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# NUMERICAL ANALYSIS OF COMBINED-SECTION STEEL COLUMNS

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**ABSTRACT**
Combined-section columns composed of two separate steel sections present an ideal and economic design for long columns subject to high values of bending moments and axial forces. Research dealing with design of these columns is currently insufficient. At present, most codes of practice consider each column's component to behave either separately or rigidly connected to the other components. As such, the main objective of this research is to scrutinize the behaviour of laced-section columns which are subjected to eccentric loading and propose design criteria for them. In this paper, a non-linear numerical model for these columns is developed based on the finite element method. The results of the numerical model are first verified against the outcomes of experimental investigations available in literature. Then, the model is adopted to simulate the behaviour and the capacity of the combined laced columns. The numerical model includes both the geometric and materials nonlinearities along with the effect of initial imperfections.

**KEYWORDS: Built-Up Columns, Laced Columns, Combined Steel Column, Numerical Modelling.**

## 1 INTRODUCTION

Combined columns (also referred as built-up columns) are columns which consist of two or more main chords connected by lacing bars or batten plates (Figure 1a). Main chord sections may be UPN sections, IPE sections, angles, …etc. There are many configurations for the main chord including the used sections type and the way of their arrangement as shown in Figure 1b.

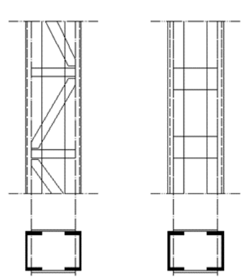


**Figure 1a Built up columns**

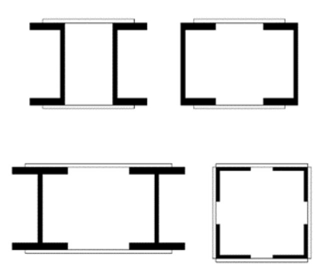


**Figure 1b Built up sections**

The main advantage of using such column is the large moment of inertia resulting from the distance separating between the centroids of the chords, which decreases the slenderness ratio and increases both axial force and bending moment capacity. Usage of combined sections steel columns presents an ideal and economic design for long columns subject to high values of bending moments and axial forces.

## 2 CURRENT DESIGN APPROACH FOR COMBINED COLUMNS

### 2.1 Eurocode, EN 1993-1-1:2005.

In section 6.4 *EN 1993-1-1:2005* proposes Eq. (1) and (2) for designing combined columns subject to axial compressive forces as well as bending moments in order to check the capacity of the critical chord subject to compressive force due to the effect of the axial force and the bending moment:

$$N_{ch,\ Ed} = 0.5\, N_{Ed} + \frac{M_{Ed}\, h_o\, A_{ch}}{2 I_{eff}} \qquad (1)$$

$$\text{Where} \quad M_{Ed} = \frac{N_{Ed}\, e_o + M^{I}_{Ed}}{1 - \dfrac{N_{Ed}}{N_{cr}} - \dfrac{N_{Ed}}{S_v}} \qquad (2)$$

The verification check for buckling should be performed for the chord with critical compression force using Eq. (3) which is commonly used for any compression member.

$$\frac{N_{ch,Ed}}{N_{b,Ed}} \le 1 \qquad (3)$$

Where, $N_{Ed}$ and $M_{Ed}$ are the external axial force and bending moment, $h_o$ is the distance between chords centroids, $A_{ch}$ is the chord area, $I_{eff}$ is the effective moment of inertia, $e_o$ is the initial imperfection, $N_{cr}$ is the Euler buckling load and $S_v$ is the shear stiffness of the column.
This method is expressed in detail by Sayed-Ahmed and ElSerwi (2017).

### 2.2 AISC 360-10 (2005).

In section 360-10 E6, *AISC 360-10 (2005)* recommends that the slenderness ratio of single chord between the lacing bars about its least radius of gyration should not exceed 75% of the slenderness ratio of the column as a whole. To take account for shear deformation Eq. (4) is used to calculate modified slenderness ratio.

$$\left(\frac{KL}{r}\right)_m = \sqrt{\left(\frac{KL}{r}\right)_0^2 + \left(\frac{a}{r_i}\right)^2} \qquad (4)$$

Where, $\left(\frac{KL}{r}\right)_0$ is the slenderness ratio of the column as a single unit, a is the distance between laced points and $r_i$ is the radius of gyration of the chord about its minor axis.

