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GENERAL BUCKLING ANALYSIS OF STEEL BUILT-UP COLUMNS USING FINITE ELEMENT MODELLING

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Abstract. The paper investigates the general buckling of an axially loaded column using the finite element method with different slenderness ratios of axes *x-x* and *z-z*. The paper deals with three different modes of buckling. The conducted numerical experiments have suggested correction factors and appropriate buckling modes of the built-up columns. The obtained modelling results were compared with data on analytical calculations made according to Lithuanian national codes STR and Eurocode 3. The FEM analysis of the built-up column has showed that both codes (STR and EC3) are giving safe enough results for a considered type of conditions for column support.

Keywords: steel built-up column, buckling modes, general buckling analysis, FEM simulation, comparison.

1. Introduction

The mechanical behaviour of structure and its separate members can be analysed using different methods. The most efficient way of determining the capacity of structural bearing is experimental investigation. However, this way is expensive enough and requires additional technical equipment. A simpler method is structural analysis using *the finite element method* (FEM). The simplification of conditions for real structural behaviour has some effect on the final result; nevertheless, this method reflects the main peculiarities of real structure.

FEM modelling is widely used for analyzing various structures made from different materials and for comparing it with the results of analytical (Kalochairetis, Gantes 2011) and experimental investigation (Blaževičius *et al.* 2011).

Beck and Doria (2008) examined the results of the resistance of the column placed in the 1st section. The obtained data were calculated according to the design codes of various countries and compared with the results of FEM modelling. FEM analysis was done using the nonlinear method taking into account the initial imperfections and bending stresses. The results of analytical analysis and FEM simulation are fairly close.

A good coincidence of experimental and FEM investigation results of tapered columns was presented by Šapalas (2000). A frame with the tapered members was numerically investigated by Samofalov and Šlivinskas (2009).

The most interesting fact is that according to requirements EC3, it is not necessary to check the buckling capacity of the entire built-up members about axis *x-x* (Fig. 1). Using personal experience and that gained by other authors (Juozapaitis *et al.* 2009; Galambos, Surovek 2008), investigation into the buckling capacity of the axially loaded column with different slenderness ratios of axes *x-x* and *z-z* has been done taking into account the assumptions of STR 2.05.08:2005 (STR) and Eurocode 3-1-1(EC3).

The carried out investigation has analysed the following situations:

1st case: the column shape is perfectly straight, both chords are loaded by the same axial force $N_{Ed}/2$ (according to STR);

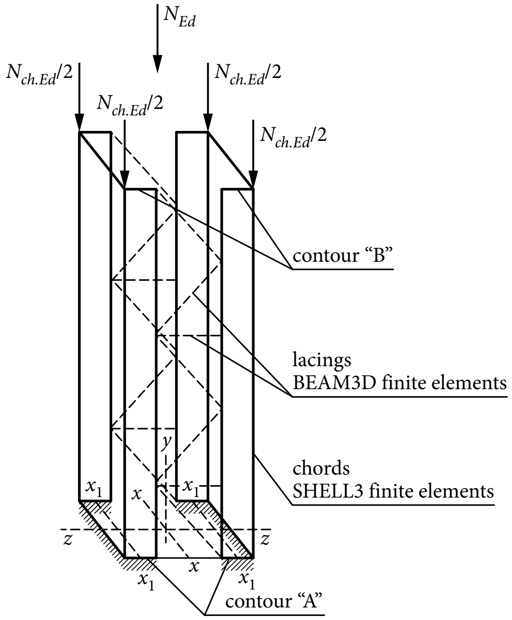

Fig. 1. An axially compressed steel built-up column

2^{nd} case: the column shape is perfectly straight, both chords are loaded by axial force $N_{ch.Ed.EC3}$ and additional bending moment $M_{Ed.EC3}$ due to initial imperfection;

3^{rd} case: the column shape is not straight due to initial bow imperfection e_0, both chords are loaded by the same axial force $N_{Ed}/2$.

The paper presents a comparison made between modelling results obtained using FEM and results of analytical calculations (Šapalas, Šaučiuvėnas 2011).

Šapalas and Šaučiuvėnas (2011) used analytical methods according to STR and EC3 and discovered that the general buckling of the steel built-up column about its main axis *x-x* was possible in some cases.

2. Initial Data

The following parameters of the built-up column were chosen (Fig. 1):

- chords – UPN300;
- lacings – angles L50×5 (EN 10056-1: 1999);
- the distance between the centres of chords – $h_0 = a = 0.6$ m.

