LIMIT STATE DESIGN OF COLD-FORMED STEEL STRUCTURES

RESEARCH BASES FOR IS: 801

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INTRODUCTION

- **Cold-formed steel members-** fabricated from thin sheets using folding, rolling or press braking operations
- Lighter, economical and offers faster construction than traditional hot rolled members

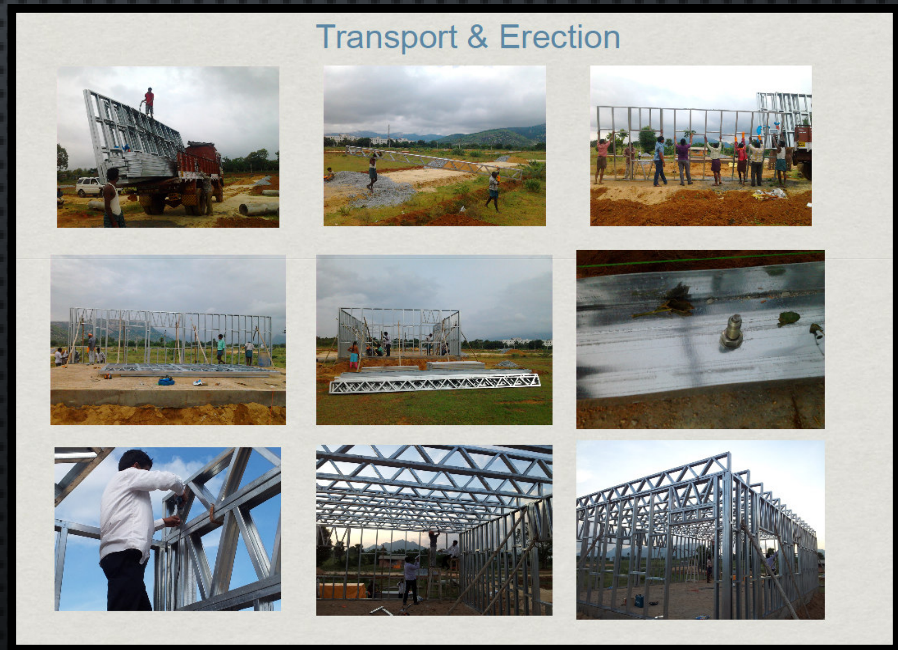


Photo Courtesy: Bharath Tej

Cold formed steel residential building (Chennai)

Cold formed steel house – Andhra Pradesh

Photo Courtesy: Bharath Tej

G+3 Construction at Raigarh

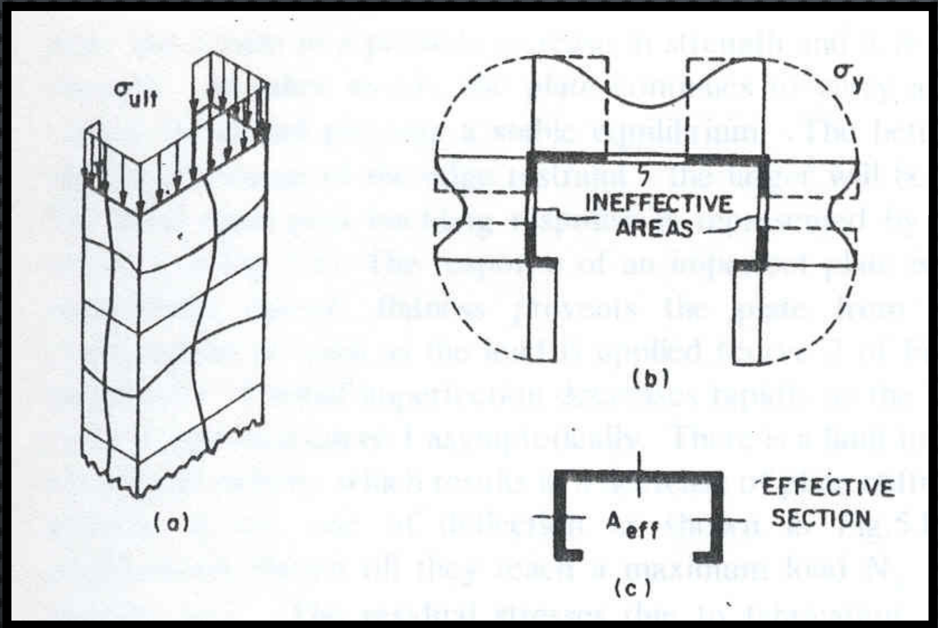
Photo courtesy – JSPL/ JB Infra

WHAT IS THE PRESSING ISSUE IN LGS CONSTRUCTION OF LGS SYSTEMS

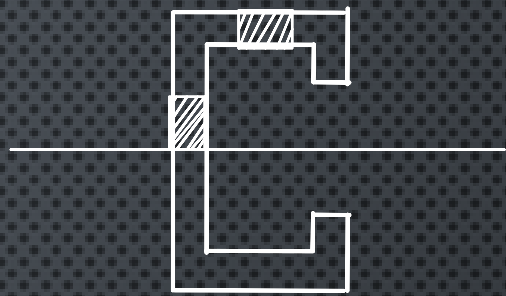
- STRUCTURAL DESIGN
- ENCLOSURE VARIETY
- COMFORT FACTORS IN LGS SYSTEMS
- SERVICES INTEGRATION
- TRAINED MAN POWER
- MINDSET MANAGEMENT
- AFTER SALE SERVICES
- INTEGRATION IN THE SOCIAL AND CULTURAL BACK DROP

CLASSICAL METHOD FOR COLD FORMED STEEL MEMBER DESIGN

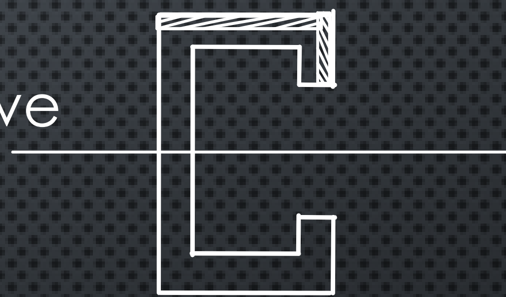
Effective width method



Local buckling-Effective width concept (fy)