### 2.3 CSA-S16-14 (2014).

In section 19, *CSA-S16-14 (2014)* recommends that the slenderness ratio of each combined column's component to be about its least radius of gyration should not exceed that of the built up member, the compressive resistance of the column should be based on
1) The slenderness ratio of the built up column about appropriate axis when buckling mode does not involve relative deformations to produce shear force in lacings.
2) The equivalent slenderness ratio about axis orthogonal to that of item (1) when buckling mode involves relative deformations that produce shear force in lacings as shown in Eq. (5).

$$\rho_e = \sqrt{\rho_o^2 + \rho_i^2} \qquad (5)$$

Where, $\rho_o$ is the slenderness ratio of the column as a single unit and $\rho_i$ is the local slenderness ratio of the chord about its minor axis.

## 3 NUMERICAL MODELLING OF COMBINED STEEL COLUMNS.

To predict the failure load of combined (built-up) columns, a non-linear finite element model is developed. The commercial program (ABAQUS) is used as a platform for processing the model solution of the FE equations and post processing the model results. The model assembly, element type, material model, boundary conditions, load assignment, constrains and the mesh size are used as follows:

### 3.1 Model Assembly

Laced columns with different configuration for lacing members are numerically modelled using the proposed FE model. The lacing members are configured as shown in Figure 2 as W-, WH- and X-type. 8-node shell element is used to model both the chords and the laced members.

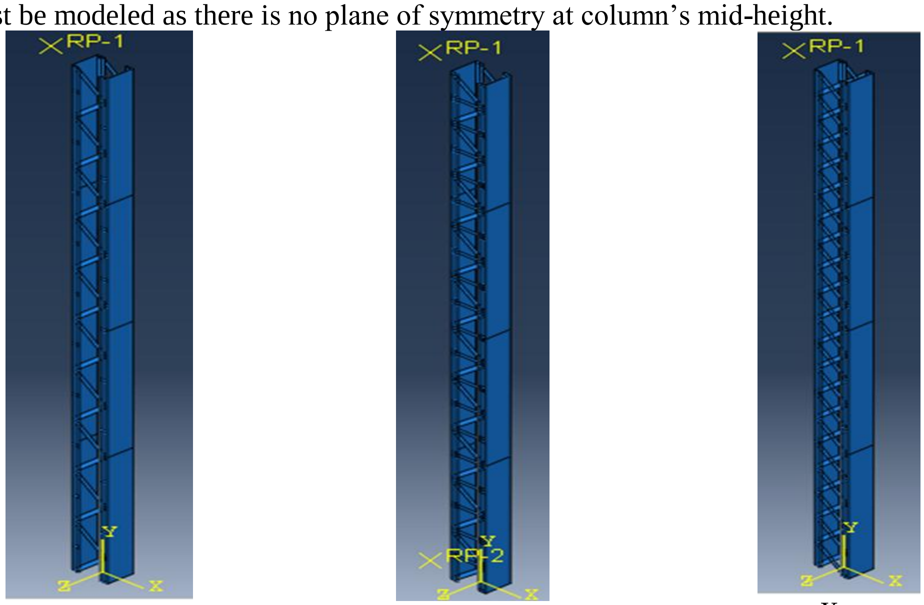
### 3.2 Material Model

Steel S235 of 235 MPa engineering yield stress and 360 MPa ultimate engineering stress is adopted for the column chords and the lacing members. The steel material is modeled as an elasto-plastic material with true stress-strain curve following the DNV-RP-C208 (2013). The modulus of elasticity used is $2.1 \times 10^5$ MPa and Poisson's ratio is 0.3 for the elastic part. For the plastic part, the provided data from the DNV is adopted based on the element thickness. Figure 3 schematically shows the adopted stress-strain curve for the steel.

