

## Buckling and strength of prestressed steel stayed columns

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**ABSTRACT:** Prestressed steel stayed columns have been used since fiftieth of the last century to enhance their critical and maximal capacities in compression. This research deals with central steel tube columns, one and two tube crossarms and spatial prestressed rod or cable stays. Firstly four columns made of stainless steel 1.4301 with one central crossarm and cable stays were tested up to extreme buckling deflections. The following numerical analysis employed geometrically and materially nonlinear analysis with imperfections (3D GMNIA) using ANSYS software. Careful analysis was successfully validated and used to obtain optimal prestressing of stays giving maximal critical loads and maximal collapse loads of the tested columns. All the following parametrical studies cover columns of the same geometrical and nonlinear material characteristics as given or resulted from testing. This enables comparison and evaluation of the significance concerning mode and value of initial deflections, value of prestressing, number of crossarms, material characteristics, sliding of stays at crossarms and ratios of maximal collapse to critical loads. The main results concerning critical loads of an “ideal column” (with amplitudes of initial deflections  $L/500000$ ) and maximal loads of an “imperfect column” (with amplitudes of initial deflections  $L/200$ ) under various prestressings of stays are discussed in a detail. In the conclusions a necessity of GNIA/GMNIA considering respective mode and value of initial deflections is emphasized (linear buckling analysis is not sufficient in such prestressed elements). Also the substantial significance of activating of stays during buckling and radical increase of both critical/maximal loads by adding the second crossarm is presented.

### 1 INTRODUCTION

With the innovative technologies and high strength materials available the prestressed steel structures are becoming always more affordable and required by both engineers and architects. Prestressed stayed columns with cable or rod stays enable design of extremely slender structural elements (Figure 1). Nevertheless, design and realization of these elements require careful techniques, because both buckling and collapse strength under prestressing require nonlinear analysis and sophisticated erection procedures.

### 2 EXPERIMENTS AND THEORY

Four columns with one central crossarm made of stainless steel 1.4301 and stainless steel cable stays were tested up to extreme buckling deformations (Servitova & Machacek 2011). Careful GMNIA using ANSYS software covering measured initial deflections was successfully validated and later used in a study to obtain optimal prestressing of stays giving maximal critical loads and maximal collapse loads of the columns (Macháček & Pichal 2018).

The following parametric study covers columns of the same geometrical dimensions as in the tests (i.e. central tube  $\varnothing 50 \times 2$  [mm] with total length 5000 mm, crossarms  $\varnothing 25 \times 1.5$  [mm] with total length  $2 \times 250 = 500$  mm, but with rod stays  $\varnothing 4$  mm) and the same nonlinear material characteristics of stainless steel concerning columns and crossarms as resulted from testing (Figure 2), while for rod stays in accord with Eurocode 3 ( $E = 200$  GPa). Together with columns



Figure 1. Examples of structures with stayed elements.

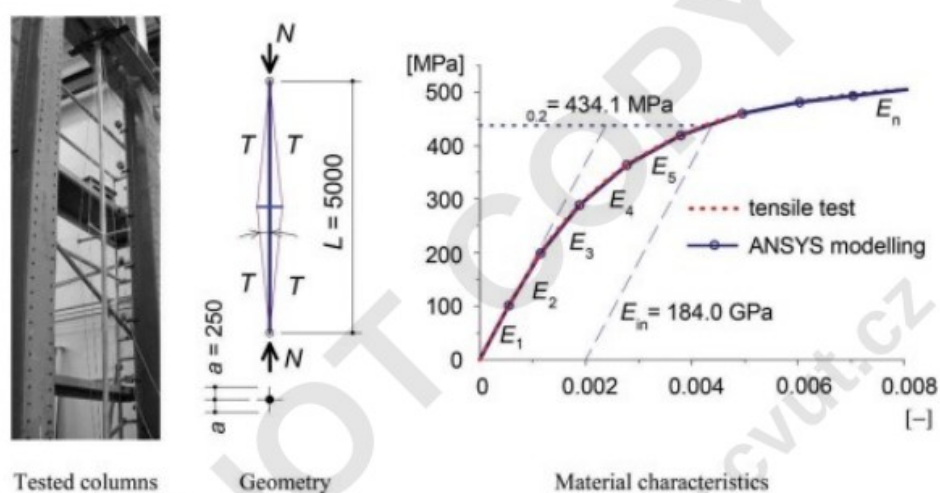


Figure 2. Tested columns and material characteristics.

having one central crossarm also the same columns with two crossarms located in the thirds of the column length were investigated.