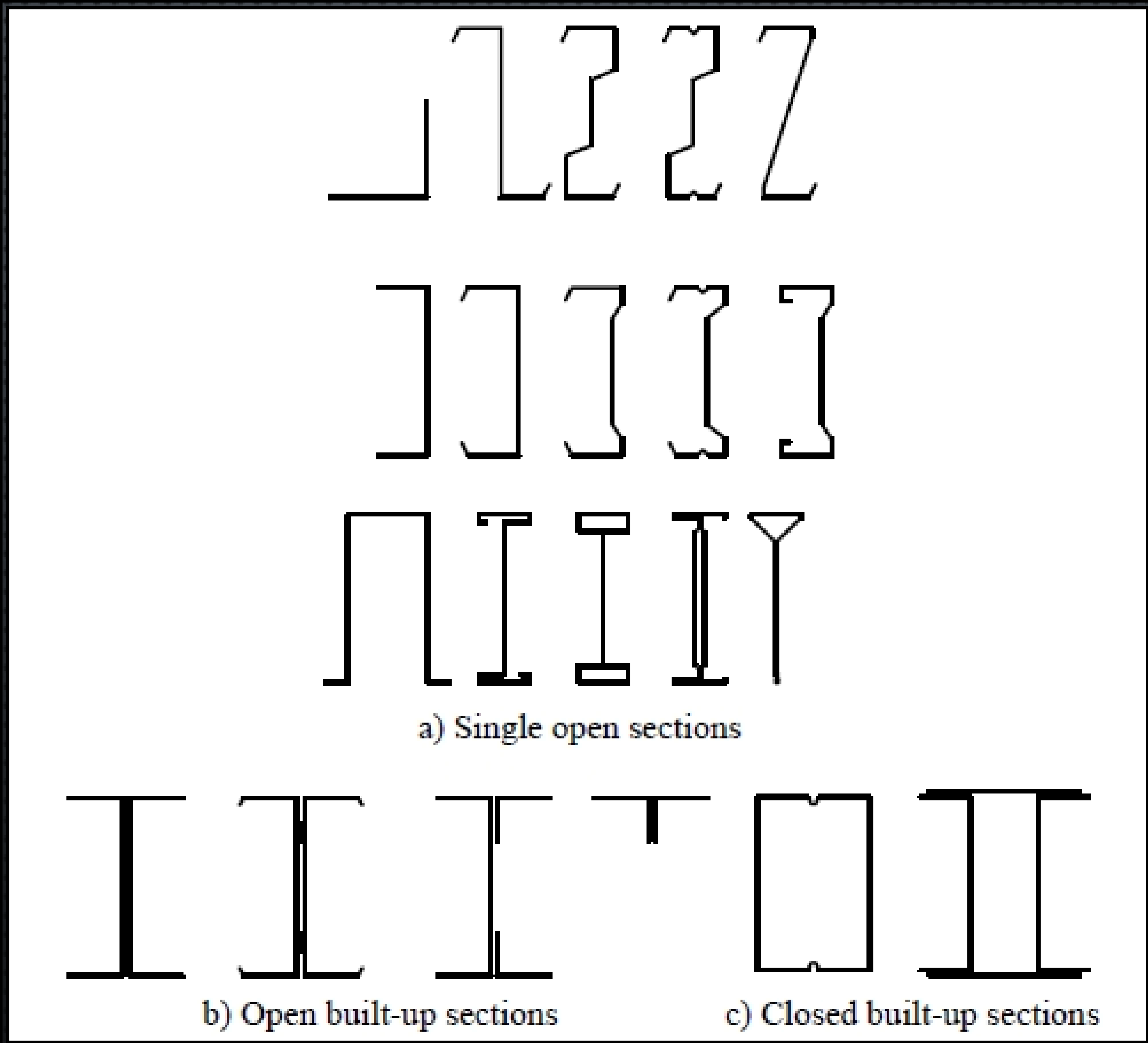
Distortional buckling-Effective thickness concept(fy)



- Reduction in width of cross sectional area to account for buckling effects
- Basically an analytical approach
- Involves lengthy calculations

Global buckling-Designed based on flexural torsional buckling equation by considering the interaction of major, minor and torsional buckling modes

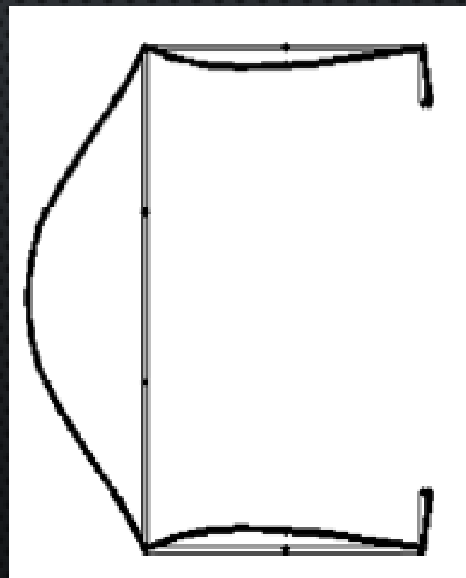
ARRAY OF COLD FORMED STEEL SECTIONS !



LOCAL BUCKLING

- Typical for a cross section rather than the whole length of the member
- Edges between the plate elements rotates without translation
- Strong post buckling reserve and occurs at short half-wavelengths

$$\tau_{cr} = \frac{k\pi^2 E}{12(1-\nu^2)\left(\frac{b}{t}\right)^2}$$

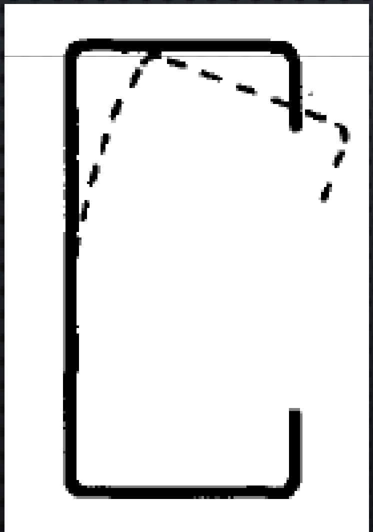


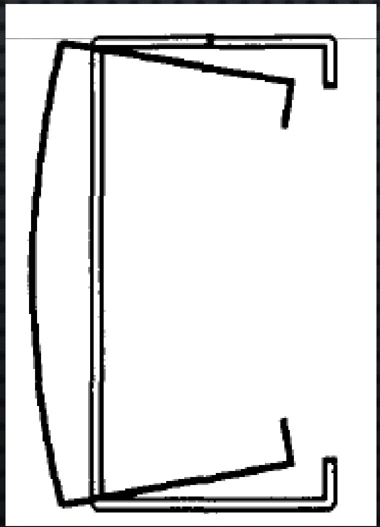
DISTORTIONAL BUCKLING

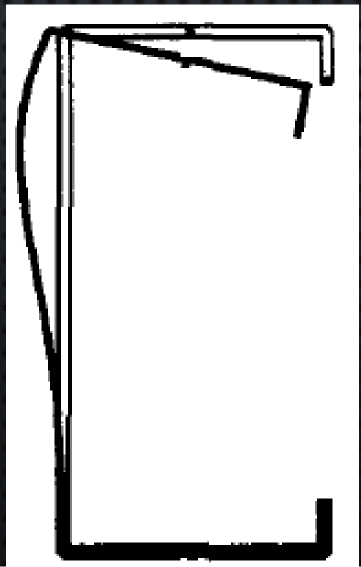
- Rotation of the flanges about the flange /web junction and lateral bending of the section