### 3.3 Boundary Conditions

To model the hinged-hinged W- and X-type columns with uniform bending moment over its length, the following boundary conditions are used:

For the upper end of the column, all nodes of the chords are connected to a reference point with a rigid body constraint of tie type, the reference point is located at a certain distance from the geometric center to model the eccentric load (Figure 4).Then, a displacement restraint is assigned to the reference point to model the hinge; it sets the displacement in X, Z direction and rotation about Y-axis to zero. Only half of the column length is modelled to make use of symmetry as such plane of symmetry is used at the column mid-height as the lower boundary condition. For WH-type columns, both the upper and lower boundary conditions are modeled as the upper boundary condition of W and X type columns, since full column must be modeled as there is no plane of symmetry at column's mid-height.




W type WH type X type

**Figure 2 Model assemblies.**

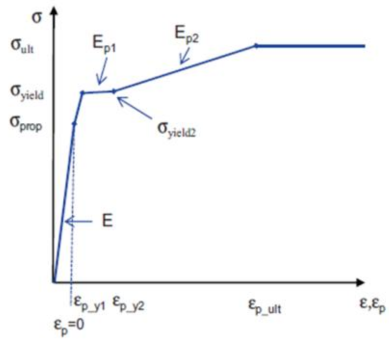



**Figure 3 Stress strain curve.**

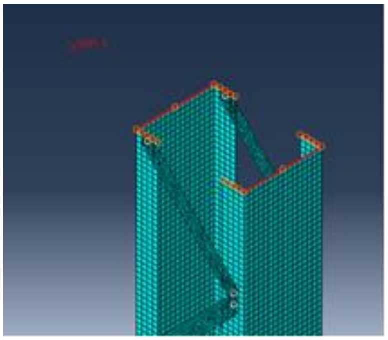


**Figure 4 Upper nodes constraint.**

### 3.4 Load Assignment

The load is assigned to the eccentric reference point with different eccentricities to model different M/N ratio as shown is (Figure 5). The load is given a value of unity and RIKS algorithm is adopted to increase it step by step: RIKS algorithm is used for the iterative process of solving the equation of the non-linear FE model.

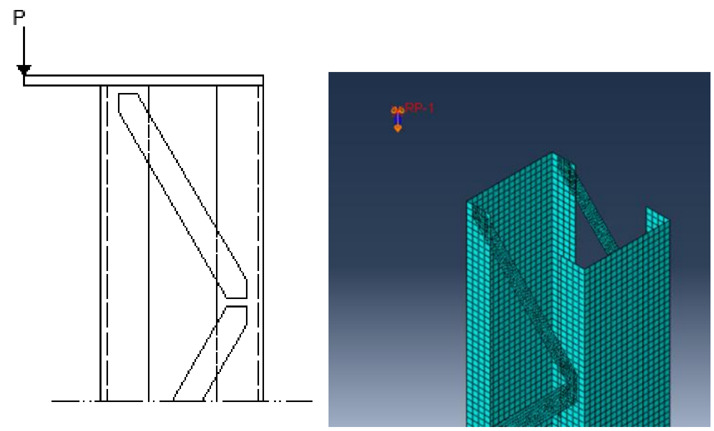



**Figure 5 Load assignment**.

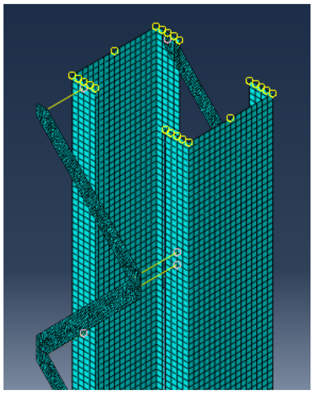


**Figure 6 Lacing-chord constraint**

### 3.5 Lacing Bars- Chords Connection

To model the hinged connection between the lacing bars and the chord, Coupling constrain is used with the degrees of freedom to be constrained: U1, U2, U3, UR1, UR2, the chord and lacing geometries are sketched to create a point of attachment to be used by the constraint (Figure 6).