Initial data on FE analysis are given in Table 1.

Two cases of support condition (Fig. 2) have been analysed:

- rigid support in the base and pin at the top (Fig. 2a);
- rigid support in the base and free top end (Fig. 2b).

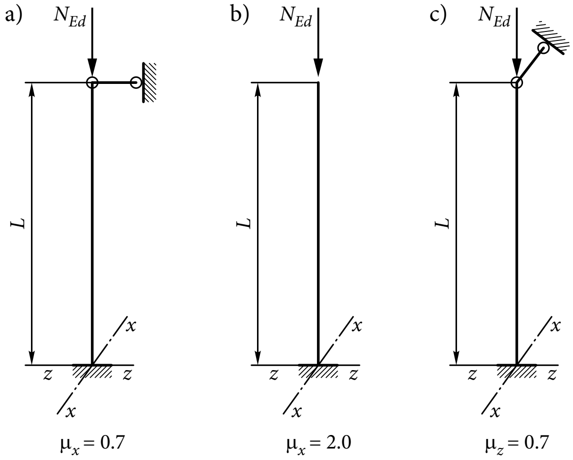

Fig. 2. End support conditions of the column: about axis *x-x* (a) and (b), about axis *z-z* (c)

Table 1. Column parameters

Parameter	1 var	2 var	3 var	4 var
L	15	30	15	30
μ_x	0.7	0.7	2.0	2.0
μ_z	0.7	0.7	0.7	0.7
$L_{eff.x}$	10.5	21	30	60
$L_{eff.z}$	10.5	21	10.5	21
λ_x	35	70	100	200
λ_z	90	180	90	180
$N_{Ed.STR}$	2020	580	1672	472
$N_{Ed.EC3}$	1530	460	1370	370
$N_{ch.Ed.EC3}$	850	280	850	280
$M_{Ed.EC3}$	51	31	98	57
$\Delta_{x.STR}$	0.61	0.23	1	1
$\Delta_{z.STR}$	1	1	0.84	0.82
$\Delta_{x1.EC3}$	0.46	0.15	0.46	0.15
$\Delta_{z.EC3}$	1	1	1	1

Notes:

$N_{Ed.STR}$ – the value of maximum axial force in the column according to the STR method;

$N_{Ed.EC3}$ – the value of maximum axial force in the column according to the EC3 method;

$N_{ch.Ed.EC3}$ – the value of axial force (taking into account an additional bending moment due to the initial bow imperfection) in one chord according to the EC3 method;

$M_{Ed.EC3}$ – the value of a bending moment according to the EC3 method;

$\Delta_{x.STR}$ – the value of the stability reserve of the column about axis *x-x* according to the STR method;

$\Delta_{z.STR}$ – the value of the stability reserve of one chord about axis *z-z* according to the STR method;

$\Delta_{x1.EC3}$ – the value of the stability reserve of one chord about axis x_1-x_1 according to the EC3 method;

$\Delta_{z.EC3}$ – the value of the stability reserve of one chord about axis *z-z* according to the EC3 method

In both cases, support about axis *z-z* is rigid (Fig. 2c).

All dimensions in Table 1 are in [m], [kN] and [kNm].

3. Buckling Analysis Applying the Finite Element Method

The column has been modelled applying an assumption that its cross sections are subjected under axial force only and end-section "A" has rigid support. End-section "B" has either support in *x* and *z* directions, either only in *x* direction (Fig. 1). Because the buckling of one lacing is not a critical case, the column chords were modelled using SHELL type finite elements, and lacings – applying BEAM3D type finite elements. Load has been applied on the top of the column. For all four variants of the columns (Table 1), buckling analysis has been performed considering three situations (Fig. 3).

The FEM model of the investigated column is shown in Fig. 4 and its flexural buckling shape modes are shown in Figs 5 and 6.

For each variant, the value of ultimate axial force (Table 1) was calculated according to STR or EC3. The values of general buckling correction factors $\alpha = N_{FEM}/N_{analit}$ for buckling loads have been obtained from FE models and analytical calculations are given in Table 2.