- Depends on the ratio of width of flange to depth of web

- Involves distortion of the flanges also







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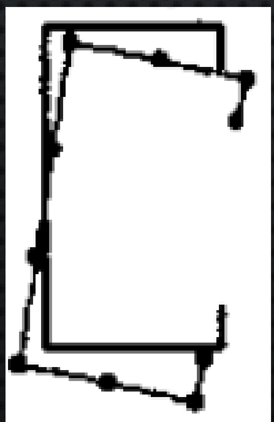
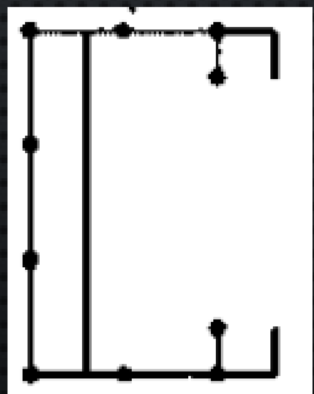
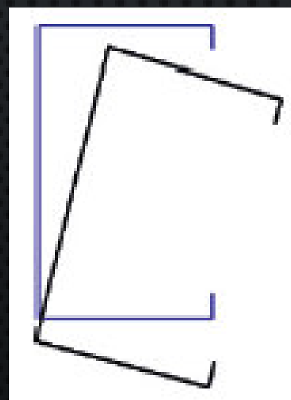
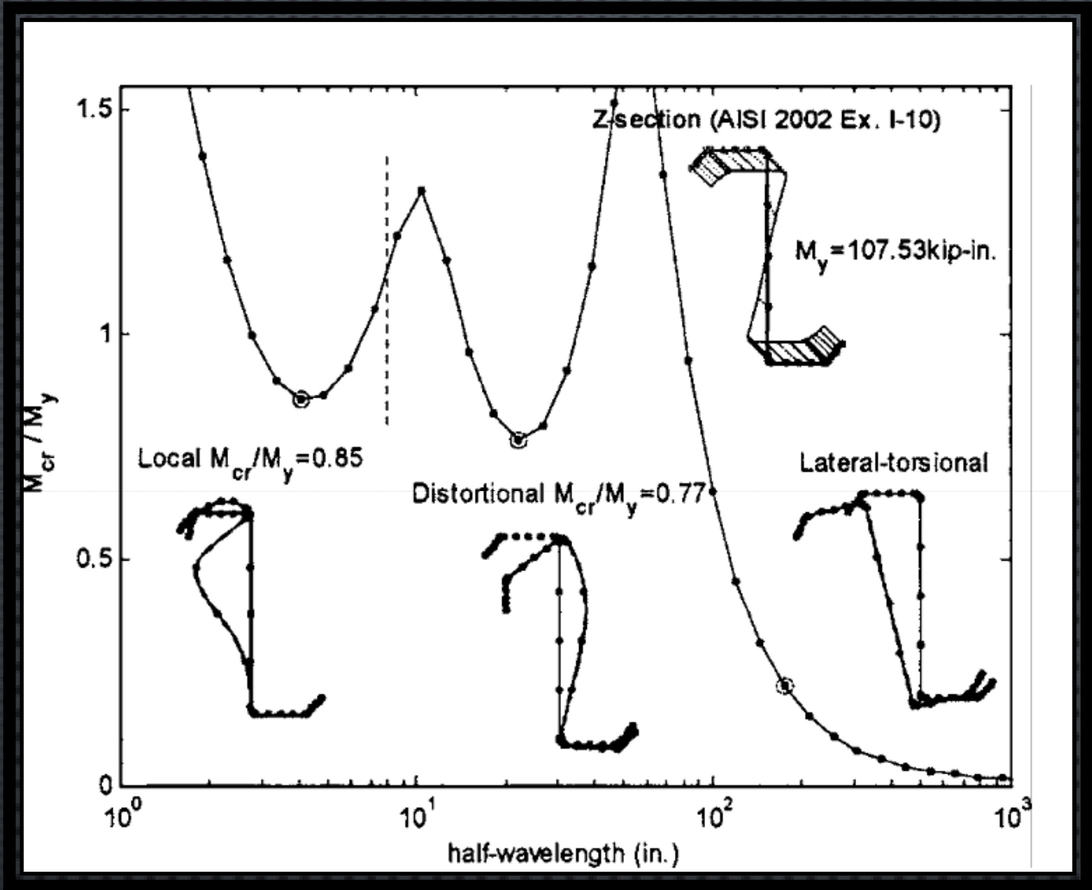
LATERAL-TORSIONAL (GLOBAL) BUCKLING

- Member translates laterally as well as the section rotates
- Occurs at longer half-wavelengths and has very little postbuckling reserve
- Observable in open sections in which the ratio of moment of inertia with respect to major and minor axis is high









Direct Strength Method of Design (DSM)

(introduced by Pekoz and Schafer)

Signature Curve of a lipped Z section

- The main instabilities of cold formed steel beams are
  - Local buckling
  - Distortional buckling
  - Lateral-Torsional buckling

Direct Strength Method of Design (DSM)

- Reduction in effective stress to account for buckling effects
- Requires elastic buckling solution
- Expressions are empirical in nature

Lateral-torsional buckling

$For\ M_{cre} < 0.56M_y \qquad M_{ne} = M_{cre}$

$For\ 2.78M_y \geq M_{cre} \geq 0.56M_y \qquad M_{ne} = \frac{10}{9}M_y\left(1 - \frac{10M_y}{36M_{cre}}\right)$

$For\ M_{cre} > 2.78M_y \qquad M_{ne} = M_y$

Local buckling

$For\ \lambda_l \leq 0.776 \qquad M_{nl} = M_{ne}$

$For\ \lambda_l > 0.776 \qquad M_{nl} = \left(1 - 0.15\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4}\right)\left(\frac{M_{crl}}{M_{ne}}\right)^{0.4} M_{ne}$

$where\ \lambda_l = \sqrt{M_{ne}/M_{crl}}$

Distortional buckling

$For\ \lambda_d \leq 0.673 \qquad M_{nd} = M_y$

$For\ \lambda_d > 0.673 \qquad M_{nd} = \left(1 - 0.22\left(\frac{M_{crd}}{M_y}\right)^{0.5}\right)\left(\frac{M_{crd}}{M_y}\right)^{0.5} M_y$