## 4 MODEL VERIFICATION

The numerical model is verified with the results of experimental investigation program obtained by Kalochairetis et. al (2014). Konstantinos's research program (2014) consists of an experimental investigation and numerical analysis performed on 5 groups of laced built-up beam-columns. The current verification is done on three of these groups which are close to the model used in this research.

The desired groups are 2000 mm long built-up beam-columns with two UPN 60 chords and lacing members composed of 25x25x3 angles, the columns are divided into five parts with panel length of 400mm. The total length of the column including the upper and lower pin supports is 2300mm. The top/bottom eccentricities of the pin supports are 100/100 (same side), 100/80 (different sides) and 50/50 (same side) for groups 1, 4 and 5, respectively.

Load-displacement curves for mid height of column (Groups 1 and 5) resulting from both the experimental investigation and numerical model are plotted in Figures 7 and 8. Further, the load-displacement curves for the first and last panel for Group 4 are plotted in Figures 9 and 10.
Table 1 summarize the results of the considered experimental data and compare it to the outcomes of the numerical model. Both the stiffness and the capacity of the columns are listed in this table with the ratio between the experimental program and the numerical analysis results.

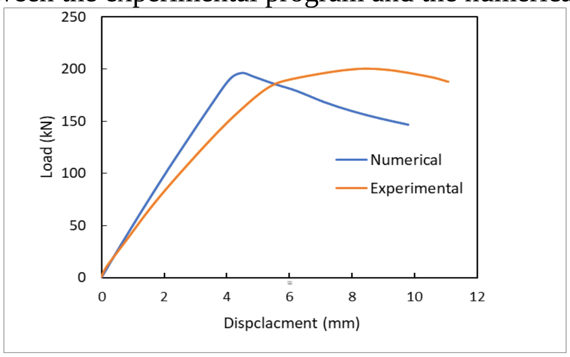



**Figure 7 Load-displacement curve for Group 1**

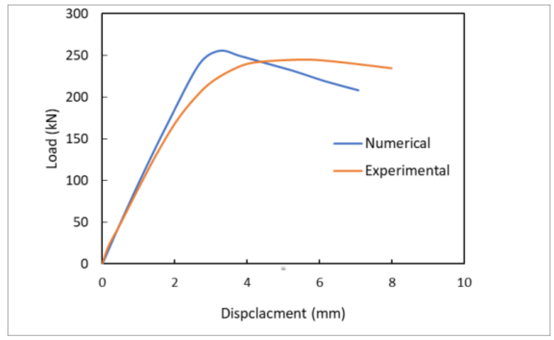



**Figure 8 Load-displacement curve for Group 5**

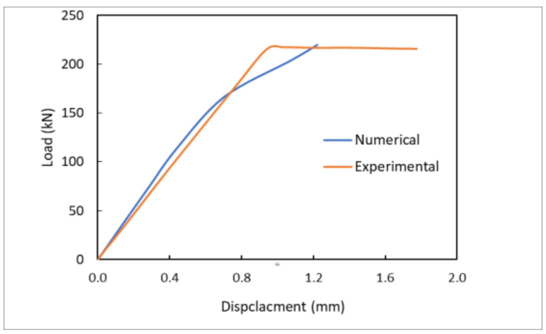



**Figure 9 Load-displacement the upper panel for Group 4**

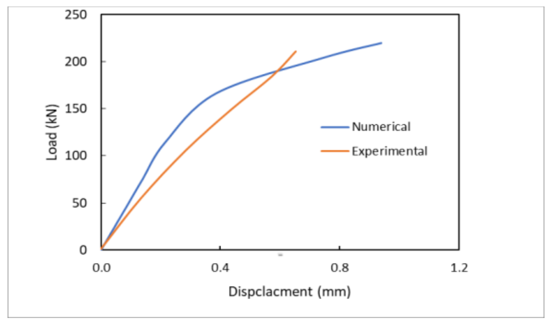



**Figure 10 Load-displacement the lower panel for Group 4**

**Table 1 Verification results**.

| Group number | $P_{FEA}$ (kN) | $P_{exp}$(kN) | $K_{FEA}$ (kN/m) | $K_{exp}$ (kN/m) | $P_{FEA}/P_{exp}$ | $K_{FEA}/K_{exp}$ |
|---|---|---|---|---|---|---|
| 1 | 196 | 200 | 50.8 | 38 | 0.98 | 1.34 |
| 4 | 255 | 220 | 261(upper) | 240 | 1.16 | 1.09 |
| 5 | 255.5 | 241.5 | 100.4 | 93 | 1.06 | 1.08 |

The verification of the three groups shows that the developed model predicts the load, displacements and failure mode in an acceptable way and the modeling technique could be reliable to perform the parametric study on it.

## 5 PARAMETRIC STYUDY

Parametric study is done to find suitable design criteria and to ensure its applicability on a wide range of columns. All used chords are channels C400 with flange 110 mm wide, 18 mm thickness and web 400 mm wide, 14 mm thickness. Initial imperfections are introduced using the recommended value from the *Eurocode, EN 1993-1-1:2005* which is $e = \frac{L}{500}$ The types of lacings are given names as shown in (Figure 2). Models are given names with the following format (Type-length- eccentricity) (e.g. W-10-0.2 is column of 10 meters height with W type lacing loaded by a load of eccentricity 0.2m).

