ENAC / PROJET DE MASTER 2020-2021
SECTION DE GÉNIE CIVIL

Influence of residual stresses on the buckling capacity of axially loaded steel column

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OBJECTIVES

Conduct measurements of residual stress distributions
- Perform the sectioning method on five different cross-sections
  - HEA160, HEM500, IPE120, IPE200, IPE360

Evaluate how existing codes predict the buckling resistance of steel members
- SIA 263:2013 (Switzerland)
- EN 1993-1-1:2005 (Europe)
- AISC 360-2016 (United States)
- CSA S16:2019 (Canada)
- AIJ LFRD:1985 (Japan)

Evaluate the buckling resistance of steel members through finite element analysis
- Eight different cross-sections
  - HEA160, HEB500, HEM300, HEM500, IPE120, IPE200, IPE360, and IPE400
- Five different critical lengths [normalised slenderness selection $\overline{\lambda}_k$ (0.44; 1.67)]
- Initial imperfection influence
- Residual stress influence
- Assessment of the buckling curves according to the Swiss and European approach

MOTIVATION

Manufacturing processes
- Quality improvements
  - Less impact on the performance of steel elements

Normative revision
- Buckling curves based on rather old studies
  - SIA 263:2013 (Switzerland)
  - EN 1993-1-1:2005 (Europe)

INTRODUCTION TO RESIDUAL STRESSES

Residual stresses as a state of equilibrated stresses along the cross-section
- No change in geometry
- $\sum \sigma_{rt} + \sigma_{rc} = 0$

Residual stress occurs due to the manufacturing process
- Cold lamination / Hot-rolled lamination / Extrusion / Forging / Welding

Residual stress as a function of the temperature
- Profile core temperature / Cooling process / Welding flame temperature

Detection of residual stresses
- Non-destructive methods
  - X-Ray / Neutron diffraction / Magnetic measurements
- Destructive method
  - Sectioning method

EXAMPLE OF FLEXURAL BUCKLING RESISTANCE DESIGN APPROACH

SIA 263:2013 (Switzerland)
- Buckling resistance

$$N_{k,Rd} = \chi_k \cdot f_y \cdot A/\gamma_{M1}$$

- Reduction factor

$$\chi_k = \frac{1}{\phi_k + \sqrt{\phi_k^2 - \overline{\lambda}_k^{\,2}}} \leq 1.$$

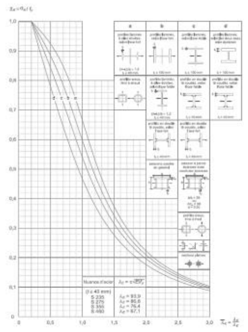
- Slenderness ratio

$$\overline{\lambda}_k = \frac{\lambda_k}{\lambda_E} \qquad \lambda_E = \pi\sqrt{\frac{E}{f_y}} \qquad \lambda_k = L_k\sqrt{\frac{A}{I}}$$

$$\phi_k = 0.5\left[1 + \alpha_k(\overline{\lambda}_k - 0.2) + \overline{\lambda}_k^{\,2}\right]$$

- Imperfection factors

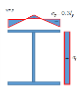
Buckling curve	a	b	c	d
Imperfection factor α_k	0.21	0.34	0.49	0.76



ANALYTICAL DISTRIBUTIONS

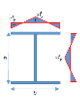
- Linear distributions
  - Galambos and Ketter (1958)

$$\sigma_t = \frac{\sigma_{rc}}{1 + \frac{d \cdot t_w}{b_f \cdot t_f}\left(1 - \frac{2 \cdot t_f}{d}\right)} \text{ and } \sigma_c = 0.3 \cdot f_y$$



  - European Convention for Constructional Steelworks (1985)

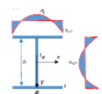
$$if\ \frac{h}{b} \leq 1.2, then\ \alpha = 0.5\ else\ if\ \frac{h}{b} \leq 1.2, then\ \alpha = 0.3$$



- Parabolic distributions
  - Young (1975)

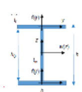
$$\sigma_{c1} = 165\left[1 - \frac{h_0 \cdot t_w}{2.4 \cdot B \cdot t_f}\right] \qquad \sigma_{c2} = 100\left[1.5 + \frac{h_0 \cdot t_w}{2.4 \cdot B \cdot t_f}\right]$$

$$\sigma_t = 100\left[0.7 + \frac{h_0 \cdot t_w}{2.0 \cdot B \cdot t_f}\right]$$



  - Bradford and Trahair (1985)

$$\sigma_f = \sigma_y\left[a_1 + a_2\left(\frac{2 \cdot y}{B}\right)^2\right] \qquad \sigma_w = \sigma_y\left[a_3 + a_4\left(\frac{2 \cdot z}{B}\right)^2 + a_5\left(\frac{2 \cdot z}{B}\right)^2\right]$$