$where\ \lambda_d = \sqrt{M_y/M_{crd}}$

M_y- Moment corresponding to yield stress

M_{cre}, M_{crl}, M_{crd}- Critical global, local, and distortional buckling moments

Elastic buckling solution can be arrived using

- finite element method
- finite strip method
- Spline finite strip method
- Analytical expressions

Proposed chapter wise layout for IS:801

IS:801 (Revised Code Draft (Chapter-wise Layout)	IS:800 -2007 (Chapter-wise Layout)
SECTION 1 General	SECTION 1 General
SECTION 2 Materials	SECTION 2 Materials
SECTION 3 General Design Requirements	SECTION 3 General Design Requirements
SECTION 4 Element Design (Moved to Appendix)	
SECTION 5 Limit State Design	SECTION 5 Limit State Design
SECTION 6 Design of Tension members	SECTION 6 Design of Tension members
SECTION 7 Design of Compression members(DSM)	SECTION 7 Design of Compression members
SECTION 8 Design of members subjected to bending(DSM)	SECTION 8 Design of members subjected to bending
SECTION 9 Members subjected to combined forces	SECTION 9 Members subjected to combined forces
SECTION 10 Connections	SECTION 10 Connections
SECTION 11 Direct Strength Method of Design	
SECTION 12 Design Assisted by Testing	SECTION 14 Design Assisted by Testing
SECTION 13 Durability	SECTION 1 Durability5
SECTION 14 Fire Resistance	SECTION 16 Fire Resistance
Appendices	