63 models are developed in the parametric study, 21 models for each type of lacing configuration. For each type of lacing, columns of height 10, 15 and 20 meters are developed with load eccentricity 0, 0.2, 0.5, 0.8, 1.0, 1.2m and for each height.

For each column, the maximum capacity is found using the following three methods:

- Method 1: Load from finite element.
  It is the load obtained from the results of solving the finite element equation using the commercial software used (ABAQUS).
- Method 2: Eurocode method as indicated in Sayed-Ahmed and Elserwi (2017).

  $$N_{ch,Ed} = 0.5\,N_{Ed} + \frac{M_{Ed}\,h_0\,A_{ch}}{2I_{eff}} \tag{6}$$

  Where $$M_{Ed} = \frac{N_{Ed}\,e_0 + M^{I}_{Ed}}{1 - \frac{N_{Ed}}{N_{cr}} - \frac{N_{Ed}}{S_v}} \tag{7}$$

  Finally, the verification check for buckling should be performed for the chord with critical compression force as follows:

  $$\frac{N_{ch,Ed}}{N_{b,Ed}} \le 1 \tag{8}$$

  $N_{cr} = \frac{\pi^2 E I_{eff}}{L^2}$ is the effective critical force of the built up member.

  $N_{Ed}$ is the design value of the compression force to the built up member.

  $N_{ch,Ed}$ is the design compression force in the chord at mid length of the built up member.

  $N_{b,Ed}$ is the design value of the buckling resistance of the chord calculated as a typical compression member with $\lambda = \sqrt{\lambda^2_{global} + \lambda^2_{local}}$

  $M_{Ed}$ is the design value of the maximum moment in the middle of the built-up member considering second order effects

  $M^{I}_{Ed}$ is the design value of the maximum moment in the middle of the built-up member without second order effects.

  $h_0$ is the distance between the centroids of chords.

  $A_{ch}$ is the cross-sectional area of one chord.

  $I_{eff} = 0.5\,h_0^2\,A_{ch}$ is the effective second moment of area of the built-up member.

  $S_v$ is the shear stiffness of the laced panel.
- Method 3: Proposed method.
  It is the load which satisfy the old AISC used equations for beam-column sections with some modifications:

  $$\frac{P_u}{P_n} + \frac{B_1 M_u}{M_n} = 1 \tag{9}$$

  Where

  $P_u$ is the ultimate applied load.

  $M_u$ is the ultimate applied bending moment = $P_u \times e$

  e is the load eccentricity.

  $B_1$ is magnification factor to consider second order analysis due to shear deformations and buckling effect, its calculation will be discussed later.

