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Buckling Capacity of Pretwisted Steel Columns: Experiments and Finite Element Simulation

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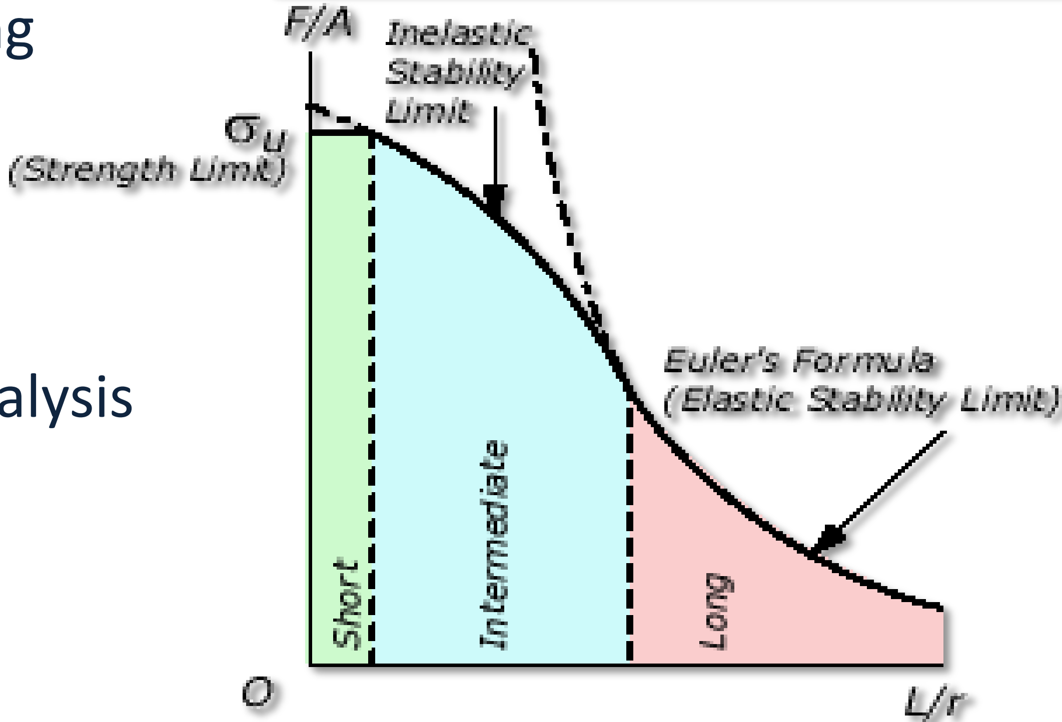
Outline

- Introduction and Background
- Previous Studies
- Elastic Buckling Analysis using Perturbation Analysis
- Experimental Tests
- Nonlinear Finite Element Analysis
- Remarks and Conclusions



Introduction and Background

Pretwisting

- ✓ Steel structures are increasingly used in constructions as they proved to be more user- and environmental-friendly.
- ✓ Columns usually buckle along the plane of least resistance. However, the column resistance varies at each point along its centroidal axis when its section is permanently pretwisted.
- ✓ During buckling, the deformed configuration of the pre-twisted column is no longer perpendicular to the axis of least resistance. This will result into nonlinear differential equations, which describe the equilibrium of the member, whose solution is not simple.

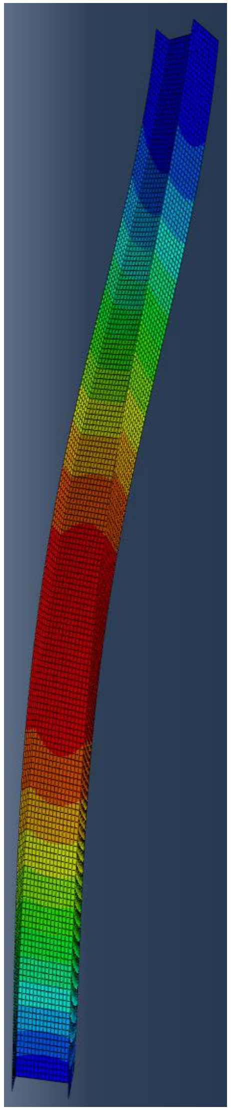
Introduction and Background

- <u>Effect of Pretwisting</u>

  - Inducing a natural pretwist along the length of a column section makes the column have a different resistance at every point along its centroidal axis.

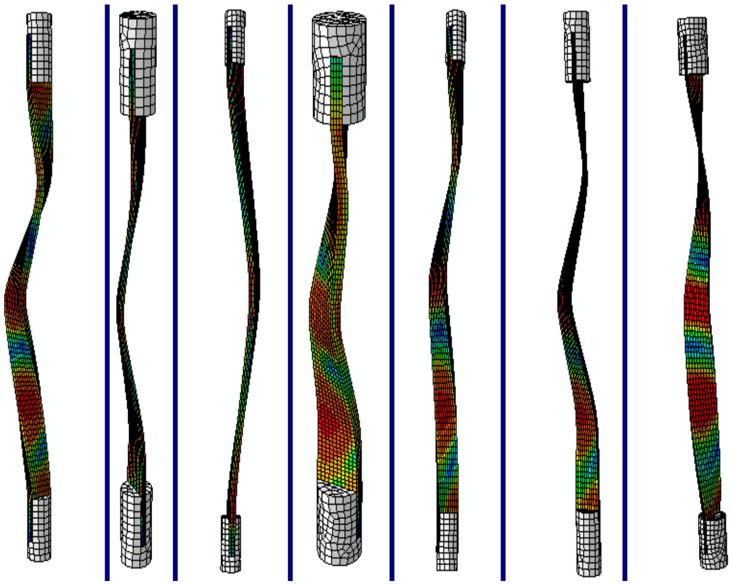
  - Transition between the two flexural planes (minor and major) varying the direction of weak resistance at every point along the column's length.

  - This research work aims at throwing the light on the potential improvement in the buckling capacity of pre-twisted UC-section steel columns.



Previous Studies

- Insufficient theoretical and experimental works were found in the literature on the study of buckling of pre-twisted members. Mainly, analytical studies to derive exact solution and model the stability and static performance of pretwisted rods and beams.
- Recent experimental and numerical studies by Abed and his co-workers to investigate the buckling capacity of pretwisted bars.



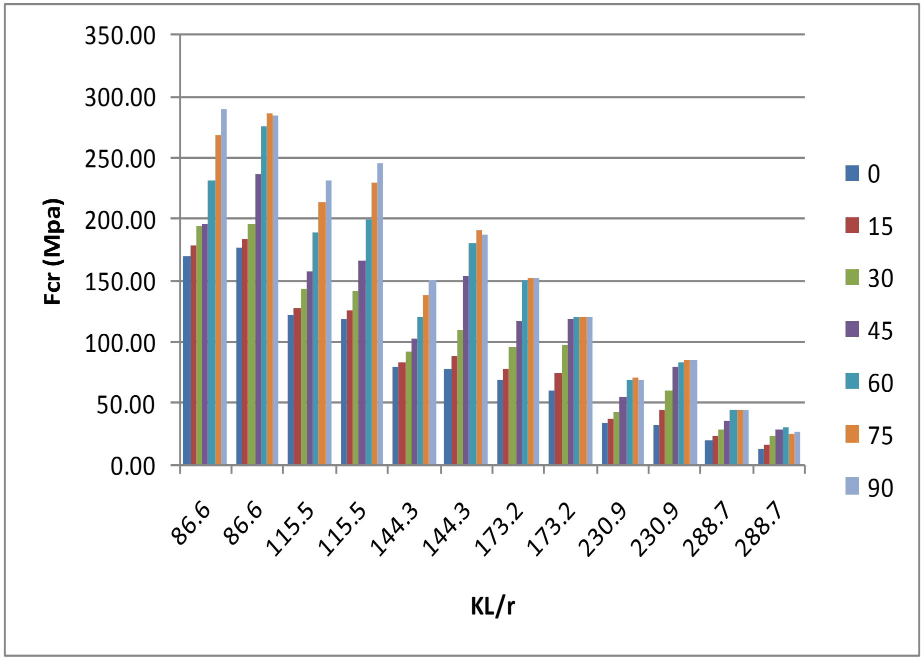
Abed et al. (2012)

Barakat and Abed (2010)

Previous Studies

- Buckling strength ratio and the critical stress sharply increase as the angle of twist increase up to 90 degrees for lower slenderness ratio (KL/r ≤ 144)

- A model that predicts the buckling behavior of pretwisted bars was developed within range up to 90° .



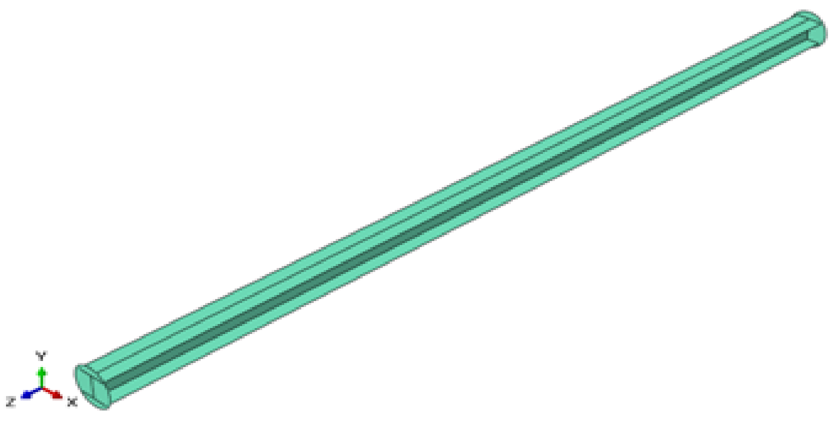
$$P_{cr}^{\text{Pretwisted}} = \left(1 + \frac{\phi_p}{360}\right)^4 P_o \quad \text{when} \quad \frac{KL}{r} > 4.71\sqrt{\frac{E}{F_y}}$$

$$P_{cr}^{\text{Pretwisted}} = \left(1 + \frac{\phi_p}{360}\right)^{2.2} P_o \quad \text{when} \quad \frac{KL}{r} \leq 4.71\sqrt{\frac{E}{F_y}}$$

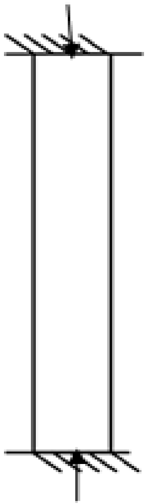
Abed et al. (2012)