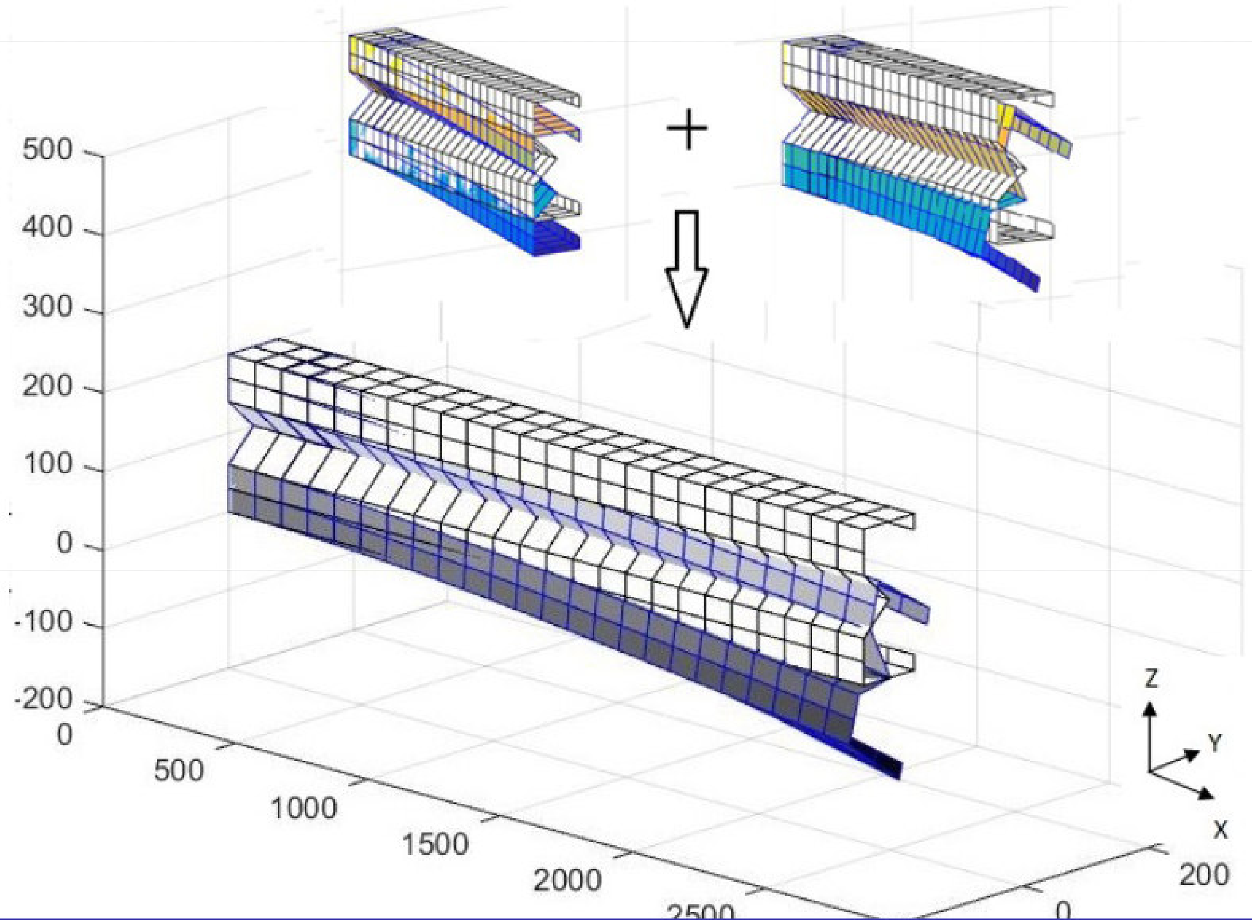
Generalized Beam Theory(GBT) principles

Base papers for generalized beam theories

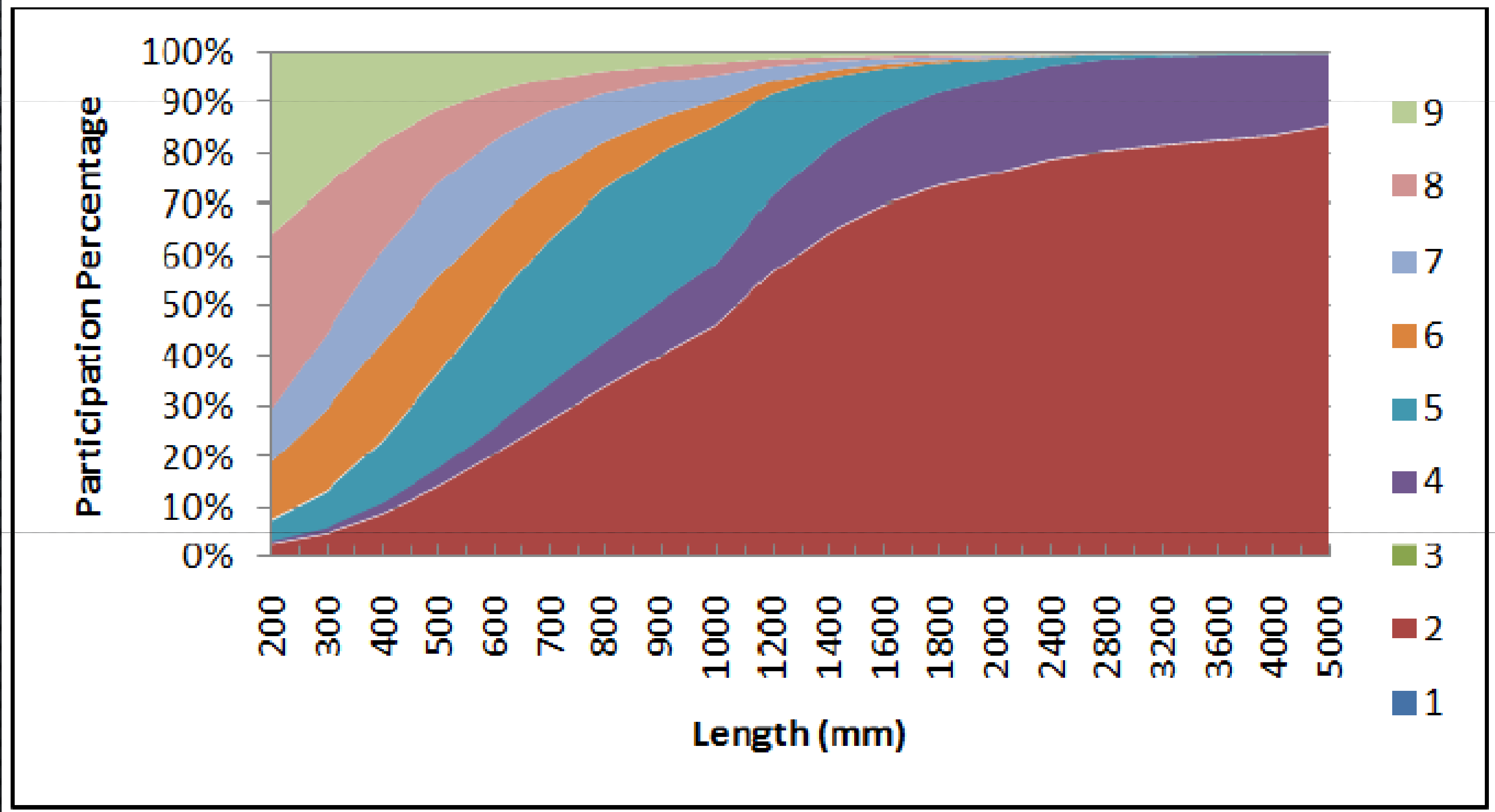
- Rakhi, J., and Jayachandran, S. A. (2014). "Determination of rigid and distortional mode shapes using Generalized Beam Theory for cold-formed steel sections." Proc., 10th Structural Engineering Convention, IIT Delhi.
- Rakhi, J., and Jayachandran, S. A. (2015)."Linear Behaviour of thin walled open sections using GBT" Proc., International conference on Civil, Structures and Transportation Engineering (ICCSTE), University of Ottawa, Canada

Typical results produced by Rakhi Jain

Deformed Cantilever



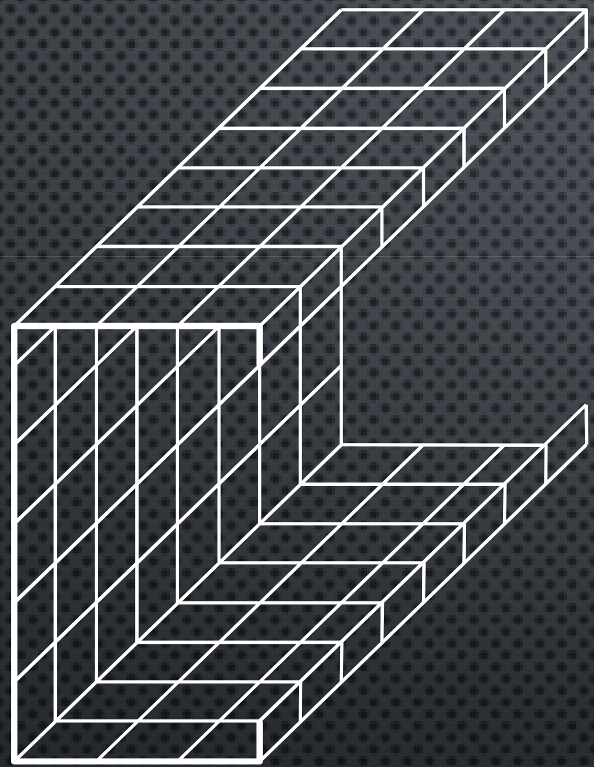
Mode participation using generalized beam theories

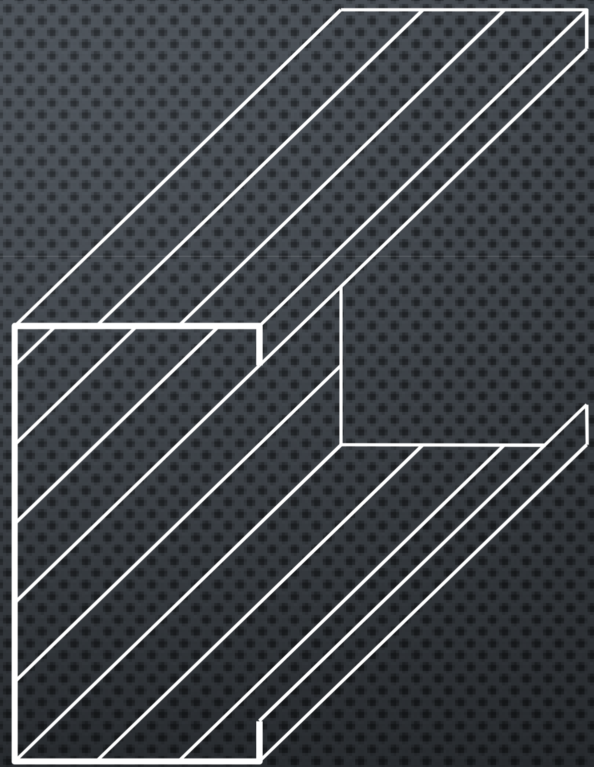


Base papers for cross sectional evaluation

Ajeesh, SS and Arul Jayachandran, S., Simplified semi-analytical model for elastic distortional buckling prediction of cold-formed steel flexural members, *Thin-walled Structures*, Vol. 106 (9), pp. 420-427, 2016.