Linear buckling analysis (LBA) applied to prestressed stayed columns provides reasonable critical loads only for a limited values of prestressings (in the so called prestressed “zones” 1 and 3 according to investigations of Hafez et al. 1979). Due to a sudden change of the internal energy in a distinctive buckling of the prestressed column and the following restoring of the equilibrium the LBA (Macháček & Pichal 2018, Saito & Wadee 2008) can't be used in mid prestressings (“zone” 2).

Therefore, geometrically and materially nonlinear analysis with imperfections (3D GMNIA) using ANSYS software was employed. The shapes of initial deflections (symmetrical and antisymmetrical, see Figure 3) were introduced in accordance with the first two modes resulting from 2D LBA of columns without any prestress, using SCIA Engineer software (Machacek & Pichal). To model “ideal columns” the negligible values of amplitudes  $w_0 = L/500000$  (i.e. approaching to zero) were introduced, while for “imperfect columns” the amplitudes  $w_0 = L/200$  (corresponding to cold-formed steel tubes in accordance with EN 1993-1-1) were employed.

The 3D finite element (FE) model in ANSYS used elements BEAM188 for the column and crossarm, while LINK188 (with no-compression option) for stays. The mesh optimization resulted into meshing  $L/250$  and  $a/25$  (for designation see Figure 2). First initial deflections were introduced, followed by the relevant prestress through a thermal change (cooling) and finally imposing an axial loads to the column. Newton-Raphson (N-R) iteration was used in the numerical solution.

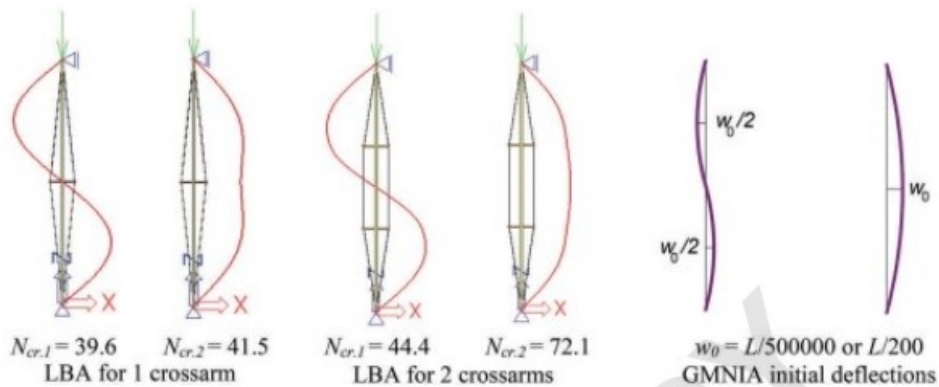


Figure 3. Initial deflections introduced in the studies (LBA for the stays fixed to crossarms).

### 3 PRINCIPAL RESULTS OF STUDIES

#### 3.1 Columns with 1 and 2 crossarms using GMNIA and GNIA

The principal results of 3D GMNIA concerning stayed columns with one central crossarm and columns with two crossarms located in the thirds of the column length are shown in Figure 4. The critical loads of “ideal columns” and maximal loads of “imperfect columns” under various prestress are demonstrated.

The maximal loads in Figure 4 resulted from antisymmetrical initial deflections for columns both with 1 and 2 crossarms. However, the critical loads of “ideal columns” with one central crossarm are determined by symmetric initial deflection, while in the case of two crossarms by antisymmetric initial deflections. The decisive initial deflection mode generally depends on the column geometry, initial deflection amplitudes and level of prestress. When the first two critical loads resulting from the LBA corresponding to the antisymmetric and symmetric modes get closer (as in the studied geometry, see Figure 2), the interactive mode for “imperfect columns” with low initial deflection amplitudes (lesser than required by Eurocode) may be decisive (Saito & Wadee 2008).