Elastic Buckling Analysis using Perturbation Analysis

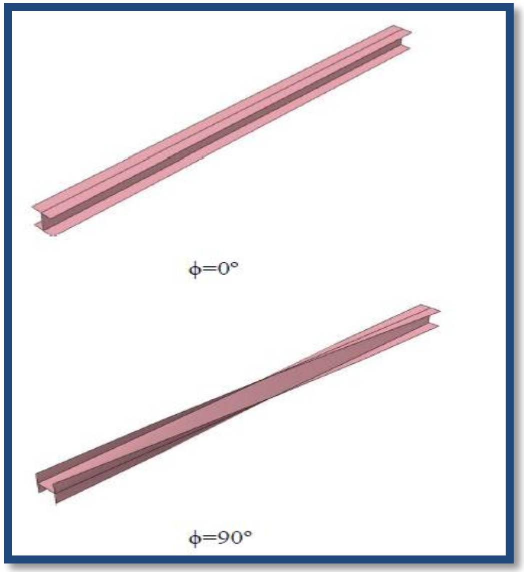
Linear Finite element analysis

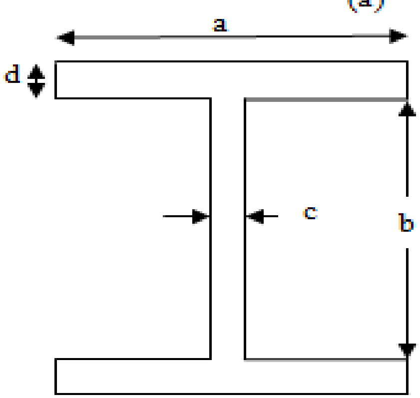


(a)



(b)





(c)

Section Name	a (mm)	b (mm)	c (mm)	d (mm)
UC100×100×17	100	84	6	8
UC152×152×30	152.9	138.8	6.5	9
UC150×100×21	100	130	6	9

(d)

A range of pretwisted angles between 0 and 180 was investigated for each section

Elastic Buckling Analysis using Perturbation Analysis

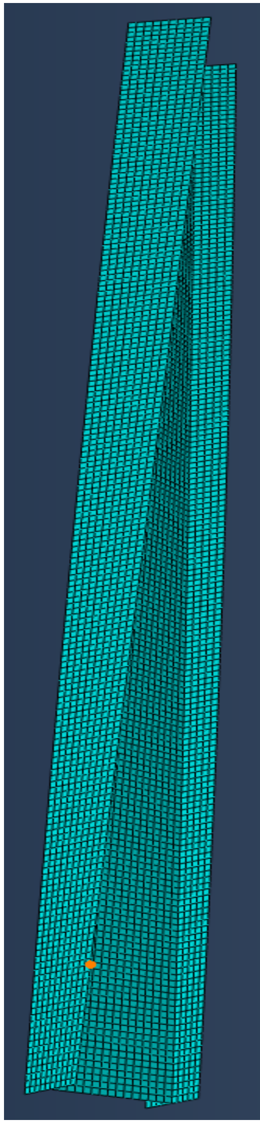
Linear Perturbation Analysis

- Buckling of pretwisted columns is solved numerically using linear perturbation analysis technique that is already implemented in the finite element software ABAQUS.
- The linear perturbation analysis step is created such that the response can only be linear, estimating elastic buckling by the use of Eigen value extraction.
- The key point in an Eigen value problem is making the model stiffness matrix singular, an incremental load pattern, whose magnitude is not of great importance, will be scaled by the load multipliers λ_i such that the Eigen value problem can be defined by the following equation:

$$(K_0^{NM} + \lambda_i K_\Delta^{NM}) u_i^M = 0$$

where u^M is the displacement vector $and\ K_\Delta^{NM}$ is the tangent stiffness matrix that is related the differential loading pattern while K_0^{NM} corresponds to the initial loading condition.

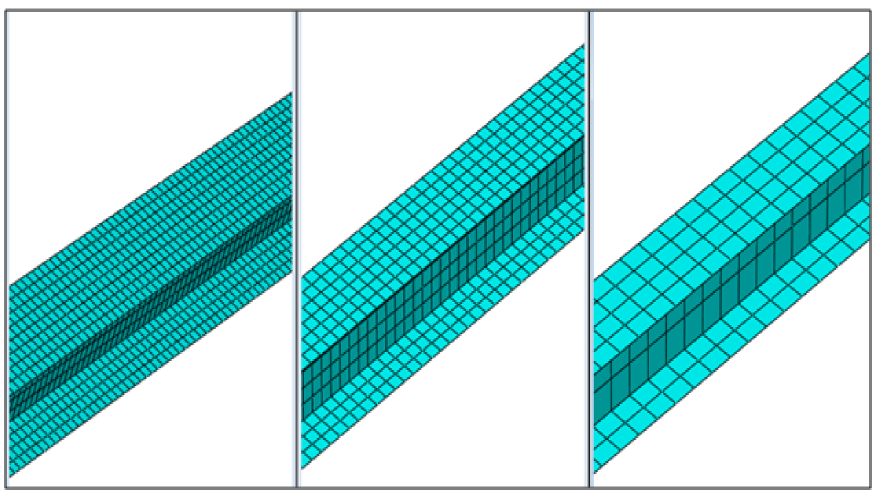
The superscripts M and N are the degrees of freedom for the whole system while the subscript *i* denotes the i^{th} buckling mode.



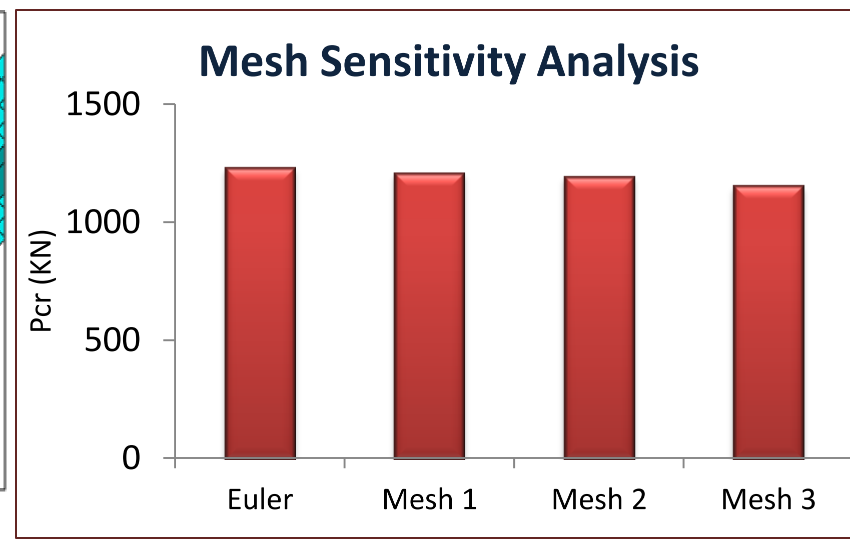
Elastic Buckling Analysis using Perturbation Analysis

Mesh Sensitivity Analysis

- 4-node 3D shell elements of S4R ABAQUS type were utilized
- Different Mesh configurations were checked to select a proper element size to obtain the desired level of accuracy with the least computational time.



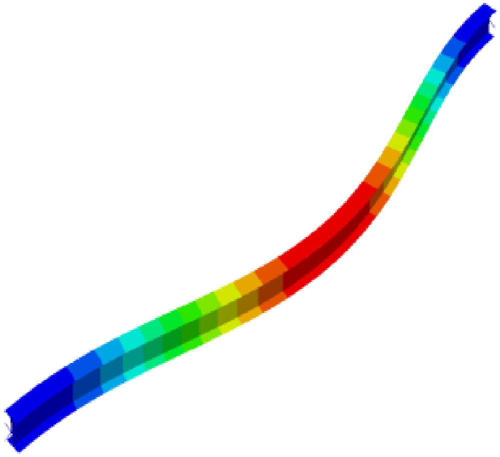
Mesh1 Mesh2 Mesh3

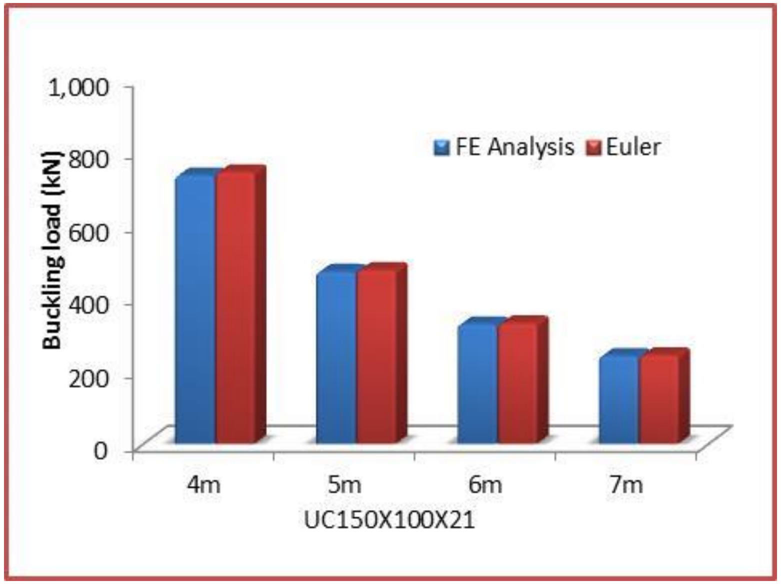


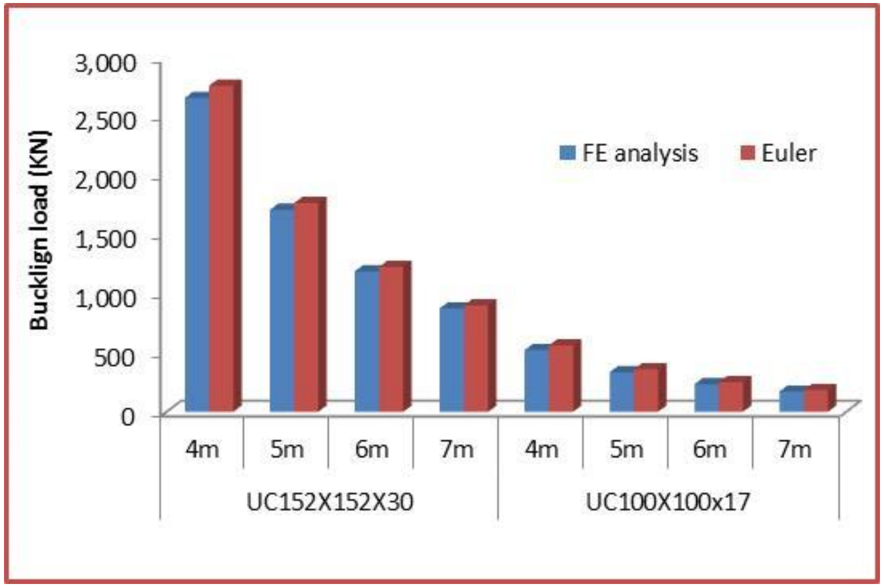
Elastic Buckling Analysis using Perturbation Analysis

Model Verification

- FE results for straight (untwisted) columns were verified against Euler Buckling Equation