Ajeesh,SS. and Arul Jayachandran, S., A constrained spline finite strip method for the mode decomposition of cold-formed steel sections using GBT principles, *Thin-walled Structures* (Tentatively accepted).


finite element


finite strip

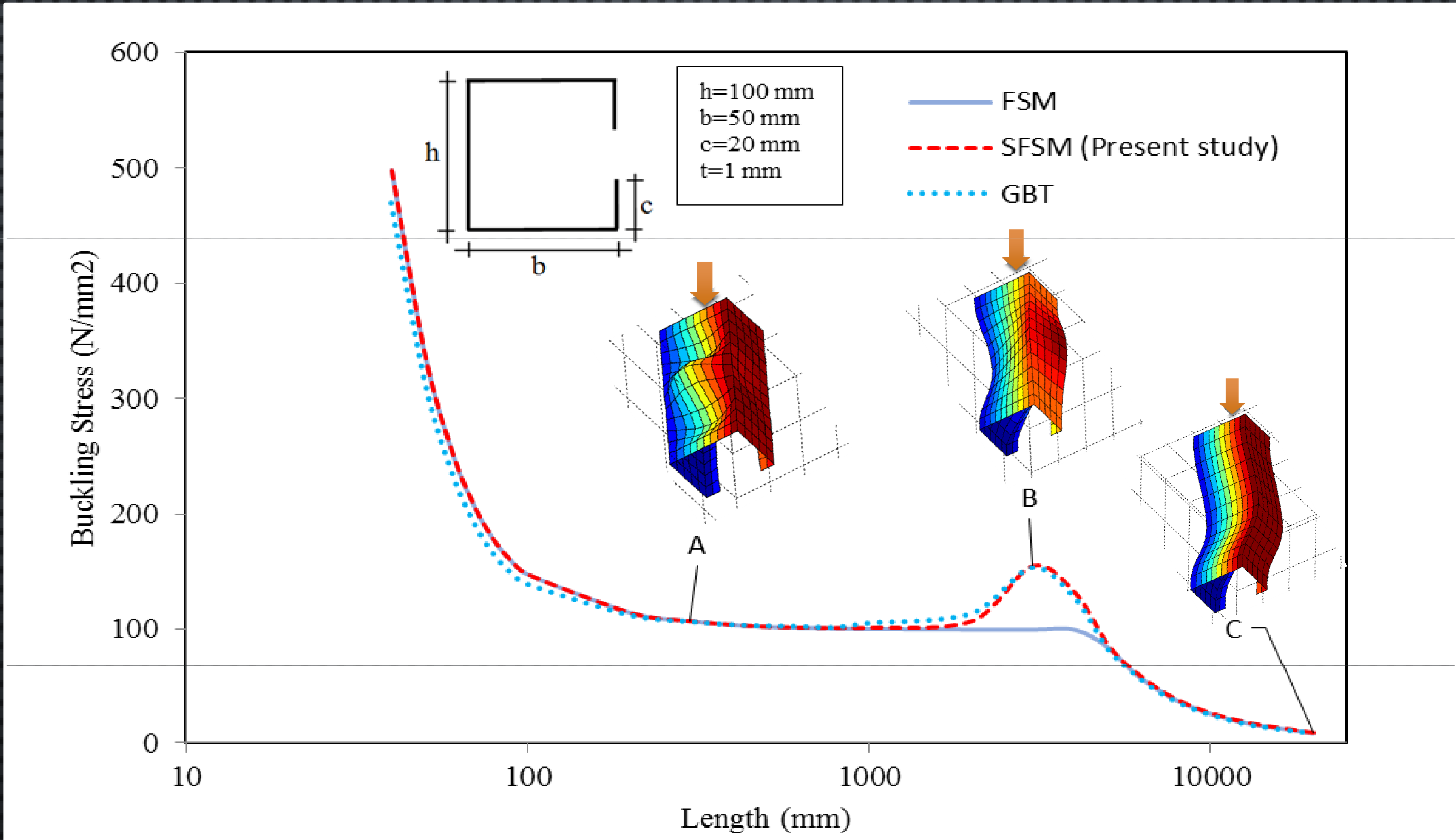
Numerical Evaluation of Cold formed steel members

SPLINE FINITE STRIP ANALYSIS OF COLD-FORMED STEEL MEMBERS

CUFSM (John Hopkins, USA)
THINWALLED (Univ of Sydney)
GBTUL (Unif of Lisbon)
TWLIGHT-IITM (IITM)

Contributors:
Dr.Aravind – 1987-FSM
Dr.Madasamy-1991-SFSM
Ajeesh -2016 -cSFSM

Buckling analysis of lipped channel column with fixed ends

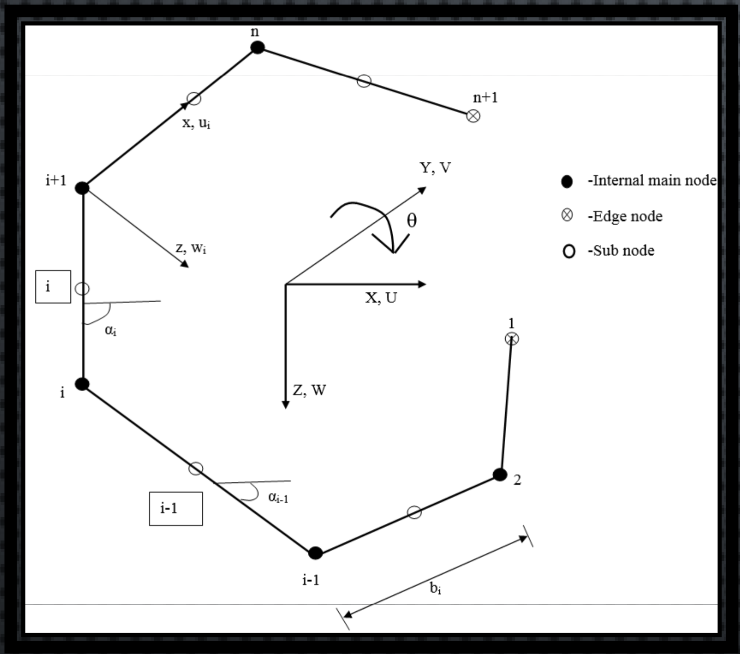


Comparison of SFSM results with FSM and GBT

Decomposition of buckling modes in SFSM using Generalized Beam Theory(GBT) principles

