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NUMERIČKA EVALUACIJA FLEKSIONOG IZVIJANJA NAKNADNO TERMIČKI OBRAĐENIH I HLADNOOBLIKOVANIH STUBOVA ELIPSASTOG POPREČNOG PRESEKA

Rezime:

Šuplji profili elipsastog poprečnog preseka se od skora mogu naći na tržištu. U važećem Evrokodu za čelične konstrukcije EN 1993-1-1, ne postoje odredbe koje se odnose na elipsaste preseke. Cilj ovog rada je predstaviti komparativnu analizu ponašanja hladnooblikovanih i naknadno termički obrađenih aksijalno pritisnutih stubova elipsastog poprečnog preseka. Analizirani su zglobno oslonjeni stubovi različitih vitkosti, uključujući uticaj početnih geometrijskih imperfekcija. Nelinearno ponašanje materijala modelirano je na osnovu rezultata testova na zatezanje prikazanih u prethodnim ispitivanjima. Dobijeni numerički rezultati pokazuju slično ponašanje pri izvijanju za sve stubove veće vitkosti, dok u slučaju manjih vitkosti, izvijanje hladnooblikovanih elemenata odgovara nižim krivama izvijanja.

Ključne reči: krive izvijanja, elipsasti šuplji profili, fleksiono izvijanje, numerička analiza

NUMERICAL EVALUATION OF FLEXURAL BUCKING OF HOT-FINISHED AND COLD-FORMED EHS COLUMNS

Summary:

Elliptical hollow sections (EHS) have been recently introduced to the construction market. However, in the current Eurocode standard for steel structures EN 1993-1-1, there are no design criteria defined for EHS. The aim of this paper is to present a comparative numerical analysis of behaviour of cold-formed and hot-finished EHS columns exposed to flexural buckling under pure axial compression. Pin-ended columns of various slendernesses without lateral restrains and with incorporated geometrical imperfections are analysed. Material nonlinear behaviour is included through experimental tensile test results adopted from previous researches. According to obtained numerical results, similar buckling behaviour is observed for both hot-finished and cold-formed columns of higher slenderness, while in the lower slenderness region, cold-formed compressed members tend to lower buckling curves.

Key words: buckling curves, elliptical hollow sections, flexural buckling, numerical analysis

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1. INTRODUCTION

Square, circular and rectangular hollow sections have been widely used in construction for the last few decades. However, elliptical hollow sections (EHS) have only recently been introduced to the construction market. Comparing to circular hollow sections (CHS), EHS of the same area have greater bending capacity around the major axis of inertia. The other advantage of EHS is their aesthetic appearance, therefore they are used in exposed steelwork. In the past years, elliptical hollow sections are implemented as columns in the Zeeman building at the University of Warwick (2003), in the Barajas airport building in Madrid (2004) and the Cork airport in Ireland (2006), then as supporting members for a glass façade in the Heathrow airport building in London (2007) and as an arches of the pedestrian Society bridge in Scotland (2005) [1].

However, in the current Eurocode standard for steel structures EN 1993-1-1 [2], there are no design criteria defined for EHS. Recent studies investigated behaviour of elliptical cross-sections under axial compression [3], bending [4] and combined actions [5]. A procedure for elliptical cross-section classification is proposed [6] and research of flexural buckling of EHS columns has been performed [7]. However, mentioned studies were exclusively focused on hot-finished hollow sections. The other option for tubular element production is cold-forming. Considering different fabrication processes in the case of cold-forming than in the case of hot-finishing method, and as an effect, different material properties, dissimilar behaviour of hot-finished and cold-formed structural members is expected.

The process of cold-forming is conducted at ambient temperature by compressing and squeezing steel sheets through set of rollers. In order to produce a tube section, steel sheets are afterwards welded. Additional rolling could be performed in order to get elliptical shape from circular section. Hot-finishing process consists of the same procedures as cold-forming, but with an addition of subsequent heat treatment in a furnace. It is noted that mentioned hot-finishing process differs from hot-forming process. The latter one does not include any rolling in ambient conditions, but only at temperatures above the material re-crystallization temperature, which means that the whole manufacturing process is conducted at elevated temperatures. Although hot-finished and hot-formed sections are often treated equally in design, recent research shows that their mechanical properties are actually different [8].