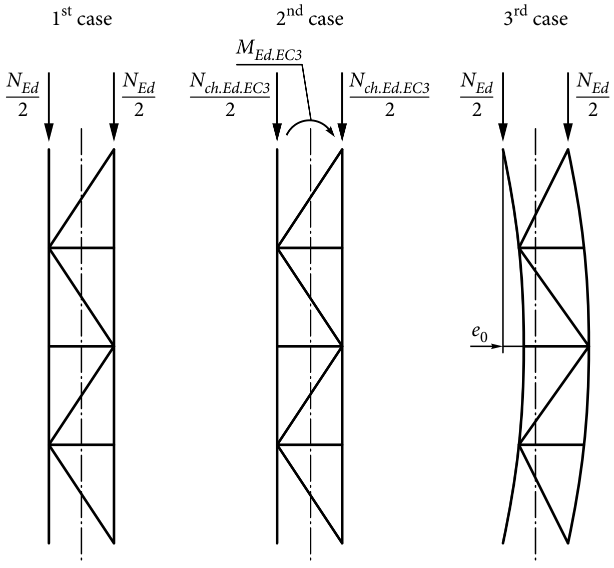

Fig. 3. Three situations of the buckling analysis of the column

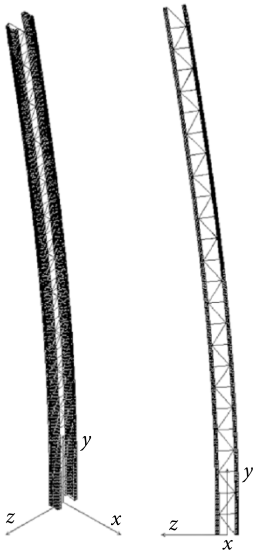

Fig. 5. The mode of the flexural buckling shape of the steel built-up column about axis *x-x* (in-plane)

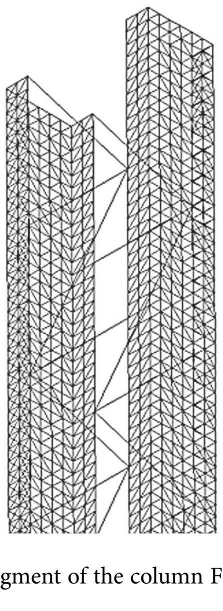

Fig. 4. Fragment of the column FEM model

Fig. 6. The mode of the flexural buckling shape of the steel built-up column about axis *z-z* (out-of-plane)

Table 2. The values of general buckling correction factors α_x, α_z

Parameter	1 var	2 var	3 var	4 var
1st situation				
α_x	–	–	1.51	1.38
α_z	1.78	1.58	2.14	1.94
2nd situation				
α_x	–	–	1.48	1.16
α_z	2.11	1.63	1.92	1.38
3rd situation				
α_x	–	–	1.84	1.76
α_z	2.35	1.98	2.61	2.46