DEVELOPMENT OF RESTRAINT MATRIX FOR MODE DECOMPOSITION

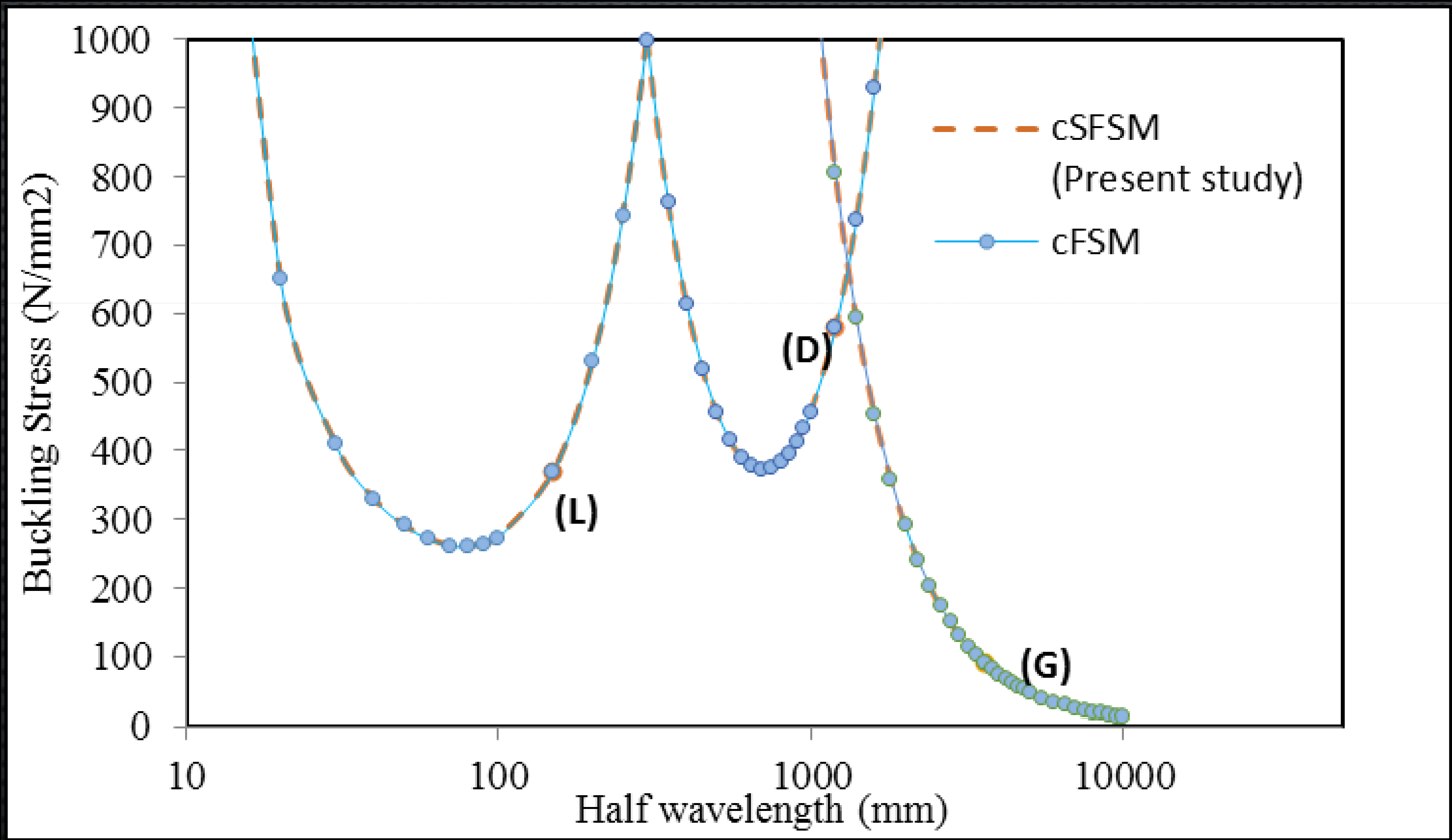
The restraint matrices for local ,distortional and global buckling is evaluated using GBT principles



General cross section with nodes location and coordinate axes

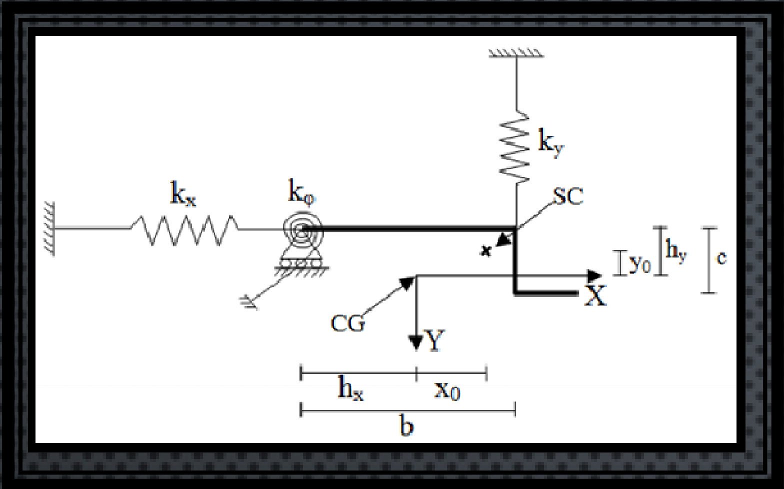
GBT basic assumptions

- Based on Vlasov's hypothesis, ie in-plane shear strain and transverse strain has to be zero
- The warping displacement (v) has to be linear in x direction between two main nodes
- The longitudinal warping displacement is not constantly equal to zero along the whole length for entire cross section
- The cross section is in transverse equilibrium.



BUCKLING MODES FOR LIPPED ZED SECTION WITH SIMPLY SUPPORTED (S-S) END CONDITION

SIMPLIFIED EXPRESSION FOR ELASTIC DISTORTIONAL BUCKLING



Critical buckling load

$$P_{cr} = \frac{\alpha_3 \pm \sqrt{\alpha_3^2 - 4\alpha_1\alpha_4}}{2\alpha_1}$$

$$\alpha_1 = -\frac{(I_x + I_y)}{A} - h_x^2$$

$$\alpha_2 = I_w + I_x(x_0 - h_x)^2 + \frac{GJ}{\eta E} + \frac{K}{\eta^2 E}$$

$$\alpha_3 = \eta E\left[2y_0 I_{xy}(x_0 - h_x) - \alpha_2 + I_y(\alpha_1 - y_0^2)\right]$$

$$\alpha_4 = \eta^2 E^2\left[I_{xy}^2(x_0 - h_x)^2 - I_y\alpha_2\right]$$

$$\eta = \left(\frac{\pi}{\lambda_{cr}}\right)^2$$

Critical half buckling wave length

$$\lambda_{cr} = \pi\left(\frac{EI_{wc}}{k_y b^2 + k_\phi}\right)^{0.25}$$

Total restraint

$$K = k_y b^2 + k_\phi$$

$$For\ 4\left(\frac{b}{h}\right)^{1.6} < 1 \qquad k_\phi = \frac{16D}{h}\left(\frac{b}{h}\right)^{1.6}$$

$$For\ 4\left(\frac{b}{h}\right)^{1.6} \geq 1 \qquad k_\phi = \frac{4D}{h}$$

$$For\ 4\left(\frac{c'}{h}\right)^{5} < 1 \qquad k_y = \frac{4D}{b^3}\left(\frac{c'}{h}\right)^{5}$$

$$For\ 4\left(\frac{c'}{h}\right)^{5} \geq 1 \qquad k_y = \frac{D}{b^3}$$

WORK BY AJEESH ON DISTORTIONAL BUCKLING

Methods for elastic distortional buckling of flexural members	Codes of practice		
	AS/NZ 4600 (2005)	AISI S100 (NAS-2007)	IS-801 (Proposed)
Analytical/semi-analytical expression	✓ Hancock model	✓ Schafer model	✓ Ajeesh Model?? (Ajeesh and Arul TWS 2016)
Classical/spline finite strip method	✓	✓	✓
Decomposition of buckling modes in SFSM	✗	✗	✓ (Ajeesh and Arul TWS 2016) Completed
Mode identification in SFSM	✗	✗	✓ (Completed)