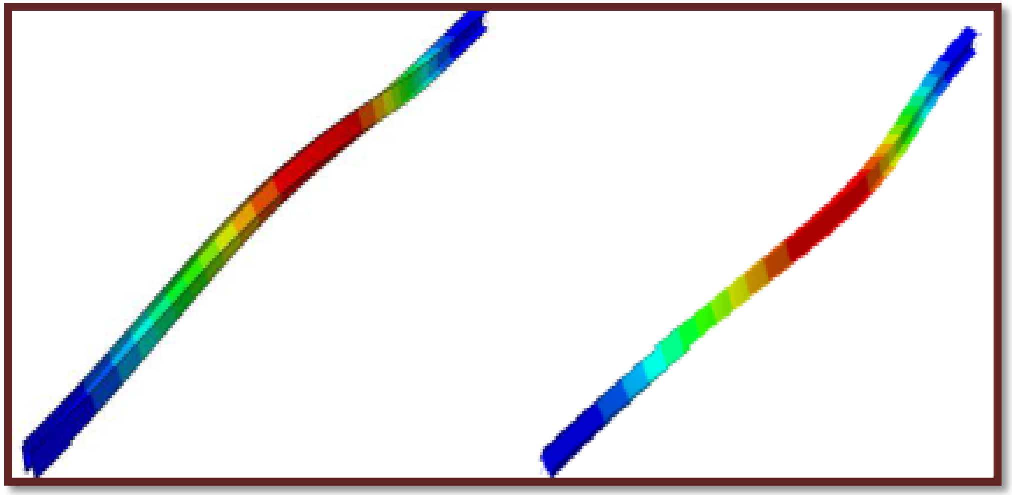


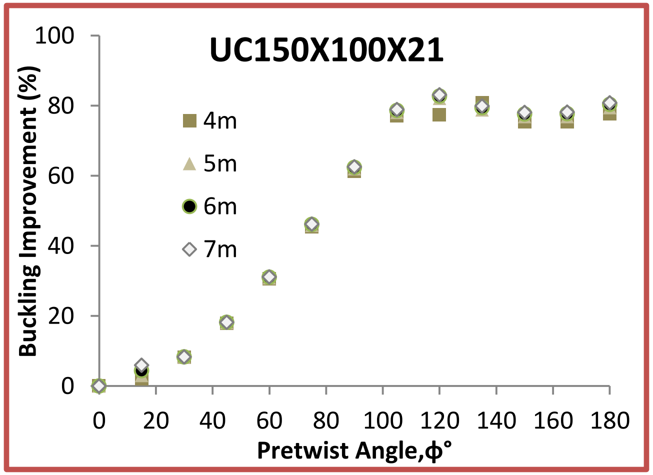


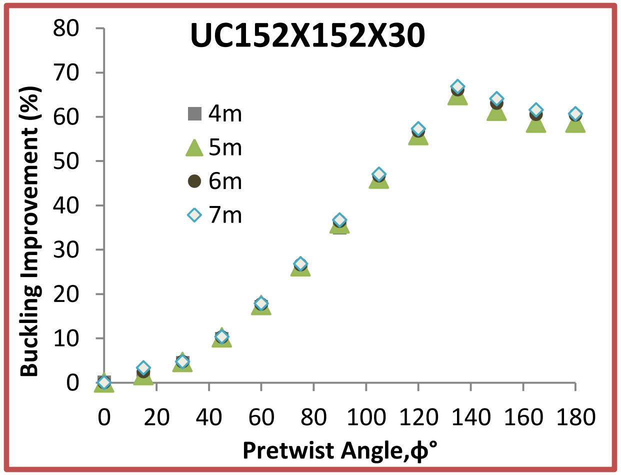
Elastic Buckling Analysis using Perturbation Analysis

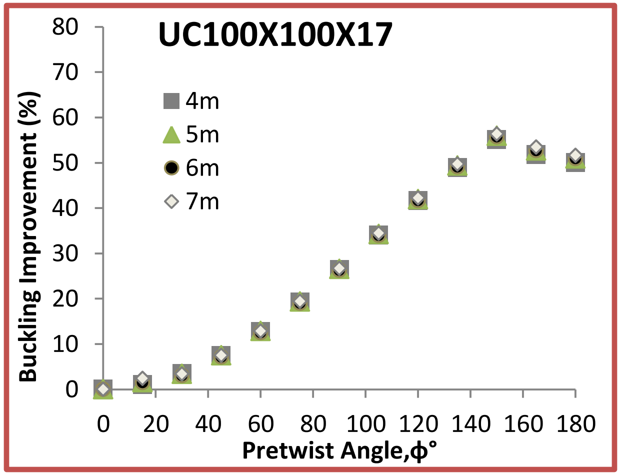
Results for Fixed-ended B.C.s

- Length has no effect
- 70 – 90 % buckling capacity improvement at angle of twists between 120-150.