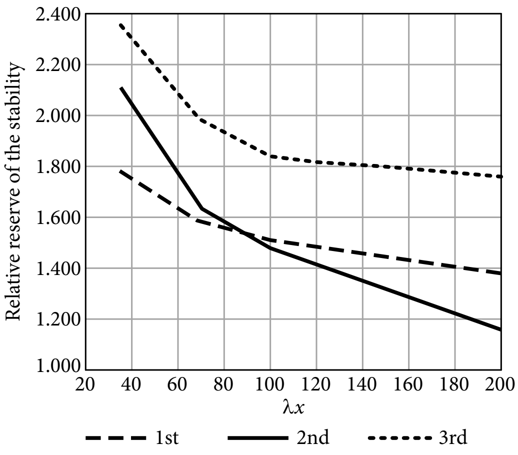

Fig. 7. General buckling correction factors α_x, α_z for three situations

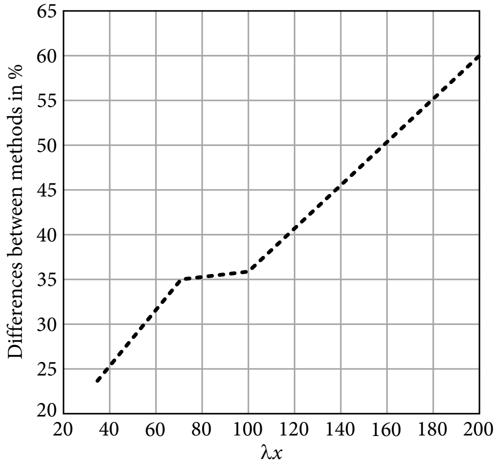

Fig. 8. Difference between the 2nd and 3rd situation

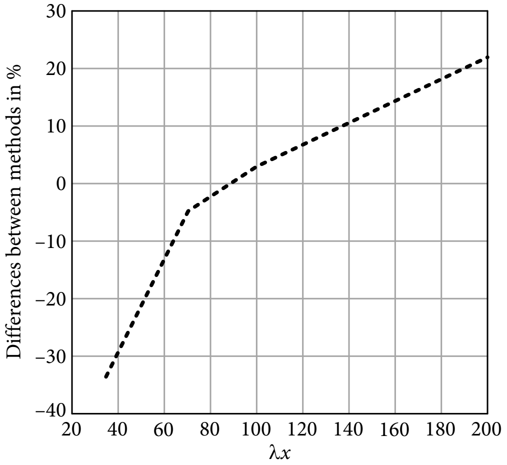

Fig. 9. Difference between the 1st and 2nd situation

4. Comparison of Results

The values of general buckling correction factors defined by FEM modelling are presented in Fig. 7.

As shown in Table 2 and Fig. 7, the values of buckling correction factors for the 2nd and 3rd situation are different (analytically they should be the same). A comparison of experimental results obtained using two ways of the same assumptions of EC3 showed a more precise way of modelling the 2nd situation (Fig. 8) – modelling a straight column without imperfection but applying a recalculated value of axial force for each chord with an additional bending moment.

The difference between the results obtained applying STR and EC3 methods is not that big and makes only 22%–30% (Fig. 9). Then, the slenderness ratio of the column is $\lambda_x = 35$ and the stability correction factor is 2.11 according to EC3 and 1.78 according to the STR method. Thus, in agreement with the EC3 method for not slender column stability, reserve is 30% greater than that compared to the STR method.

When the value of slenderness ratio is $\lambda_x = 200$, the value of the buckling correction factor is 1.16 according to EC3 and 1.38 according to STR. Therefore, according to the EC3 method for very slender column stability, reserve is 23% smaller than that for the STR method.

The 1st and 2nd variants show column buckling (Fig. 6) about axis *z-z* (out-of-plane). The buckling case is one chord buckling about the minor axis of the column. Analytical calculation discloses that when using EC3 assumption this buckling mode is similar to that (Table 1) used for STR.

The calculation results of the 3rd and 4th variants show column buckling (Fig. 5) about *x-x* axis (in-plane). The buckling mode is the general buckling of the built-up column about the main axis. Due to analytical calculation and in accordance with the STR method, this buckling mode is the same (Table 1).

However, according to EC3 method the most critical buckling mode of one chord about column's minor axis should be taken (Table 1). Such buckling mode is also achieved later; then the values of general buckling correction factor are bigger (Table 2).

In both STR and EC3 design methods, the analytical values of axial buckling resistance N_{Ed} are smaller than numerical modelling values (values of general buckling correction factors are always higher than one). This means that both methods are safe enough for such a type of the column and their final conditions.

5. Conclusions

1. The article presents modelling the steel built-up column using FEM according to the assumptions of National Lithuania Code STR and Eurocode 3.
2. The difference between STR and EC3 methods is not that big and varies from 22% to 30%.
3. When the value of column slenderness ratio is $\lambda_x \leq 80$, stability reserve according to the EC3 method is greater than that of STR. Then, slenderness is $\lambda_x > 80$ and the reserve of buckling resistance using the STR method is larger.
4. For the 1st and 2nd variants, the mode of the column buckling shape is one chord buckling about the minor axis of the column; this buckling mode is the same according to EC3 and STR. For the 3rd and 4th variants, the mode of the column buckling shape is the built-up column that lost stability about the main axis. However, according to the EC3 method the most critical buckling mode of one chord about the column's minor axis should be taken.
5. The presented results of FEM modelling of the steel built-up column with applied end conditions affirm the both methods (STR and EC3) being safe enough.