  $M_n = F_y Z$ is the maximum nominal moment capacity.

  Z is the plastic section modulus.

$P_n$ is the nominal axial capacity and it is calculated as follows:

$$P_n = F_{cr} A_g \tag{10}$$

Where $F_{cr}$ is the critical stress and determined as the following:

$$\lambda_x = \sqrt{\left(\frac{L_x}{r_x}\right)^2 + \left(\frac{L_z}{r_z}\right)^2} \tag{11}$$

Where , $L_x$ is the buckling length about x axis.
$L_z$ is the length between connected points of one chord.
$r_x$ is the radius of gyration about x axis.
$r_z$ is the minor radius of gyration of the chord.

$$\lambda_c = \lambda_x \sqrt{\frac{F_y}{\pi^2 E}} \tag{12}$$

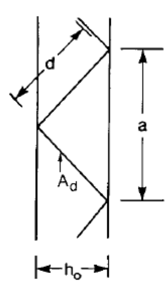
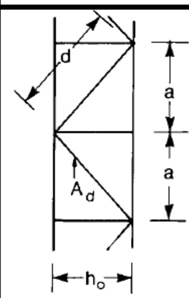
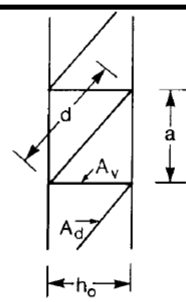
$$\text{if } \lambda_c \le 1.1 \rightarrow F_{cr} = F_y (1 - 0.384 \lambda_c^2) \tag{13}$$

$$\text{if } \lambda_c > 1.1 \rightarrow F_{cr} = \frac{F_y}{\lambda_c^2} \tag{14}$$

$$\text{Where } F_e = \frac{\pi^2 E}{\left(\frac{KL}{r}\right)^2} \tag{15}$$

$A_g$ is the gross cross section area.
$S_v$ is the shear stiffness determined as mentioned in the Eurocode shown in (Table 2).

**Table 2 Calculation of shear stiffness for different lacings**

| Lacing type | W lacing type | WH lacing type | N lacing type |
|---|---|---|---|
| System |  |  |  |
| $S_V$ | $\frac{nEA_d a h_0^2}{2d^3}$ | $\frac{nEA_d a h_0^2}{d^3}$ | $\frac{nEA_d a h_0^2}{d^3\left[1 + \frac{A_d h_0^3}{A_V d^3}\right]}$ |
| n is the number of planes of lacings<br>$A_d$ and $A_V$ refer to the cross sectional area of the bracings | | | |

Calculation of $B_1$:

$$B_1 = \frac{1}{1 - \frac{P_u}{S_v} - \frac{P_u}{P_{E,mod}}} \tag{16}$$

Where $$P_{E,mod} = \frac{P_E}{1 + \frac{P_E}{S_v}} \tag{17}$$

$P_E$ is the Euler buckling load.

# 6 RESULTS

## 6.1 Results for W Lacing Type Columns

For W lacing models, results of the above three methods in terms of the maximum normal force with its corresponding moment are shown in (Table 3), then an interaction diagram is drawn for each column length using results from the three methods on the same chart as shown in (Figure 11, 12 and 13).