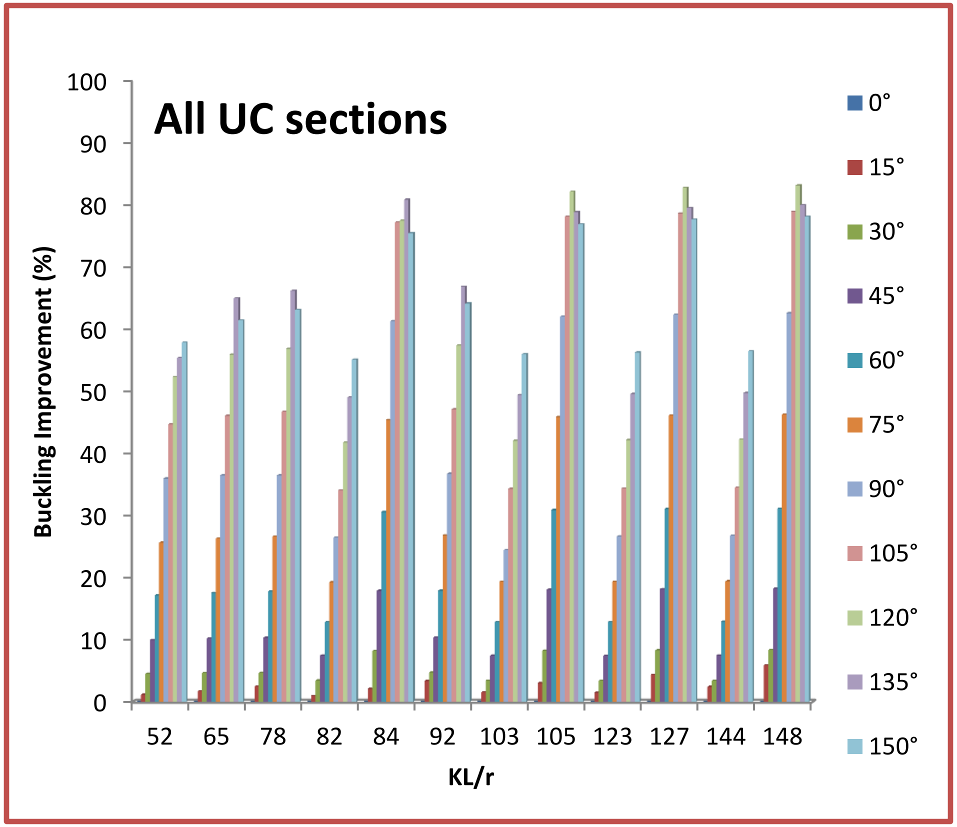


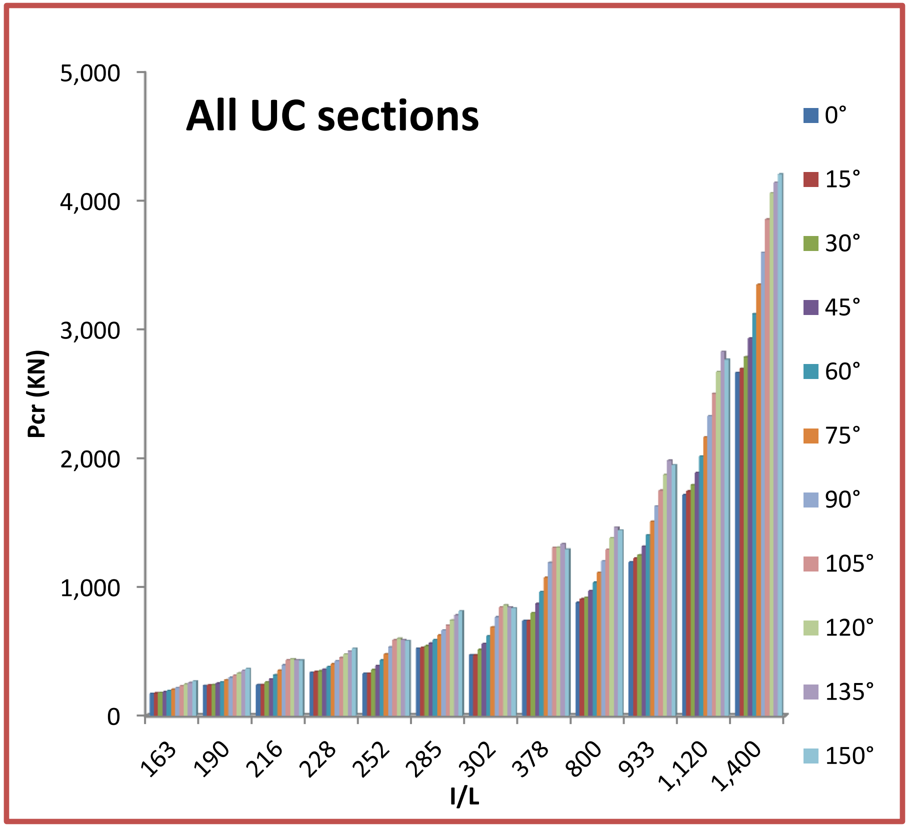


Elastic Buckling Analysis using Perturbation Analysis

Results for Fixed-ended B.C.s

- Histograms of Buckling improvement versus slenderness ratio up to φ = 150°

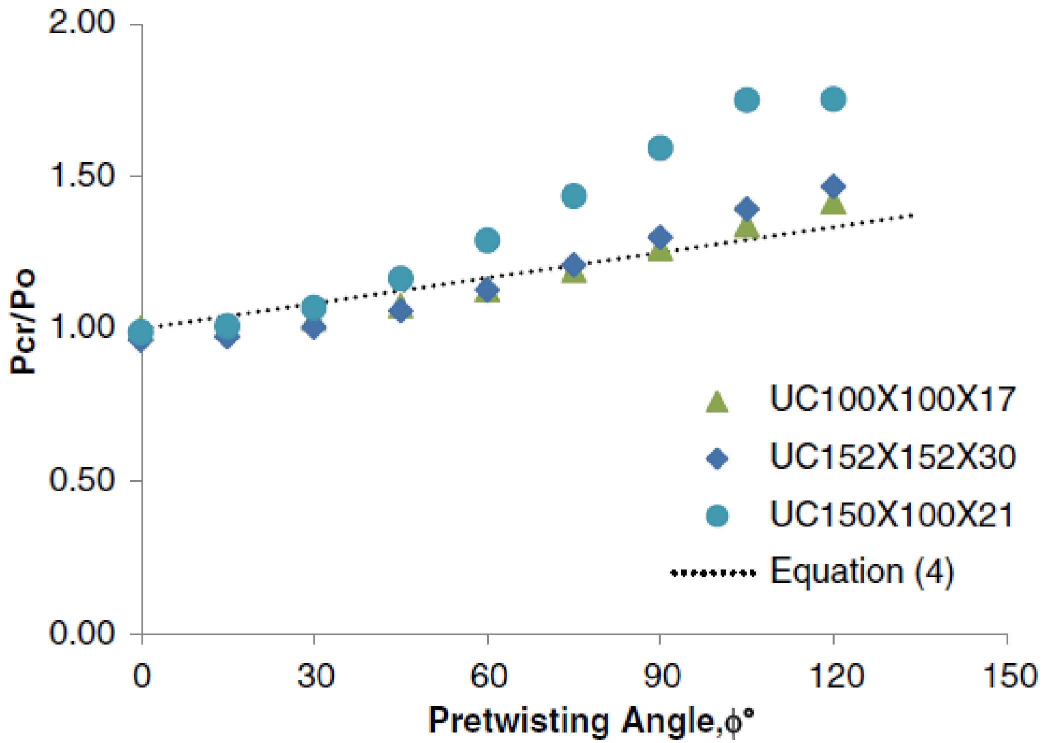




Elastic Buckling Analysis using Perturbation Analysis

- Results for Fixed-ended B.C.s

- Comparisons with previous equation that was developed for pretwisted bars with rectangular cross-sections.



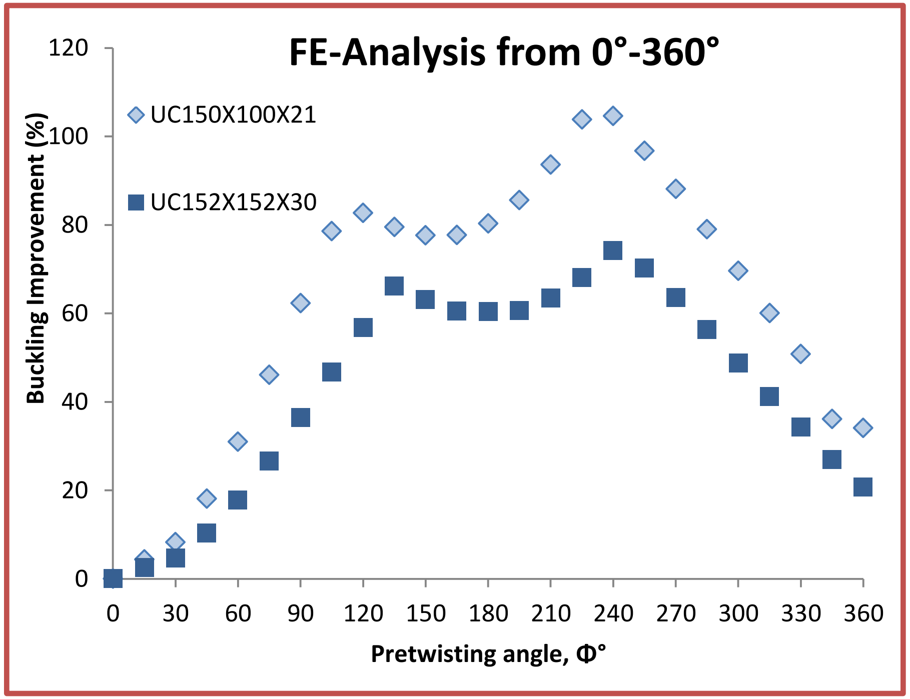
$$P_{cr}^{pretwsited} = \left[1 + \frac{\phi}{360}\right]^n P_o. \qquad \text{when } \frac{KL}{r} > 4.71\sqrt{\frac{E}{F_y}}$$

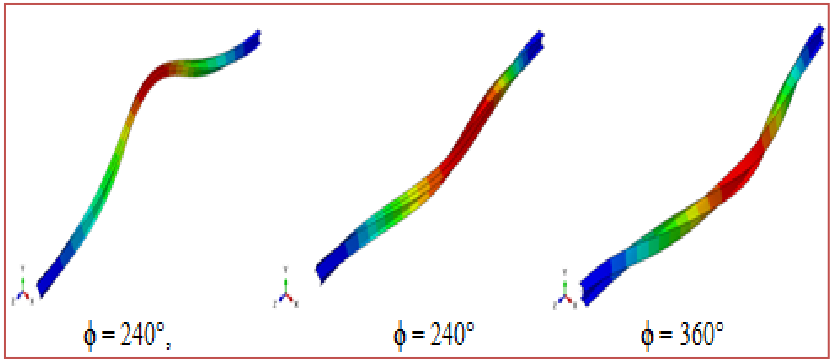
Abed et al. (2012)

Elastic Buckling Analysis using Perturbation Analysis

- Results for Fixed-ended B.C.s

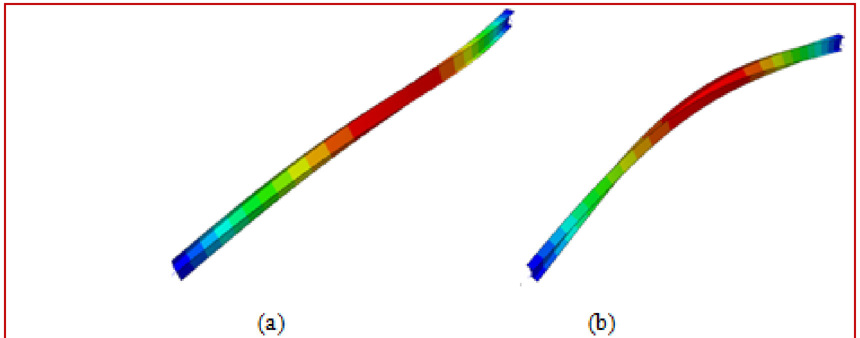
  Finite element analysis run for 0°-360° under fixed-ended boundary condition



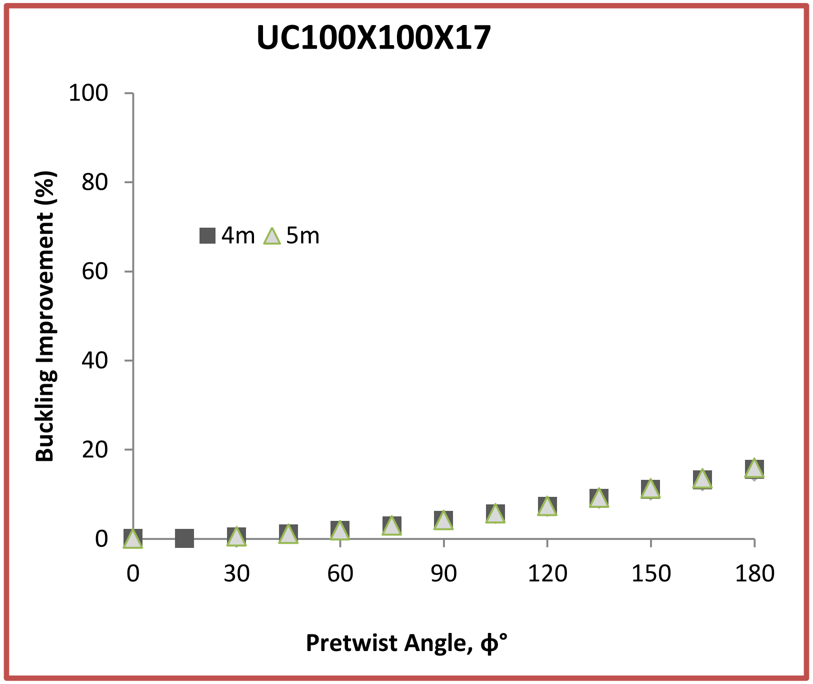


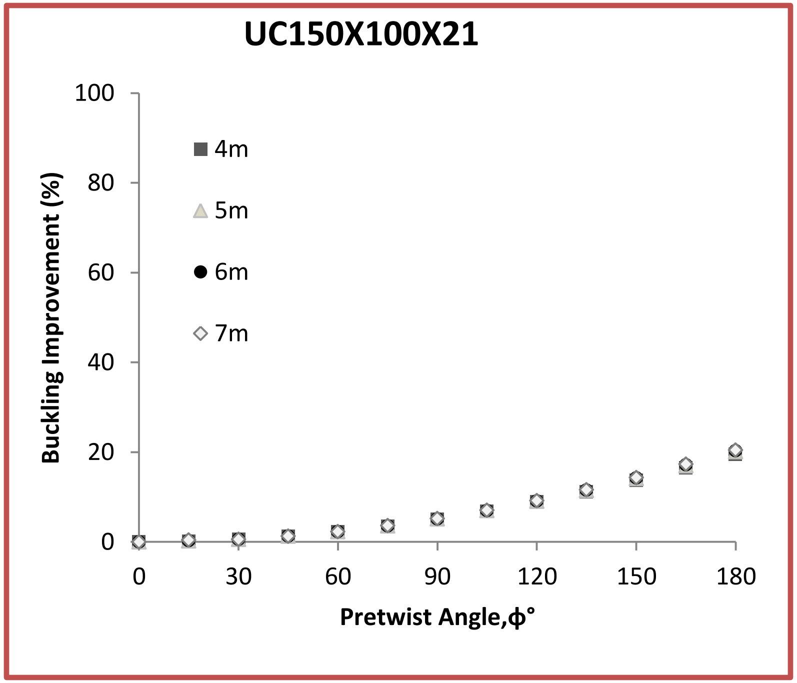
Elastic Buckling Analysis using Perturbation Analysis

- Results for Pinned-ended B.C.s
  - Length has no effect
  - No significant buckling capacity improvement up to 180 angle of twist.



Buckling modes of pin-ended columns (a) non-boxed, ϕ=90°, (b) boxed, ϕ=180°.