IS-801 design information for distortional buckling in flexure is completed

Base papers for design of tension members

Prabha, P., Arul Jayachandran, S., Saravanan, M. and Marimuthu, V., Prediction of the tensile capacity of cold-formed angles experiencing shear lag, *Thin-walled Structures*, Vol. 49 (11), pp. 1348-1358, 2011.

Ram Arkala., Development of background material for the revision of cold-formed structural steel code IS: 801-1975, *MTech Thesis-Guided by* ***S.Arul Jayachandran***, IIT Madras, 2013.

Provision for the design of tension members

$$T_{dn} = 0.9\, A_{nc} f_u / \gamma_{m1} + \beta A_{go} f_y / \gamma_{m0} \qquad (1)$$

$$\beta = 0.697 - 0.0045 (w/t)\, (bs/Lc)\, (fy/fu) \quad \beta \geq 0.4 \qquad (2)$$

Base papers for design of Compression members

Anil Kumar, MV. and Kalyanaraman, V., Evaluation of Direct Strength Method for CFS Compression Members without Stiffeners, *J of Structural Engineering (ASCE)*, Vol.136 (7), pp. 879-885, 2010.

Anil Kumar, MV. and Kalyanaraman, V., Design Strength of Locally Buckling Stub-Lipped Channel Columns, *Journal of Structural Engineering (ASCE)*, Vol. 138 (11), pp. 1291-1299, 2012.

Anil Kumar, MV and Kalyanaraman, V., Distortional Buckling of CFS Stiffened Lipped Channel Compression Members, *Journal of Structural Engineering (ASCE)*, Vol. 140 (12), pp. 04014099-14, 2014.

Anil Kumar M.V. ,Interaction of local, distortional and overall buckling in cold-formed steel lipped channel compression members *PhD Thesis, Guided by* ***Prof.V.Kalyanaraman,*** IIT Madras, Chennai, India.(2012)

Provision for the design of Compression members

$$P_{ucd} = \chi_u A_g f_y$$

$$\chi_u = 0.16 + 0.87(\chi_{ue}\chi_{ul}\chi_{ud}) \geq min\ (\chi_{ue}, \chi_{ul}, \chi_{ud})$$

$$\chi_{ue} = \frac{1}{\phi + \left(\varphi^2 - \lambda_e^2\right)^{0.5}}$$

$$\phi = 0.5\left[1 + \alpha_e(\lambda_e - 0.2) + \lambda_e^2\right]$$

$$\chi_{ul} = \begin{vmatrix} 1 & for \quad \lambda_l \leq 0.6 \\ \left(1 - \frac{\alpha_1}{\lambda_l^{\beta}}\right)\left(\frac{1}{\lambda_1^{\beta}}\right) \leq \chi_{ul,\max} & for \quad \lambda_l > 0.6 \end{vmatrix} \qquad where,\ \lambda_l = \sqrt{\frac{P_y}{P_{crl}}}$$

$$\chi_{ud} = \begin{vmatrix} 1 & for \quad \lambda_d \leq 0.584 \\ \left(1 - \frac{0.23}{\lambda_d^{0.6}}\right)\left(\frac{1}{\lambda_d^{0.6}}\right) & for \quad \lambda_d > 0.584 \end{vmatrix} \qquad where,\ \lambda_d = \sqrt{\frac{P_y}{P_{crd}}}$$

Base papers for design of flexural members

Nandini, P. and Kalyanaraman, V., Strength of cold-formed lipped channel beams under interaction of local, distortional and lateral torsional buckling, *Thin-walled Structures*, Vol. 48 (10-11), pp. 872-877, 2010.

Nandini P. Interaction of local and distortional buckling with lateral torsional buckling in cold-formed lipped channel beams, MS Thesis, Guide: **Prof. V.Kalyanaraman**, IIT Madras, Chennai, India.

$$M_{ndl} = \left(1\text{-}0.15\left(\frac{M_{crl}}{M_{nd}}\right)^{0.4}\right)\left(\frac{M_{crl}}{M_{nd}}\right)^{0.4} M_{nd} \leq M_{nd}$$

$$M_{nld} = \left(1\text{-}0.22\left(\frac{M_{crd}}{M_{nl}}\right)^{0.5}\right)\left(\frac{M_{crd}}{M_{nl}}\right)^{0.5} M_{nl} \leq M_{nl}$$

$$M_{nldo} = \chi_{LT} M_{ld}$$

Base papers for design of beam-column design

Vijaya Vengadesh Kumar, J., Buckling Behaviour of Cold-formed Steel Rack Uprights, *Ph.D. Thesis-Guided by* ***S.Arul Jayachandran***, IIT Madras, 2016.

Vijaya Vengadesh Kumar, J. and Arul Jayachandran, S., Experimental investigation and evaluation of Direct Strength Method on beam-column behavior of uprights, *Thin-walled Structures*, Vol. 102 (5), pp. 165-179, 2016.

Method 1: Linear Interaction equation

$$\frac{P}{\phi_c P_n} + \frac{C_{m1} M_1}{\phi_b \alpha_1 M_{1n}} + \frac{C_{m2} M_2}{\phi_b \alpha_2 M_{2n}} \leq 1$$

P, M_1, M_2 - required strength

P_n, M_{1n}, M_{2n} – nominal strength

Method 2: Non Linear Interaction equation

$$\frac{\beta_r}{\beta_n} < 1$$

$\beta_r = \sqrt{x^2 + y^2 + z^2}$ – normalized required strength.

Where, $x = \frac{C_{m1} M_{1e}}{\alpha_1 M_{1y}}$; $y = \frac{C_{m2} M_{2e}}{\alpha_2 M_{2y}}$; $z = \frac{P}{P_y}$

β_n – normalized nominal strength calculated using CUFSM

THANK YOU