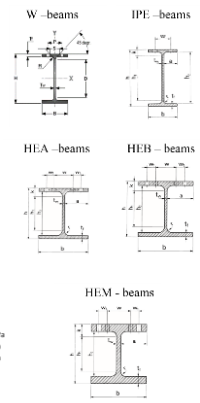
  - Szalay and Papp (2005)

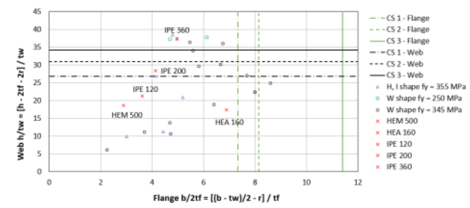
$$f(y) = c_f + a_f \cdot y^2 \qquad w(z) = c_w + a_w \cdot z^2$$

STUDIES ON MESAUREMENTS AND PROFILE SELECTION

Investigations on residual stresses available in the literature
- E. Odar, F. Nishino and L. Tall (1965)
- L. Tall, T. V. Galambos and R.L. Ketter (1964)
- R. Tramblay and C. P. Lamarche (2011)
- A. de Castro e Sousa and D. Lignos (2017)
- R.C. Spoorenberg, H.H. Snijder and J.C.D. Hoendekamp (2009)
- A. W. Huber (1956)
- N. Alpsten (1968)
- Y. Fujita, D. K. Feder and G. C. Lee (1955)

Additional profiles in analysis
- HEA160, HEM500, IPE120, IPE200, and IPE360

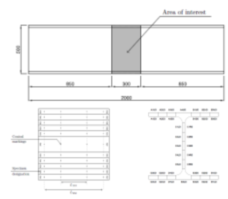




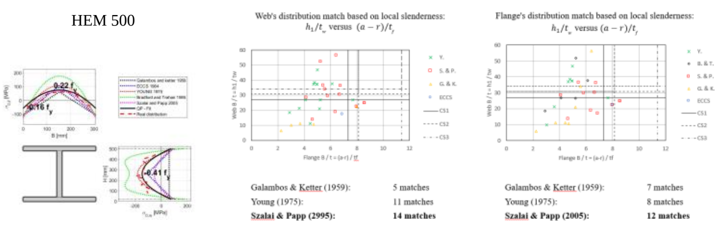
THE SECTIONING METHOD

Rupture of the equilibrium of residual stresses by mechanical process
- Sectioning method

Material relaxation
- Measurement of length's differences
- Reconstruction of the stress state



MESAUREMENTS OF RESIDUAL STRESSES



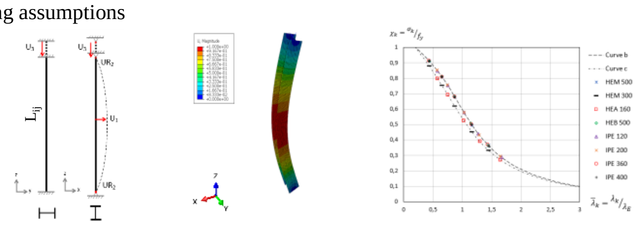
CONTINUUM FINITE ELEMENT ANALYSIS (CFEA)

Model validation test reference
- " Seismically induced cyclic buckling of steel columns including residual-stress and strain-rate effects" , C. P. Lamarche, R. Tremblay, 2011.

Material proprieties reference
- "On the inverse problem of classic nonlinear plasticity model", A. de Castro e Sousa, D. Lignos, 2018.

Generalized imperfection curves reference
- "Stability criteria for tubular-sections steel arches",2019 NTUA Athens PHD Thesis, I. D-Thanasoulas, and C. J. Gantes.

Modelling assumptions



Results
- Design specifications comparison
  - U.S. code (AISC 360-2016) – 27 best matches over 40 analysis
- Imperfection effect on the axial load capacity
  - Resistance reduction up to 10% comparing e=L/1000 and e=L/3000
- Residual stress effect on the axial load capacity
  - For $\overline{\lambda}_k$[0.65; 1.20] – Resistance reduction up to 22%
  - For $\overline{\lambda}_k$ ~ [1.50] – Global instability dominate the failure mode
  - For $\overline{\lambda}_k$ ~ [0.50] – Local buckling occurs
- Generalized imperfection curves
  - Updated imperfection factors - α_b from 0.34 to 0.17 and α_c from 0.49 to 0.20