Material nonlinearity of stainless steel (Figure 2) decreases the critical and maximal values. As shown in Figure 5, the 3D GNIA using constant Young’s modulus  $E = 200$  GPa gives for the same columns significantly higher critical and maximal values.

Note that even in the “ideal columns” with low prestress the critical load may be increased to corresponding “maximal load” due to activating of the stays on convex side of buckled shape after buckling (shown for “ideal columns” with 2 crossarms only). This is quite important in cases of no stays prestress in practice.

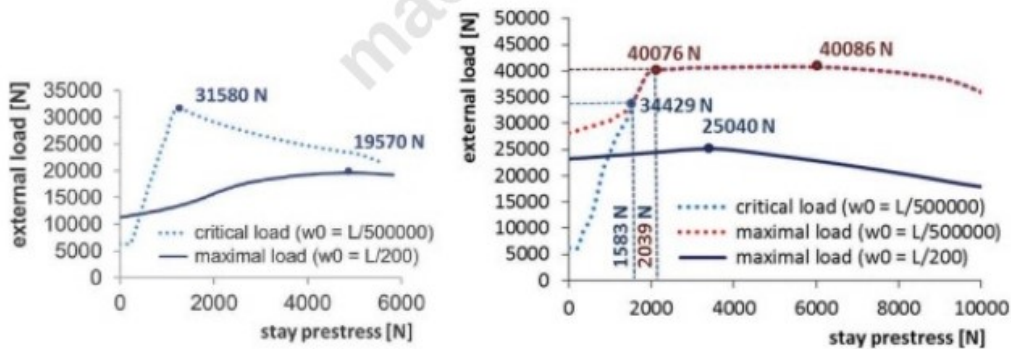


Figure 4. 3D GMNIA: Column with 1 crossarm (left), the same stayed column with 2 crossarms (right).

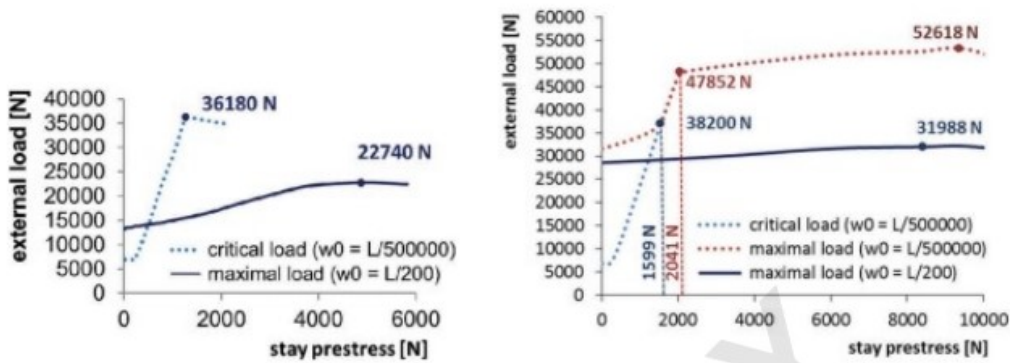


Figure 5. 3D GNIA: Column with 1 crossarm (left), the same stayed column with 2 crossarms (right).

The activating of convex side stays is explained in Figure 6 (3D GMNIA, for symmetrical initial deflections). In a low prestress the buckling starts by slackening of stays (giving “critical load”), followed by immediate activating of stays at convex side of buckling, leading to “maximal load”. On the other side in a high prestress the buckling invokes sudden changes of all stays forces – a drop in concave stays and an increase in convex ones, while both “critical load” and “maximal load” coincide.

### 3.2 Influence of initial deflection amplitude values

The cardinal influence of the value of the initial deflection amplitude follows from Figures 4 and 5. More detailed investigation in this field was performed in GNIA for the column with one central crossarm and antisymmetric initial deflection mode, resulting in maximal loads for various amplitude values as follows:  $w_0 = L/500\,000$  (nearly zero) gives  $N_{max} = 36\,180$  N;  $w_0 = L/100\,000$  gives  $N_{max} = 35\,770$ ;  $w_0 = L/50\,000$  gives  $N_{max} = 35\,430$ ;  $w_0 = L/200$  (amplitude required by Eurocode EN 1993-1-1) gives  $N_{max} = 24\,840$  N.