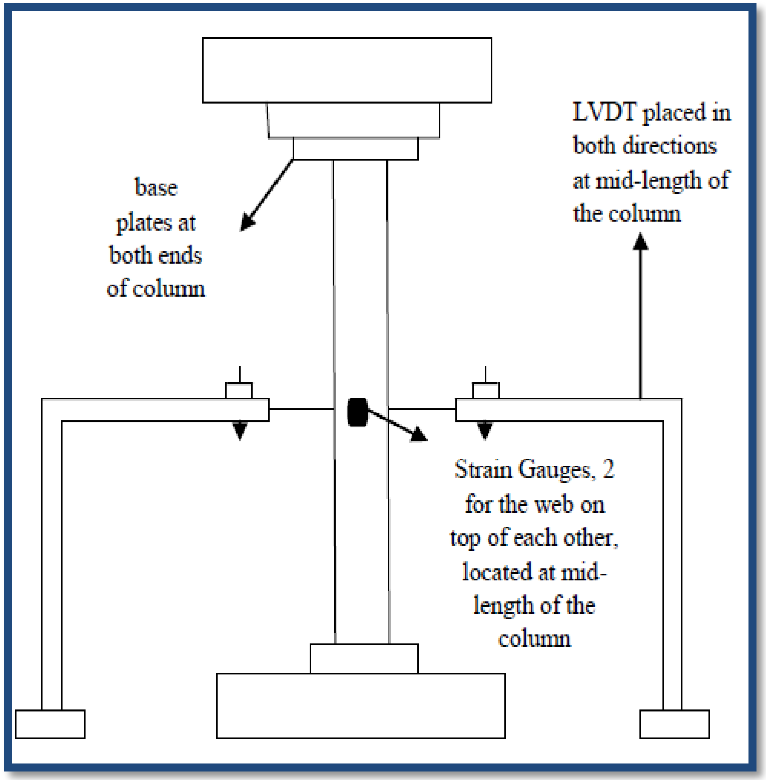




Experimental Tests

Test Setup

- Universal Testing Machine (UTM), capacity = 1200 KN
- UC 100x100x17



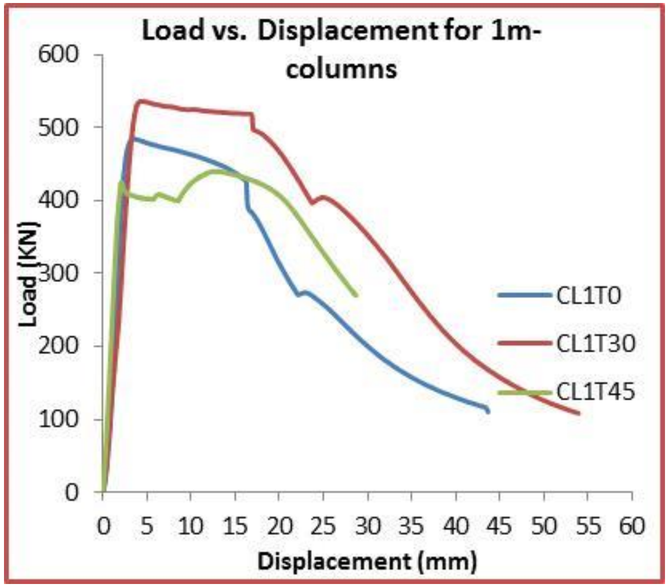
Experimental Tests

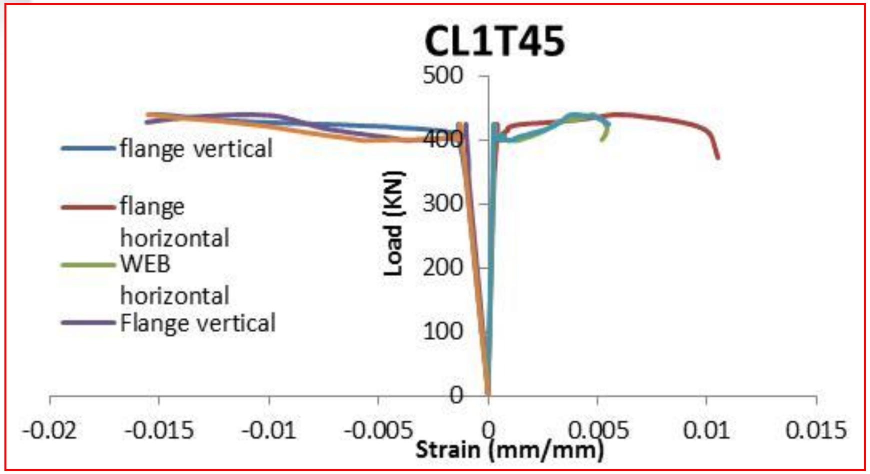
- Dimensions of UC 100x100x17 considered for testing

SECTION	LENGTH (mm)	Flange width (mm)	Total depth (mm)	Flange Thickness (mm)	Web height (mm)	Web thickness (mm)	ϕ
CL_1T_0	1022.0	99.1	102.1	6.9	88.3	6.03	0.0
CL_1T_{30}	990.0	98.7	102.0	7.7	86.6	6.03	32.4
CL_1T_{45}	1019.0	99.6	99.1	7.3	84.5	6.03	44.0
$CL_{1.5}T_0$	1526.0	98.9	100.5	7.1	86.3	6.03	0.0
$CL_{1.5}T_{20}$	1523.0	98.4	99.9	7.2	85.5	6.03	22.8
$CL_{1.5}T_{30}$	1523.0	99.5	99.5	7.2	85.1	6.03	35.7
$CL_{1.5}T_{45}$	1528.0	98.5	101.2	7.7	85.8	6.03	45.0
CL_2T_0	2022.0	100.0	99.7	7.1	85.5	6.03	0.0
CL_2T_{30}	2031.0	99.9	100.4	7.2	86.0	6.03	33.7
CL_2T_{60}	2027.0	91.5	101.7	7.9	85.9	6.03	58