**Table 3 Results for W lacing type columns**

| Model Name | Method 1 | | Method 2 | | Method 3 | | 2/1 | 3/1 |
|---|---|---|---|---|---|---|---|---|
| | P (kN) | M (kN.m) | P (kN) | M (kN.m) | P (kN) | M (kN.m) | | |
| **W-10-0** | 3621 | 0 | 3424 | 0 | 3566 | 0 | 0.95 | 0.98 |
| **W-10-0.2** | 2025 | 405 | 1905 | 381 | 2007 | 401 | 0.94 | 0.99 |
| **W-10-0.5** | 1257 | 629 | 1171 | 585 | 1265 | 632 | 0.93 | 1.01 |
| **W-10-0.8** | 917 | 733 | 849 | 679 | 928 | 743 | 0.93 | 1.01 |
| **W-10-1.0** | 777 | 777 | 718 | 718 | 789 | 789 | 0.92 | 1.02 |
| **W-10-1.2** | 675 | 810 | 622 | 746 | 687 | 824 | 0.92 | 1.02 |
| **W-10-∞** | 0 | 1016 | 0 | 938 | 0 | 1065 | 0.92 | 1.05 |
| **W-15-0** | 3321 | 0 | 2893 | 0 | 3117 | 0 | 0.87 | 0.94 |
| **W-15-0.2** | 1836 | 367 | 1611 | 322 | 1778 | 356 | 0.88 | 0.97 |
| **W-15-0.5** | 1165 | 582 | 1007 | 503 | 1158 | 579 | 0.86 | 0.99 |
| **W-15-0.8** | 861 | 689 | 737 | 590 | 866 | 693 | 0.86 | 1.01 |
| **W-15-1.0** | 735 | 735 | 627 | 627 | 743 | 743 | 0.85 | 1.01 |
| **W-15-1.2** | 642 | 771 | 545 | 654 | 650 | 781 | 0.85 | 1.01 |
| **W-15-∞** | 0 | 1024 | 0 | 846 | 0 | 1065 | 0.83 | 1.04 |
| **W-20-0** | 2972 | 0 | 2266 | 0 | 2560 | 0 | 0.76 | 0.86 |
| **W-20-0.2** | 1658 | 332 | 1281 | 256 | 1516 | 303 | 0.77 | 0.91 |
| **W-20-0.5** | 1071 | 536 | 815 | 407 | 1029 | 514 | 0.76 | 0.96 |
| **W-20-0.8** | 803 | 642 | 603 | 482 | 788 | 630 | 0.75 | 0.98 |
| **W-20-1.0** | 690 | 690 | 515 | 515 | 683 | 683 | 0.75 | 0.99 |
| **W-20-1.2** | 606 | 727 | 449 | 539 | 604 | 724 | 0.74 | 1.00 |
| **W-20-∞** | 0 | 1018 | 0 | 717 | 0 | 1065 | 0.70 | 1.05 |