### 3.3 Support at crossarms

Another study concerned influence of the stays support at the crossarms. In case of rod stays (usually made of Macalloy or Detan rods) the connection is formed by rod end forks, creating a fixed/hinge support. In case of cable stays the support may be either fixed or sliding (with

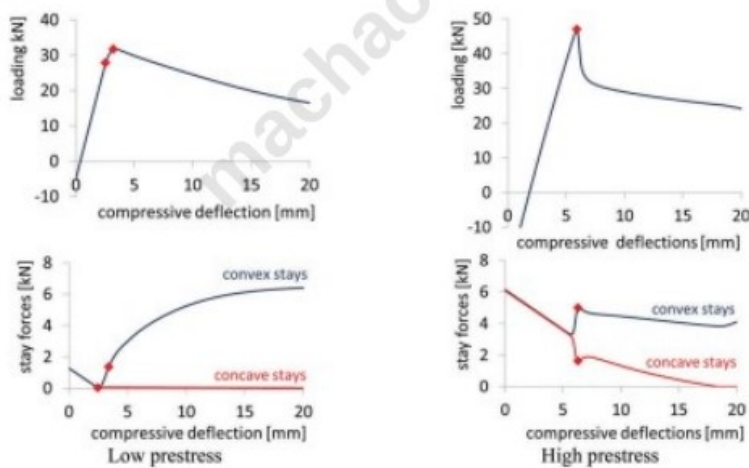


Figure 6. Activating of stays at convex side during buckling.

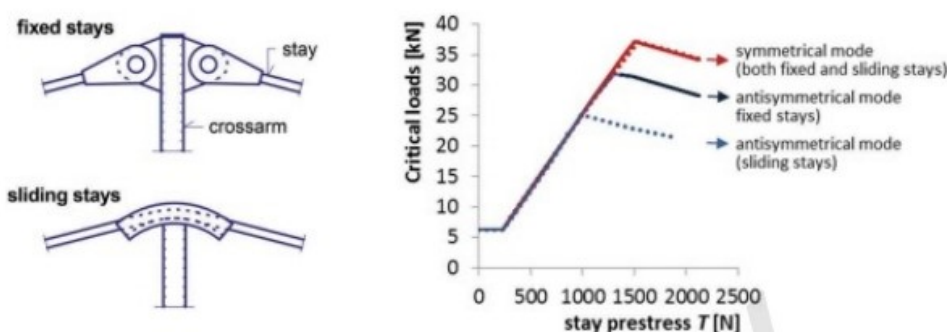


Figure 7. Column with one central crossarm – cable support variations.

cable continuing over a saddle). 3D GMNIA comparison of columns with one central crossarm having either fixed or sliding cable stays is shown in Figure 7. The column under investigation had initial deflection  $w_0 = L/500\,000$  (i.e. representing “ideal columns” and critical loads were evaluated).

#### 4 CONCLUSIONS

- Determination of both critical and collapse loadings require GNIA/GMNIA considering respective mode and value of initial deflections (LBA is not sufficient in such prestressed elements).
- Activating of stays at convex sides of buckling may increase maximal loading in comparison to critical one, especially in low prestressings (see Figures 4 and 5).
- The Eurocode prescribed initial deflections ( $L/200$ ) substantially decrease maximal loadings of “imperfect columns” in comparison to critical loadings of “ideal columns” (in Figure 4 to 62%, in Figure 5 to 61%).
- Sliding stays at crossarms decrease both critical/maximal loadings only in cases of anti-symmetrical buckling.
- Nonlinear behaviour of stainless steel material significantly decreases the maximal loading (the decrease resulting from Figures 4 and 5 is to 78%).
- Adding the second crossarm to the otherwise same column with just one central crossarm leads to substantial increase of both critical/maximal loadings (in the investigated columns up to 28%).

#### ACKNOWLEDGEMENT

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