Experimental Tests

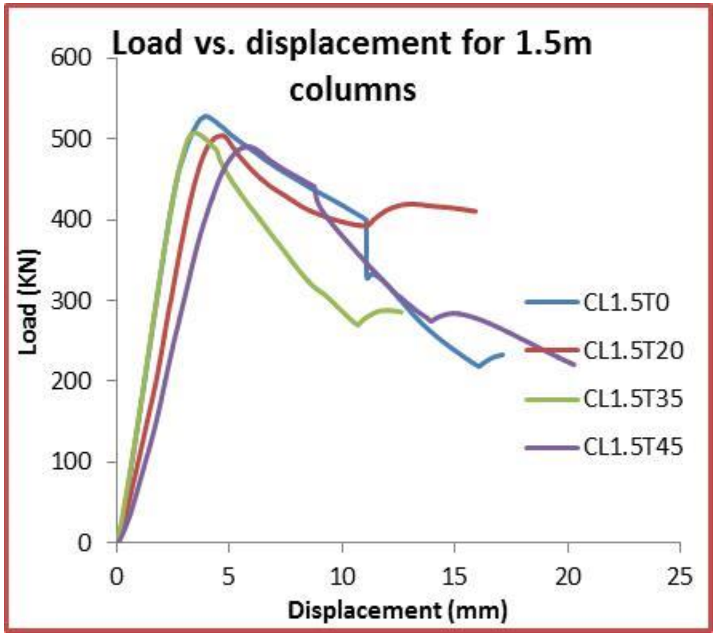
- 1.0 meter Lengths

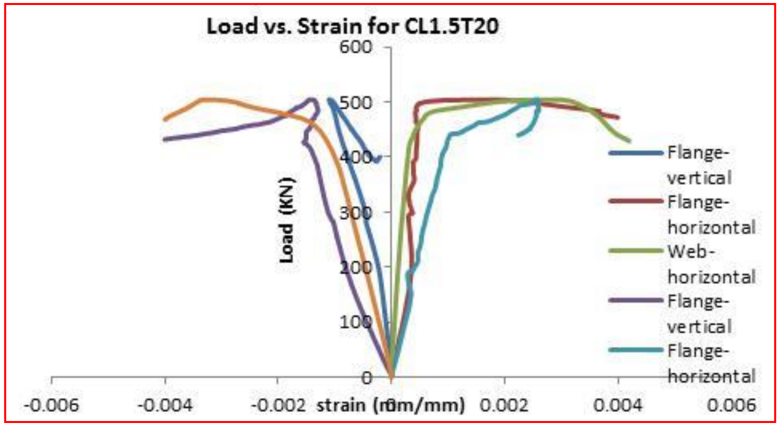




Experimental Tests

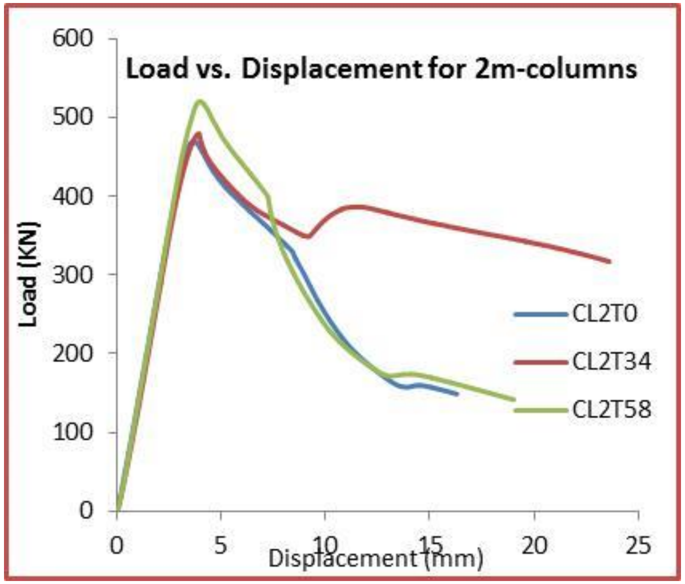
- 1.5 meter Lengths

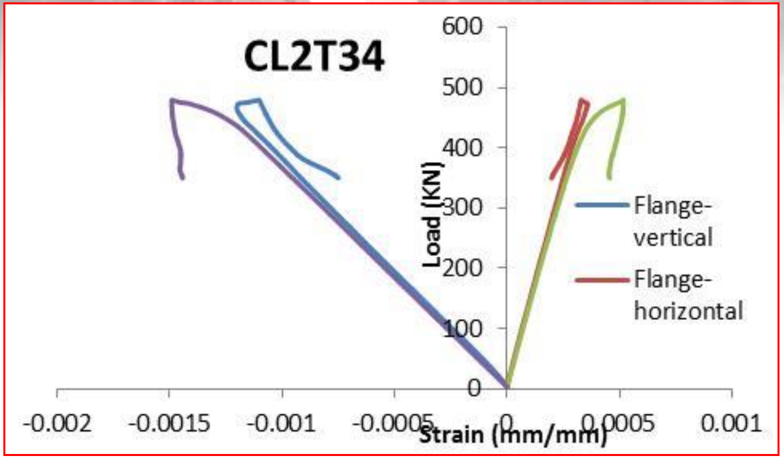


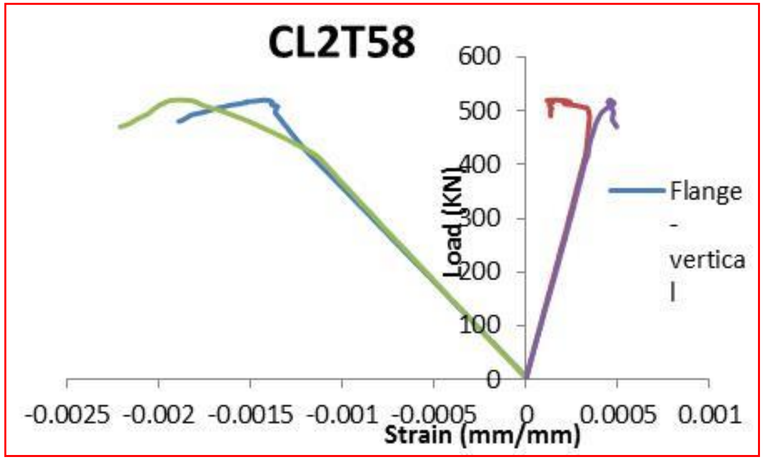


Experimental Tests

- 2.0 meter Lengths

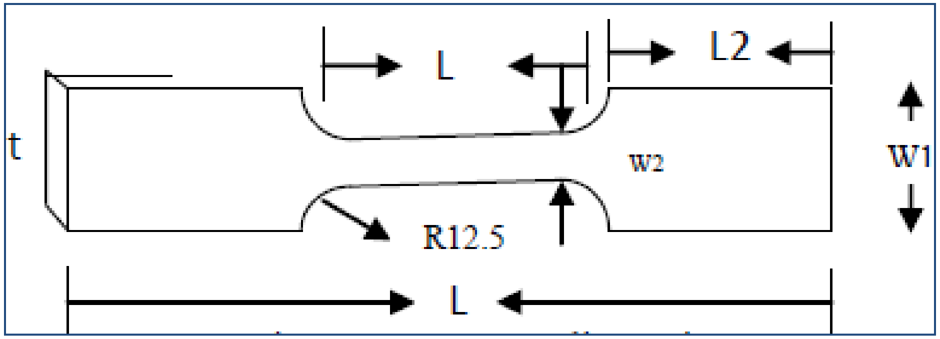






Nonlinear Finite Element Analysis

- <u>Nonlinear material</u>
  - Coupon Tests on 6 specimens from the flange and the web of H-section to define the elasto-plastic behavior of the material.

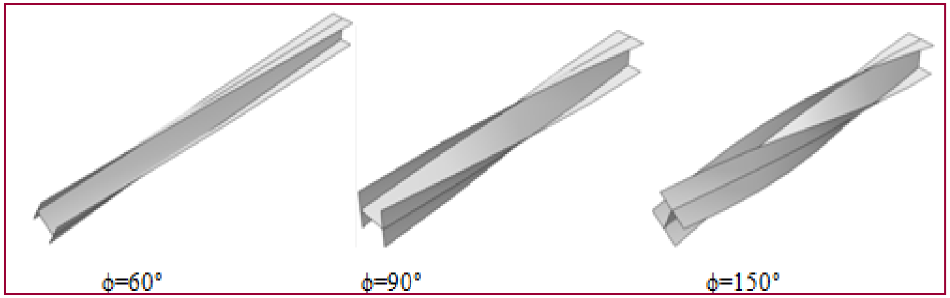


W_1 (mm)	L_2 (mm)	W_2 (mm)	L_1 (mm)
46	89	20	100

  - Geometric imperfection was also considered.
  - Buckling was modeled using two approaches:
    - Riks Analysis
    - Displacement control

Nonlinear Finite Element Analysis

- **Riks Analysis**
  - Built-upon the results achieved using Linear Perturbation analysis
  - Solves for Load and Deflection simultaneously
  - Accounts for material nonlinearity by implementing the true stress-strain curve of the material
- **Displacement-based General Static Analysis**
  - Load is input in the form of axial displacement at the end that is allowed to translate in longitudinal direction
  - A value of geometric imperfection ranging from L/1000-L/2000 induced as lateral displacement at the column mid-height



Nonlinear Finite Element Analysis

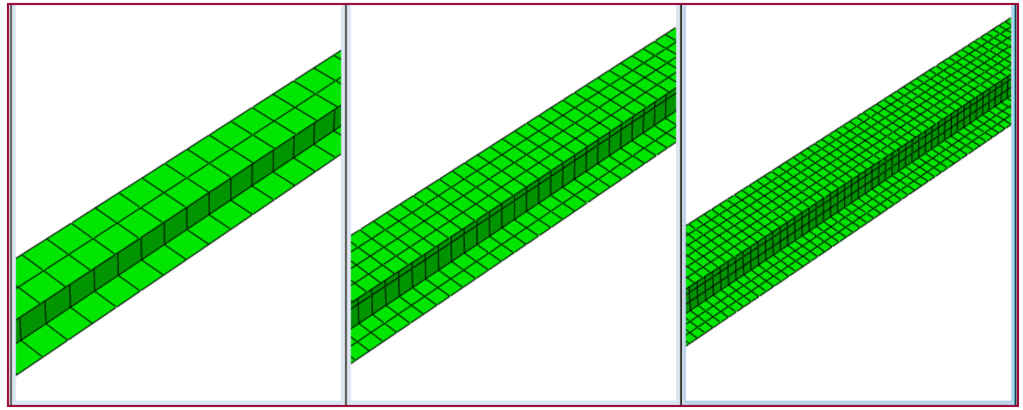
Mesh Sensitivity Analysis

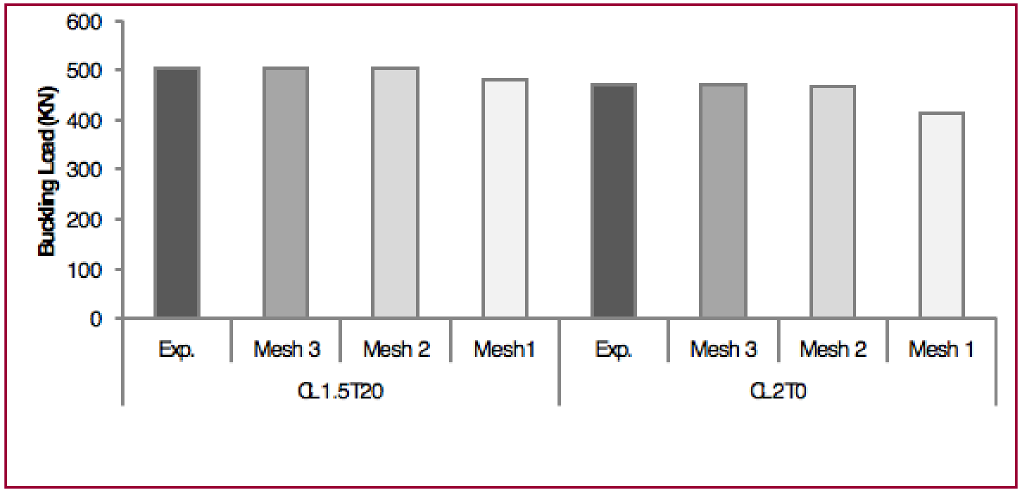
Mesh 1= 50

Mesh 2 = 25

Mesh 3 = 10

- Mesh 1 exceeded 4% for CL1.5T20 and reached around 12% with CL2T0.
- Mesh 2 and Mesh 3 both Showed < 0.5% variation.



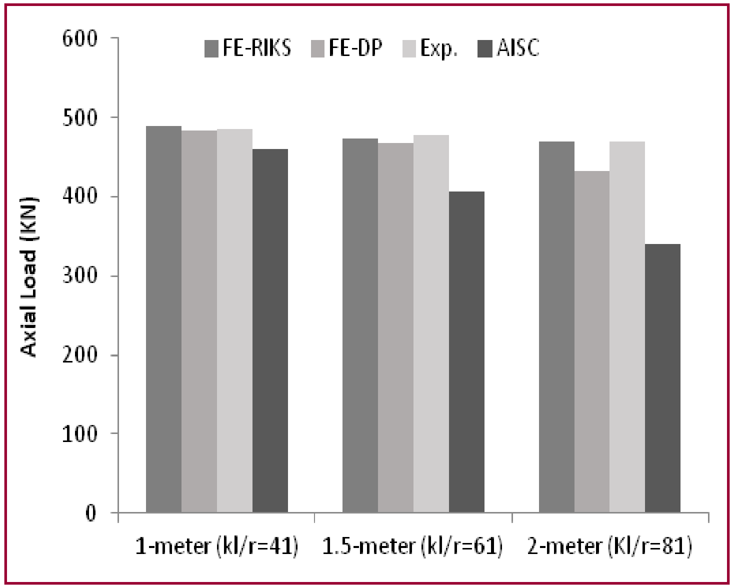


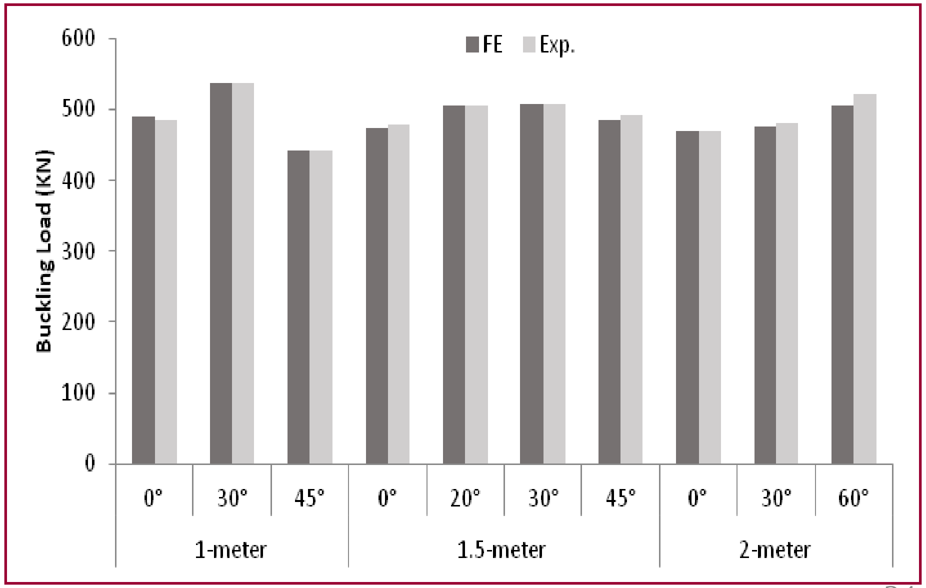
Nonlinear Finite Element Analysis

Nonlinear FE model Verification

- Experimental and Nonlinear Finite element results compared against the AISC code provisions for the prismatic columns.
- Pretwisted columns simulated through FE analysis