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PLIENINIŲ SPRAGOTŲJŲ KOLONŲ BENDROJO PASTOVUMO SKAIČIAVIMAS, MODELIUOJANT UŽDAVINĮ BAIGTINIAIS ELEMENTAIS

V. Šapalas, G. Šaučiuvėnas, A. Komka

Santrauka. Straipsnyje nagrinėjami plieninių spragotųjų kolonų elgsenos ypatumai, atsižvelgiant į skirtingas STR 2.05.08:2005 ir EC3-1-1 metodikas. Didžiausią susidomėjimą kelia faktas, kad, taikant EC3 metodiką, nėra nagrinėjama spragotosios kolonos kluptis apie didesnio standumo *x–x* ašį (1 pav.). Naudojantis turima ir kitų autorių patirtimi apžvelgta spragotosios centriškai gniuždomos kolonos elgsena, siekiant nustatyti jos klumpamąją galią, kai kolonos liauniai yra didesnio standumo, o mažesnio standumo plokštumoje yra skirtingi. Nagrinėtos trys skaičiuotinės situacijos: 1) spragotoji kolona idealiai tiesi, o abi kolonos juostos perima vienodas ašines jėgas (STR2.05.08:2005 prielaida); 2) spragotoji kolona tiesi, bet kolonos juostos ašinės jėgos padidintos dėl pradinio kolonos nuokrypio nuo tiesiosios ašies ir papildomo lenkiamojo momento (EC 3-1-1 prielaida); 3) kolona su pradiniu nuokrypiu, o ašinės juostų apkrovos yra vienodos (EC3-1-1 prielaida). Pradiniai modeliavimo duomenys pateikti 1 lentelėje. Kolonos juostos modeliuotos plokštelės tipo baigtinais elementais, o tinklelio strypai – strypiniais. Kolonos įtvirtinimo sąlygos ir skaičiuojamieji ilgiai pateikti 2 pav. Atlikus skaitinį modeliavimą gauti kolonos bendrojo klupumo pataisos koeficientai (2 lentelė) ir kolonos klupumo pavidalai (5 ir 6 pav.).

Kaip matyti iš 7 pav., skaitinio modeliavimo rezultatai 2-uoju ir 3-iuoju atvejais yra skirtingi, nors turėtų būti vienodi modeliuojant pagal EC3 prielaidas. Galima teigti, kad antruoju atveju (spragotoji kolona tiesi, bet kolonos juostų ašinės jėgos padidintos dėl pradinio kolonos nuokrypio ir papildomo lenkiamojo momento) gaunami tikslesni rezultatai.

Skirtumas tarp 1-ojo (STR) ir 2-ojo atvejo (EC3) nėra didelis; nuo 22 % iki 30 % (9 pav.). Kai kolonos liaunis $\lambda_x = 35$, pataisos koeficientas yra 2,11, naudojant EC3, ir 1,78, taikant STR metodą. Nedidelio liaunio kolonų bendrojo klupumo atsarga, naudojant EC3 prielaidas, yra 30 % didesnė nei taikant STR metodą. Kai liaunis $\lambda_x = 200$, pataisos koeficientas yra 1,16 pagal EC3 ir 1,38 pagal STR metodiką. Liaunų kolonų klupumo atsarga pagal EC3 yra 23 % mažesnė nei pagal STR metodą.

1-uoju ir 2-uoju atveju (1 lentelė) kolonų kluptis įvyko iš plokštumos apie *z–z* ašį (6 pav.), nes šioje plokštumoje kolonų liaunis didesnis. Kolonų klupumo pavidalas atitinka analitinius skaičiavimus tiek STR, tiek EC3 metodu.

3-uoju ir 4-uoju atveju (1 lentelė) kolonos klupo apie *x–x* ašį (5 pav.), nes šioje plokštumoje kolonos liaunis gerokai didesnis (2 pav.). Klupumo pavidalas atitinka analitinius skaičiavimus pagal STR metodiką. Taikant EC3 metodiką kolona turėjo klupti iš plokštumos, t. y. apie *z–z* ašį. Šis klupumo pavidalas taip pat buvo pasiektas, tačiau vėliau (žr. pataisos koeficientus 2 lentelėje.). Taip yra todėl, kad pagal EC3 metodiką tiesiog nereikalauja visos kolonos pastovumo tikrinti apie *x–x* ašį.

Atlikus skaitinius modeliavimus galima teigti, kad abu metodai STR ir EC3 yra saugūs (pataisos koeficientai visada didesni už vienetą) duotomis kolonos galų įtvirtinimo sąlygomis. Tik mažo liaunio kolonų $\lambda_x \leq 80$ didesnė atsarga gauta STR metodu, o liaunų kolonų, kai $\lambda_x > 80$ didesnė atsarga gauta taikant EC3 metodą.

Reikšminiai žodžiai: plieninė spragotoji kolona, klupumas, bendrojo pastovumo skaičiavimas, modeliavimas baigtiniais elementais.

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