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NUMERICAL ANALYSIS OF COMBINED-SECTION STEEL COLUMNS

GEORGE ISKANDER[1], EZZELDIN SAYED-AHMED[2], and EMAM SOLIMAN[1]

[1]Dept of Structural Engineering, Ain Shams University, Cairo, Egypt
[2]Dept of Construction Engineering, American University in Cairo, Cairo, Egypt

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 behavior 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 behavior 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 1(a)). 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 1(b).

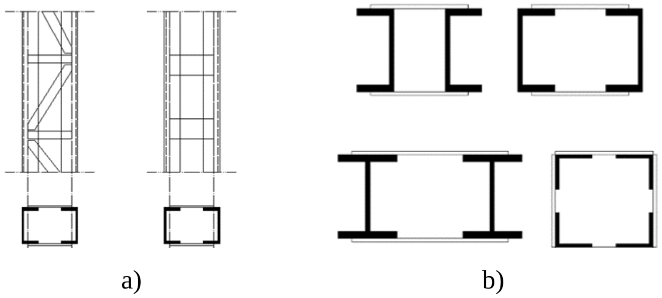

a) b)

Figure 1. Built up columns (a) and sections (b).

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. Research dealing with design of these columns is currently insufficient with the currently available ones reported elsewhere (Iskander 2018).

2 CURRENT DESIGN APPROACH FOR COMBINED COLUMNS

2.1 Eurocode, EN 1993-1-1 (2005)

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;

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

Where,

$$M_{Ed} = \frac{N_{Ed}\, e_o + M^{I}_{Ed}}{1 - \frac{N_{Ed}}{N_{cr}} - \frac{N_{Ed}}{S_v}} \tag{2}$$

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.

$$\frac{\mathrm{N_{ch,Ed}}}{\mathrm{N_{b,Ed}}} \leq 1 \tag{3}$$

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, $N_{b,Ed}$ is the chord axial capacity and S_v is the shear stiffness of the column. This method is discussed in detail elsewhere (Sayed-Ahmed and ElSerwi 2017).

2.2 AISC 360-10 (2010)

AISC 360-10 (2010) 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;

$$\left(\frac{\mathrm{KL}}{\mathrm{r}}\right)_{\mathrm{m}} = \sqrt{\left(\frac{\mathrm{KL}}{\mathrm{r}}\right)_{0}^{2} + \left(\frac{\mathrm{a}}{\mathrm{r_i}}\right)^{2}} \tag{4}$$

where, $(KL/r)_0$ 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)

CSA-S16-14 (2014) recommends that the slenderness ratio of each combined column's chord 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):

$$\rho_e = \sqrt{\rho_o^2 + \rho_i^2} \tag{5}$$

where ρ_o is the slenderness ratio of the column as a single unit and ρ_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-liner 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 DNVGL-RP-C208 (2013). The modulus of elasticity used is 2.1×10^5 MPa and Poisson's ratio is 0.3 for the elastic part. For the plastic part, the provided data from the DNVGL is adopted based on the element thickness. Figure 3 schematically shows the adopted stress-strain curve for the steel.

3.3 Boundary Conditions

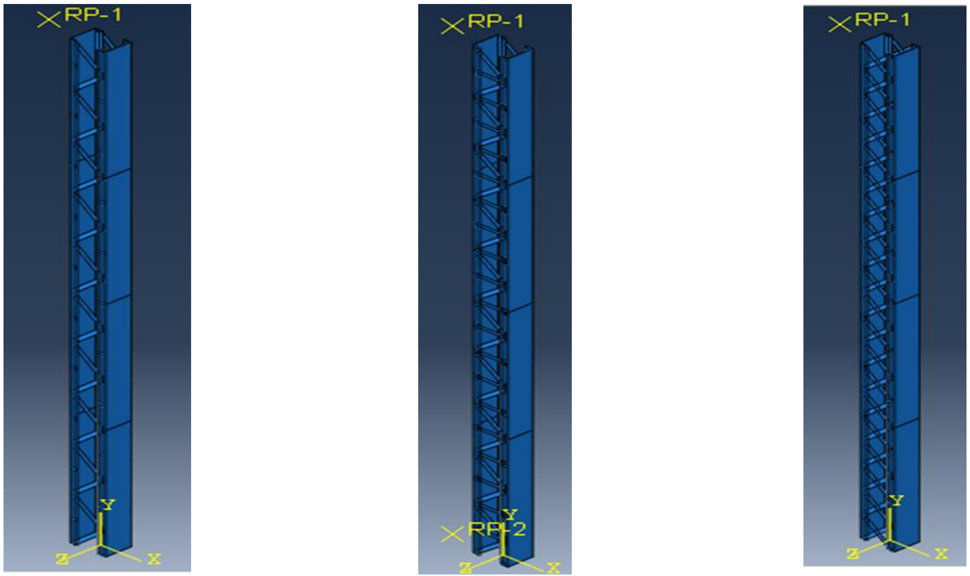
To model the hinged-hinged W- and X-type columns with uniform bending moment over its length, the following boundary conditions are used:

- 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.

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.



W type   WH type   X type

Figure 2. Model assemblies.

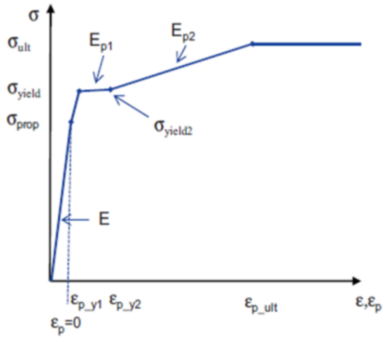


Figure 3. Stress strain curve.