The aim of this paper is to present comparative numerical analysis of behaviour of cold-formed and hot-finished EHS columns exposed to flexural buckling under pure axial compression. As less common in the market, hot-formed sections are not included into this research. Numerical modelling is performed in the finite element software package ABAQUS [9]. Pin-ended columns with different slenderness, both hot-finished and cold-formed are analysed under axial loading. Geometrical properties of column cross-sections are adopted according to EHS products that could be found on a market nowadays [10]. Material nonlinear behaviour is included through experimental tensile test results presented in previous researches [7,11,12].

2. NUMERICAL ANALYSIS

The flexural buckling study presented in this paper analyses elliptical hollow sections of geometry corresponding to hot-finished sections manufactured by Tata Steel [10], with an aspect ratio of two. In order to avoid the influence of local buckling occurrence, it is decided to analyse sections of the class 1, 2 or 3 [2]. Limiting slenderness value for class 4 was calculated through equivalent diameter, according to equations proposed by Gardner and Chan [6]. The adopted cross-section for analysis is EHS of overall dimensions 150x75 mm and wall thickness of 5 mm.

Four different numerical column models were developed, with member lengths of 700, 1500, 2300 and 3100 mm, as it was performed in experimental research of flexural buckling of hot-finished EHS columns done by Chan and Gardner [7]. Therefore, a range of nondimensional column slenderness of the importance for describing buckling curves is included. Columns are pin-ended and, as only buckling about minor axis is simulated, there were no lateral supports added along the column height.

Numerical simulations are performed in the finite-element software package ABAQUS [9]. Finite elements implemented in numerical models are shell elements S4R with reduced integration and with six degrees of freedom per node. Uniform mesh density is chosen with finite element size of 7.5 mm, adopted according to mesh convergence study.

In the first step of numerical simulation, Eigenvalue analysis is conducted in order to determine buckling modes. Secondly, the modified Riks method is used for simulating the member behaviour in plastic stress domain, accounting material and geometrical nonlinearities.

Shapes of overall and local imperfections are incorporated in the model through corresponding buckling modes obtained in Eigenvalue analysis and by setting adequate imperfection amplitudes. According to recommendations given in EN 1993-1-5 [13], the advised value of geometric imperfection amplitude for numerical simulation is 80 % of fabrication tolerance. For out of straightness of circular hollow section, the fabrication tolerance is 1/500 of member length [14,15]. However, for numerical analysis performed in this research, the imperfection is applied through half-sine wave function with the amplitude of 1/1000 of member length, as well as it was done by Chan and Gardner in numerical parametric study and that showed the best agreement with experimental results [7]. Based on Chan's and Gardner's experimental research of the elliptical section compressive resistance [3], the local imperfection magnitude is applied as 1/100 of section thickness.

Material properties of cold-formed and hot-finished steel sections are taken into account through results of tensile coupon tests that are conducted in experimental investigations of elliptical and oval hollow sections. Quach and Young [11] obtained stress-strain curves for material coupons taken from different parts of section along a perimeter, for both cold-formed and hot-finished EHS. In the case of hot-finished sections, insignificant differences in material behaviour of the flattest coupons and corner coupons are observed. Contrary, material properties of cold-formed sections are not uniform throughout elliptical perimeter – corner coupons have greater yield stress and tensile strength, but smaller ductility. This is due to the manufacturing process, as curved parts of section were subjected to local cold bending. In the research of hot-finished EHS done by Chan and Gardner [7], only coupons from the flattest portion of section were tested. Similarly, when cold-formed oval hollow sections were investigated by Zhu and Young [12], only mechanical properties of flat coupons are obtained.

The summation of all stress-strain curves implemented in numerical models in this research is presented in Figure 1 and in the following list:

- hot-finished coupon (HF) tested by Chan and Gardner [7],
- hot-finished coupon (HF) tested by Quach and Young [11],
- cold-formed coupon (CF) from the flattest part of section tested by Quach and Young [11],
- cold-formed coupon (CF) from the most curved part of section tested by Quach and Young [11],
- cold-formed coupon (CF) from the flat part of oval hollow section tested by Zhu and Young [12].