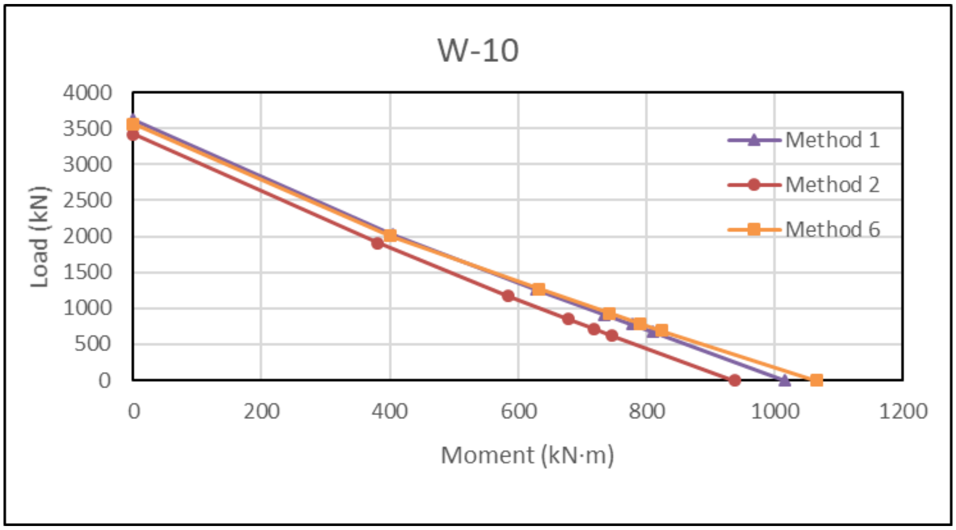



**Figure 11 Interaction diagram for W lacing type height 10 m with initial imperfections**

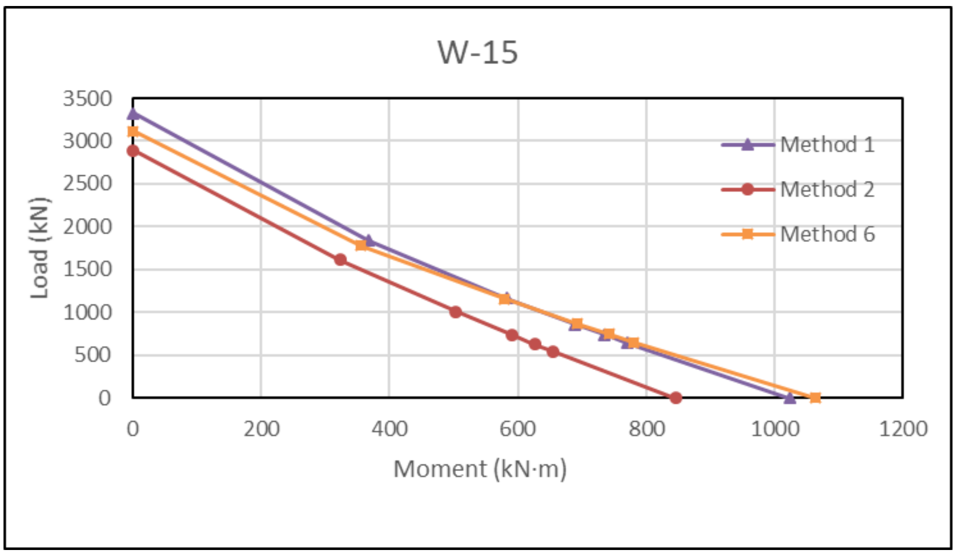



**Figure 12 Interaction diagram for W lacing type height 15 m with initial imperfections**

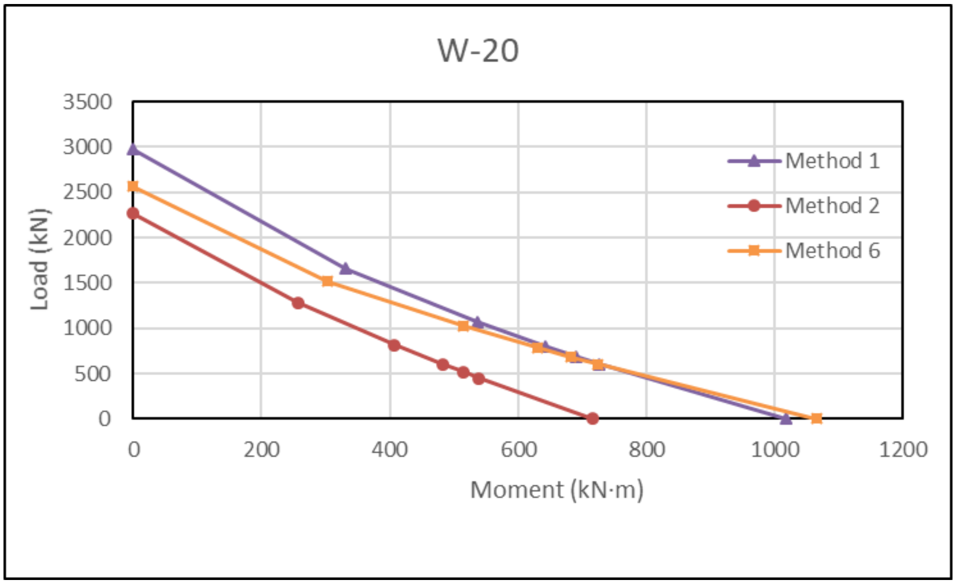



**Figure 13 Interaction diagram for W lacing type height 20 m with initial imperfections**

### 6.2 Results for WH and X Lacing Type Columns

Results for WH and X lacings with comparison between different used methods as well as interaction diagrams are available elsewhere (Iskander et al. 2018).

## 7 CONCLUSION

From the results mentioned in (section 6) and based on the verification (section 4) it is clear that the proposed method could predict the maximum capacity of the built-up column taking into confederation the lacing configuration, the column height, load eccentricity (bending moment over axial load ratio).

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