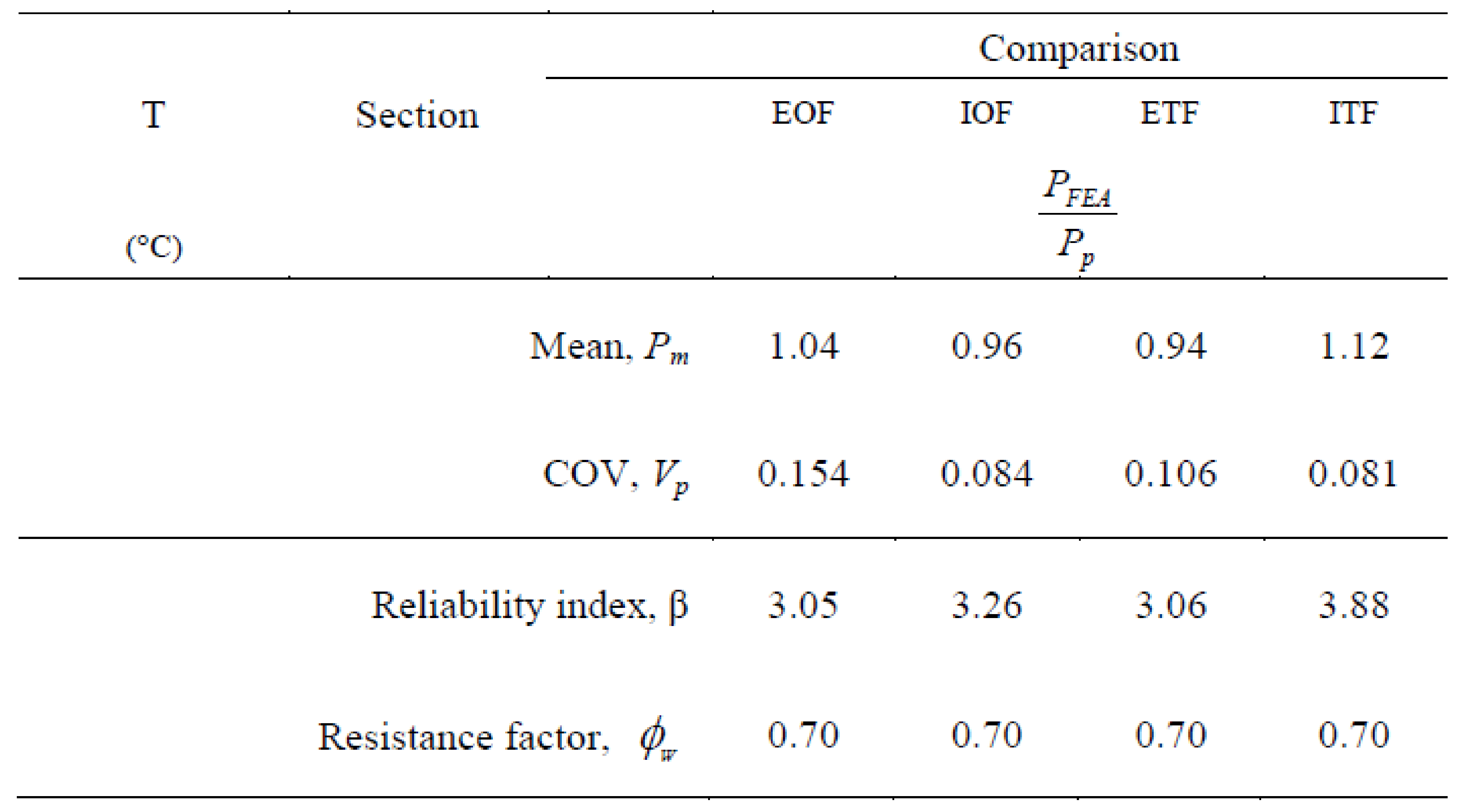
Notes: The above coefficients apply when $h/t \leq 87$, $N/t \leq 100$, $N/h \leq 1.6$, $r_i/t \leq 5.5$ and $\theta = 90°$.

Comparison with proposed design strengths at elevated temperatures



T	Section		Comparison			
			EOF	IOF	ETF	ITF
(°C)			$\frac{P_{FEA}}{P_p}$			
		Mean, P_m	1.13	1.07	1.26	0.98
		COV, V_p	0.071	0.074	0.087	0.084
		Reliability index, β	4.00	3.77	4.32	3.37
		Resistance factor, ϕ_w	0.70	0.70	0.70	0.70

Comparison with proposed design strengths at room temperature



T (°C)	Section		Comparison			
			EOF	IOF	ETF	ITF
			$\frac{P_{FEA}}{P_p}$			
		Mean, P_m	1.04	0.96	0.94	1.12
		COV, V_p	0.154	0.084	0.106	0.081
		Reliability index, β	3.05	3.26	3.06	3.88
		Resistance factor, ϕ_w	0.70	0.70	0.70	0.70

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Conclusions

- Numerical investigation of cold-formed high strength stainless steel square and rectangular hollow sections subjected to web crippling at elevated temperatures has been presented in this paper.
- The appropriateness of the web crippling design rules in the current specifications for cold-formed stainless steel at elevated temperatures has been examined.
- A unified web crippling equation for cold-formed high strength stainless steel tubular sections subjected to web crippling at elevated temperatures has been proposed.

Acknowledgements

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Thank you