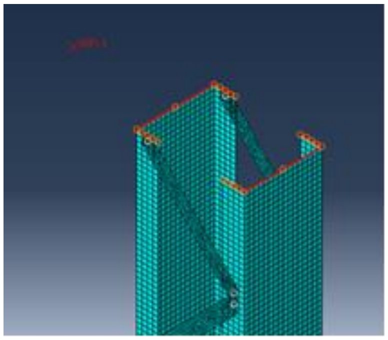


Figure 4. Upper nodes constraint.

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). Their research program consisted 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.

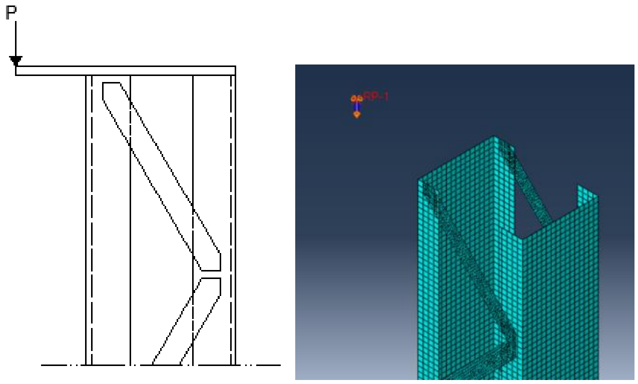


Figure 5. Load assignment.

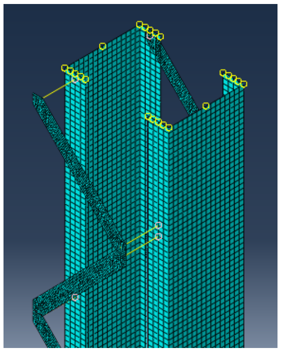


Figure 6. Lacing-chord constraint.

The considered groups are 2000 mm long built-up beam-columns with two UPN 60 chords and lacing members composed of 25×25×3 angles, the columns are divided into five parts with panel length of 400 mm. The total length of the column including the upper and lower pin supports is 2300 mm. 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.

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 intended parametric study using it.

Table 1. Results of the numerical model verification analysis.

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

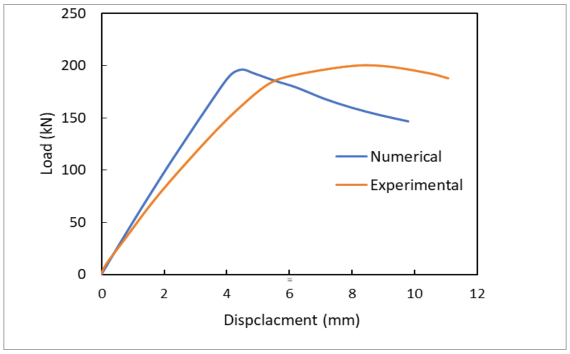


Figure 7. Load-displacement curve for Group 1.

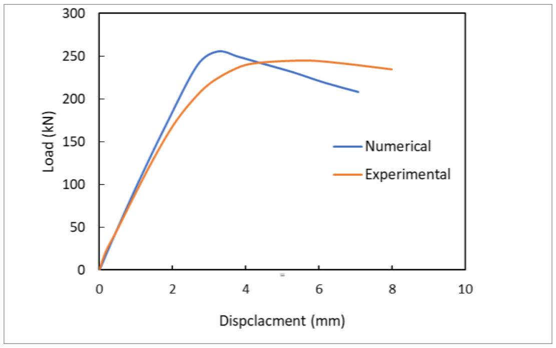


Figure 8. Load-displacement curve for Group 5.

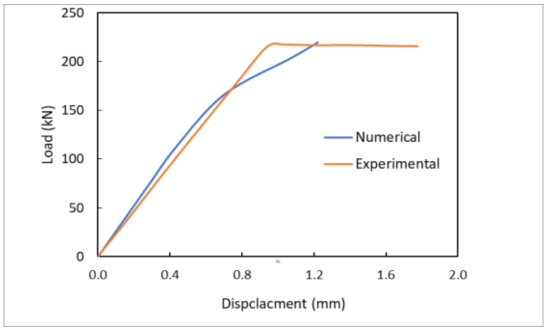


Figure 9. Load-displacement the upper panel for Group 4.

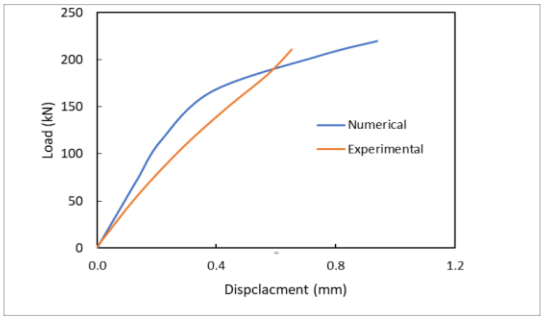


Figure 10. Load-displacement the lower panel for Group 4.

5 CONCLUSIONS

A nonlinear numerical model for combined-section steel columns is built-up and verified against experimental results available from literature. The model can successfully predict the failure load of such columns when subject to eccentric loading. The model will be used to perform a further parametric study and develop procedures to design these columns.

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