$$Kl/r > 4.71\sqrt{\frac{E}{Fy}}, \text{ for inelastic column.}$$





Nonlinear Finite Element Analysis

Nonlinear FE model Verification

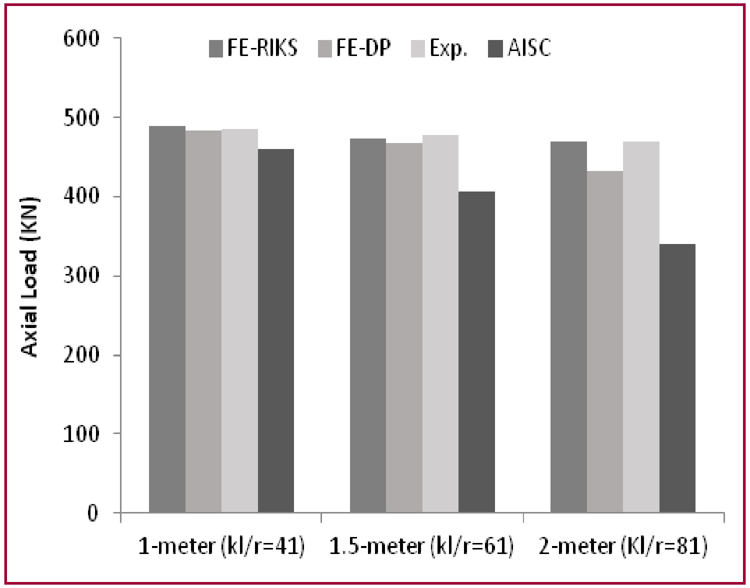
- Experimental and Nonlinear Finite element results compared against the AISC code provisions for the prismatic columns.
- Pretwisted columns simulated through FE analysis

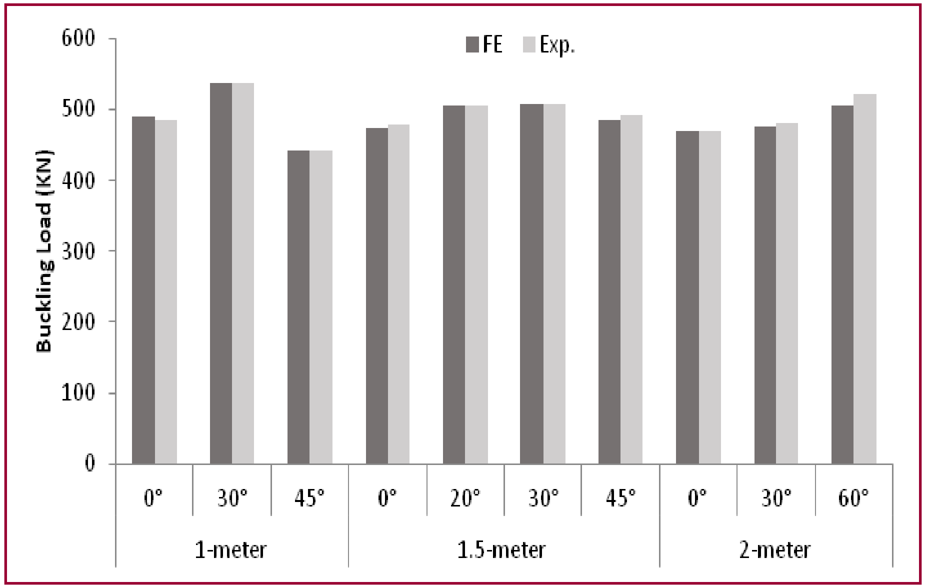
$Kl/r > 4.71\sqrt{\frac{E}{Fy}}$, for inelastic column.

$Kl/r \leq 4.71\sqrt{\frac{E}{Fy}}$, for elastic column

$F_{cr} = \left(0.658^{f_y/f_e}\right) f_y$ for inelastic buckling

$F_{cr} = 0.877F_e$, for elastic columns

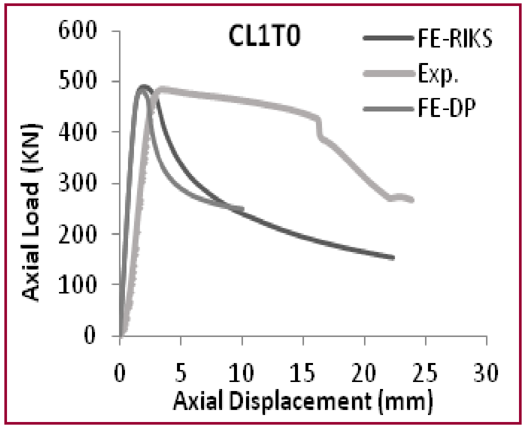


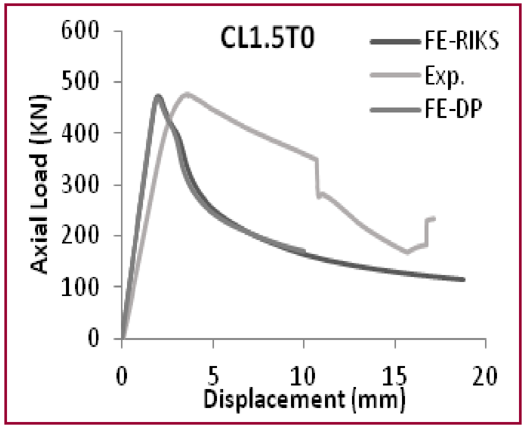


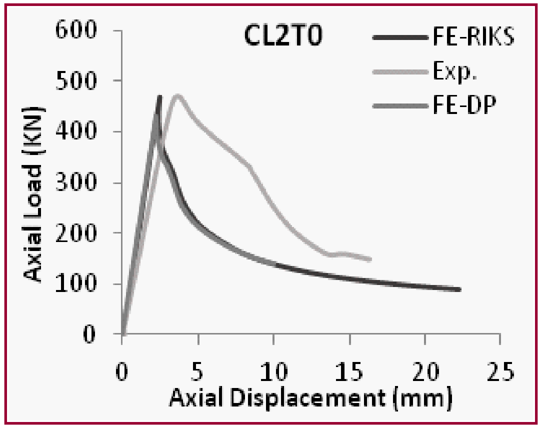
Nonlinear Finite Element Analysis

Nonlinear FE model Verification:

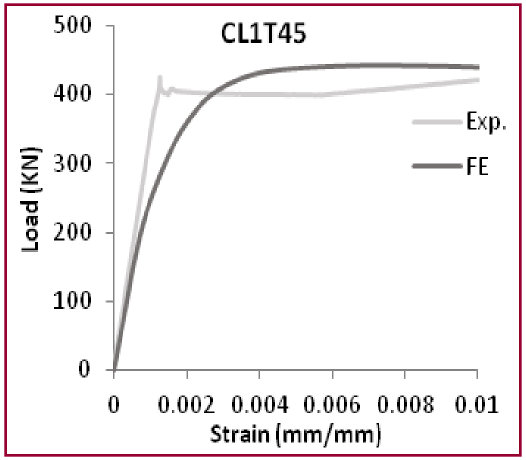
➢**Axial Load versus Displacement :**

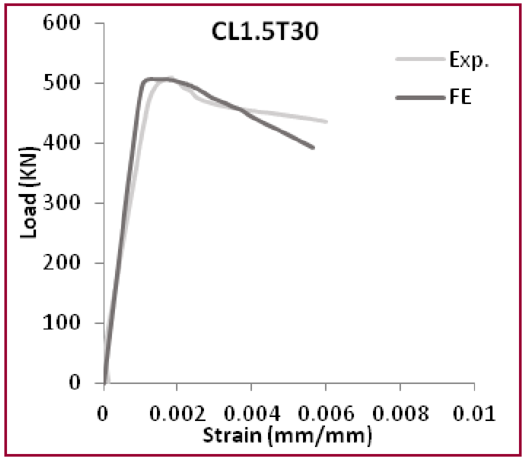


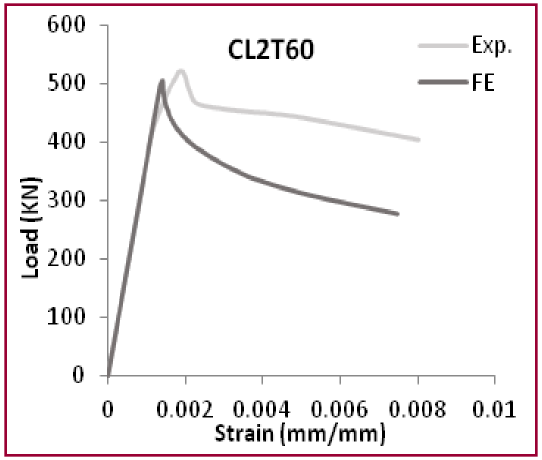




➢**Axial Load versus Strain:**



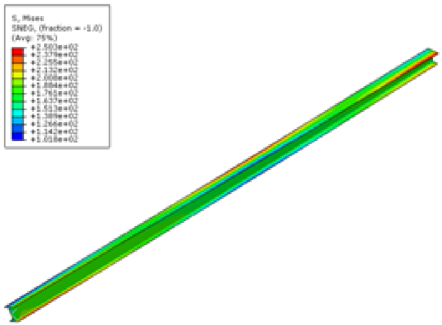




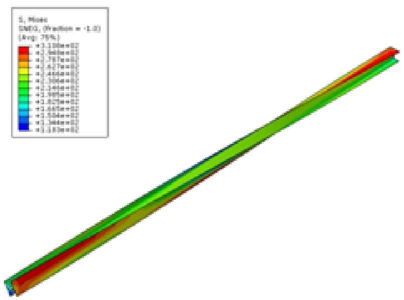
Nonlinear Finite Element Analysis

Expanded Parametric Study

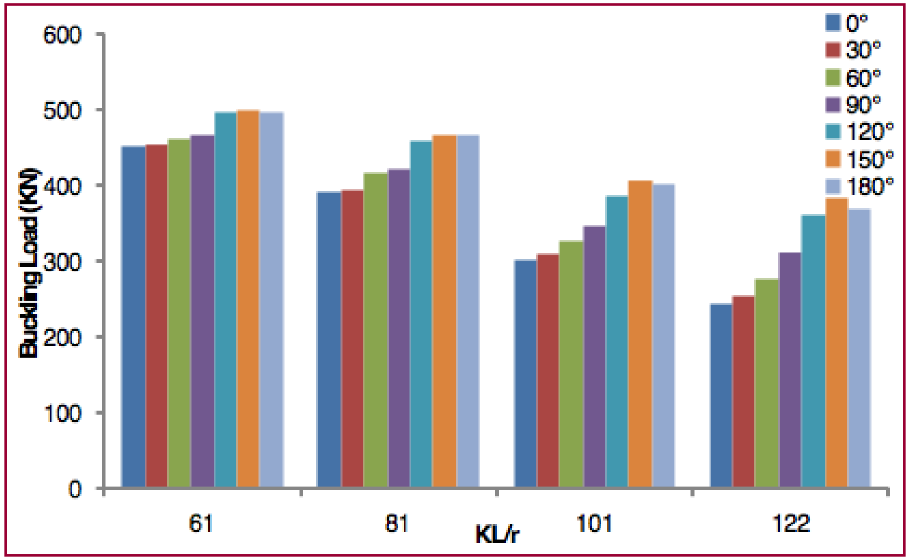
- Fixed-ended models

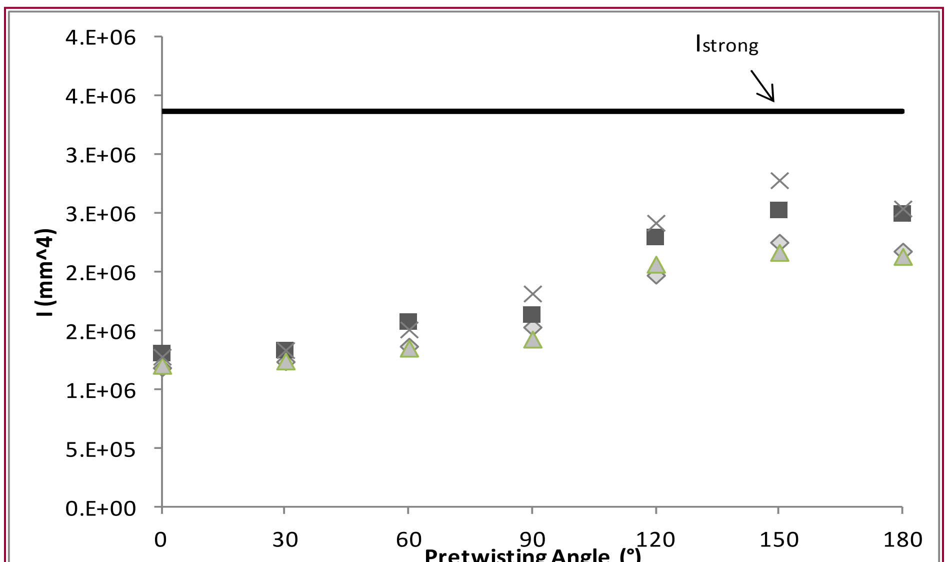


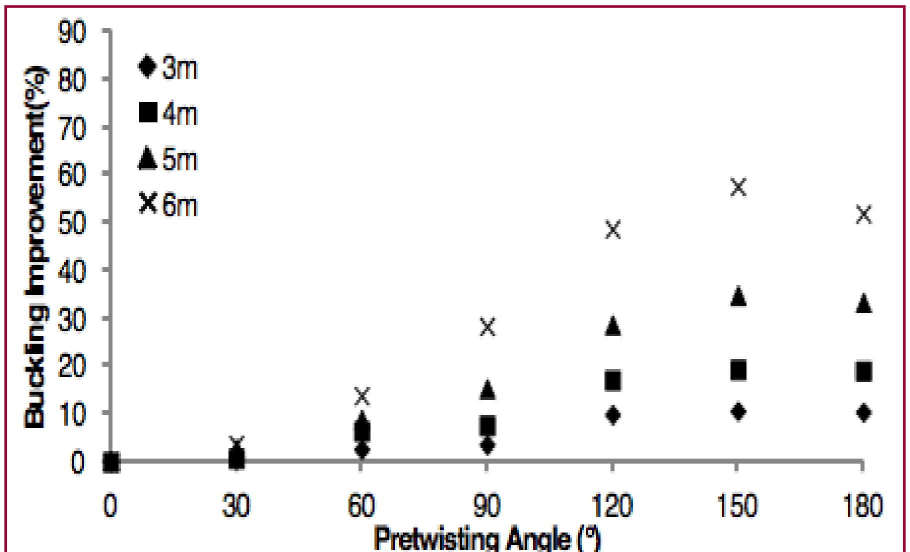
CL4T30



CL4T120



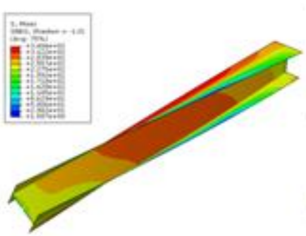




Nonlinear Finite Element Analysis

Expanded Parametric Study

- Pinned-ended models



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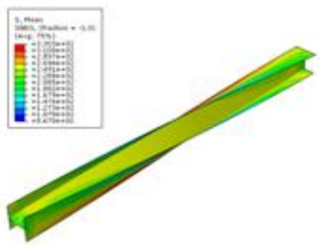

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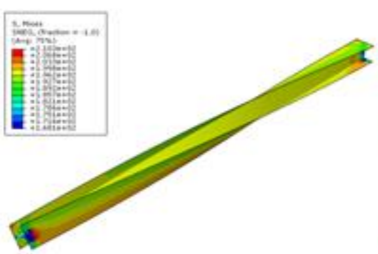

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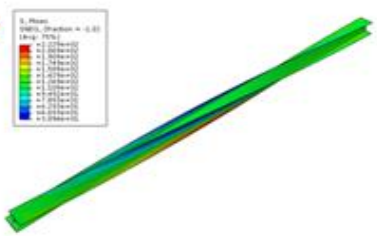

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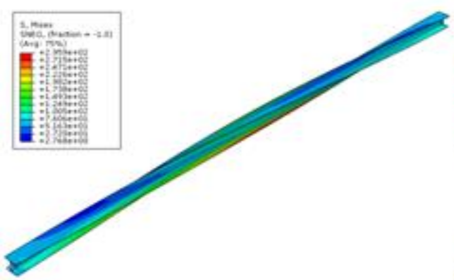
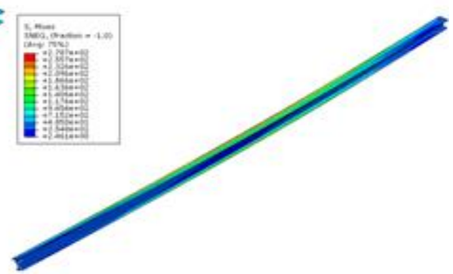
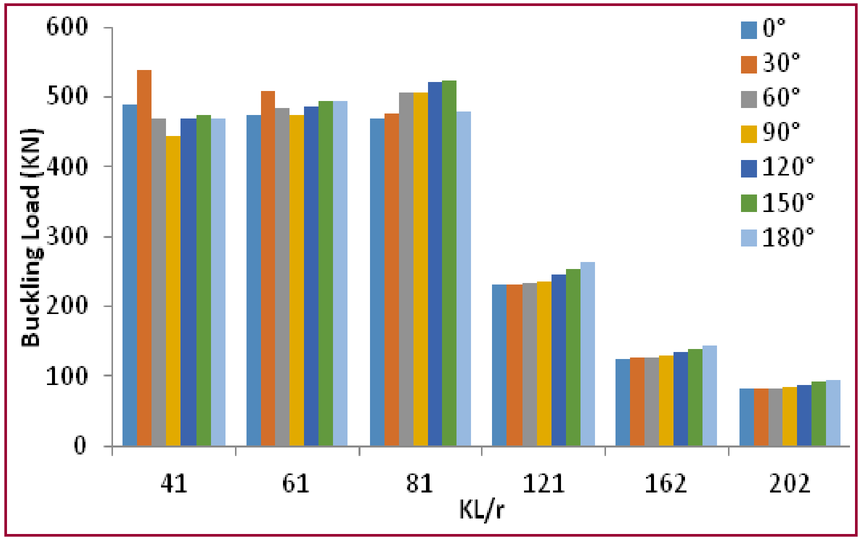
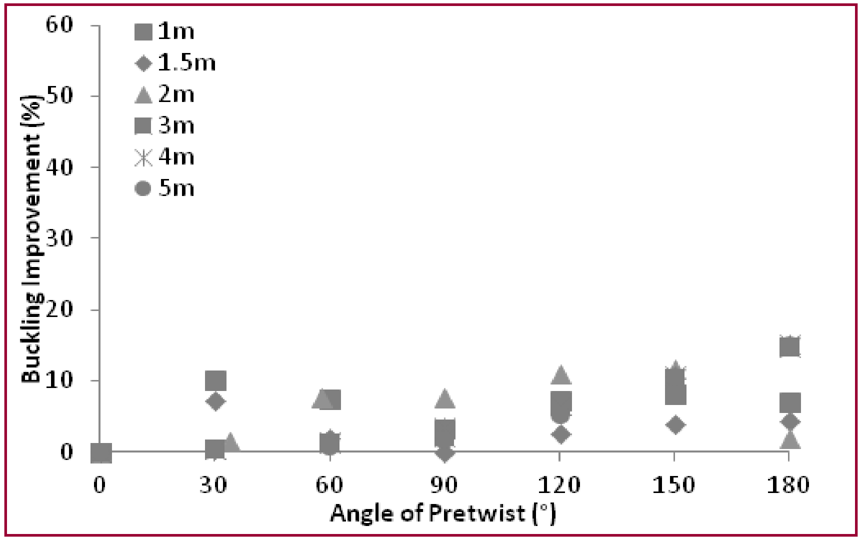


CL4T180



CL5T30





Remarks

- Pretwisting is to be perceived as an effective technique to increase the buckling capacity of any steel compression member
- Results obtained via Linear Perturbation analysis showed that there is a significant improvement (up to 90%) in the critical buckling capacity for different slenderness ratios. However, the effect of various column lengths on the buckling improvement for a given UC section was insignificant.
- The improvement in the axial capacity of pretwisted UC sections with pinned-pinned ends conditions was found to be very small (only 20%) as compared its fixed-ended counterparts, for the three UC sections used in this study.
- More experimental tests and numerical analysis are deemed necessary to reach a more generalized equation that could accurately predict the critical buckling capacity of pretwisted steel columns.

Thanks!

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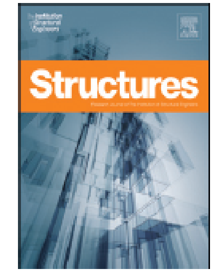

On the improvement of buckling of pretwisted universal steel columns

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A B S T R A C T

This paper investigates the improvement in elastic buckling capacity of pretwisted columns using Linear Perturbation Approach. Three different Universal Column (UC) sections of various lengths were considered in the proposed study assuming fixed–fixed and pinned–pinned end conditions. Linear perturbation analysis was first verified by comparing the critical loads of the simulated straight columns with analytical results. Numerical analysis was then extended to simulate the buckling improvement of pretwisted columns considering four different lengths of 4 m, 5 m, 6 m and 7 m, and a range of twisting angles between 0° and 180°. The results showed that the initial twisting has positively impacted the axial capacity of the pretwisted columns. This noticeable improvement is supported by the significant increase in the buckling capacity for the three UC sections, particularly at angles of twists between 120° and 150°.