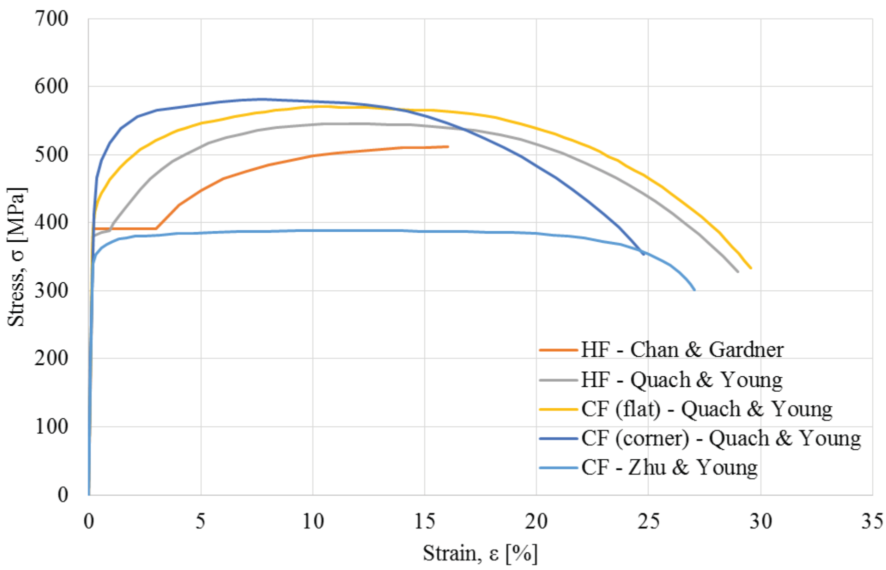

Figure 1 – Stress-strain curves for hot-finished and cold-formed steel sections

It could be observed from Figure 1 that the shape of the material stress-strain curve is different for cold-formed and hot-finished sections. Cold-formed sections exhibit gradual yielding behaviour with enhanced material properties, whereas hot-finished sections have sharp yielding stress–strain curves. The feature of the latter one is a yield plateau with noticeable yield stress f_y, while for cold-formed sections, the value of yield stress f_y is not obvious and 0.2 % proof stress $f_{0.2}$ needs to be determined. Behaviour of hot-finished steel better fits the behaviour of virgin steel material. Contrary, a cold-forming process causes a change in the stress–strain dependency of the basic material. However, even for the presented two hot-finished EHS, the lengths of the yield plateaus differ. This is due to the difference in manufacturing process after cold-rolling, as hot-finished sections tested by Chan and Gardner were exposed to the temperature of 900 ˚C, while for EHS tested by Quach and Young, heat treatment was performed at the temperature of approximately 750˚C.

The part of a stress-strain curve which shows the importance for simulation of flexural buckling is the part before reaching the material strength f_u. Therefore, the material curve obtained by Chan and Gardner is presented in Figure 1 in the same way as it is given in their research, without post ultimate material behaviour.

In order to incorporate material properties into the numerical model, except defining Young's modulus and Poisson's ratio for elastic analysis, it was necessary to define true stress and true plastic strain for describing plastic behaviour of material. It is done according to the following relations as specified in Abaqus user's manual [9]: $\sigma_{true} = \sigma(1+\varepsilon)$ and $\varepsilon_{true,pl} = \ln(1+\varepsilon) - \sigma_{true}/E$, where E is Young's modulus.

Residual stresses usually arise due to cooling effects after hot-finishing, employed welding processes or by the prevention of springback introduced during manufacturing operations. Measurement of residual stresses in elliptical hollow sections is done by Law and Gardner for hot-finished members [16] and by Quach and Young for both hot-finished and cold-formed EHS [11]. Experimental results show that residual stresses in hot-finished sections are significantly smaller than those in cold-formed sections. During a production process, cold-formed sections are exposed to plastic deformation, so after elastic unloading, residual stress is induced. During heat treatment, a considerable amount of residual stress in hot-finished sections is released, as at elevated temperatures yield stress and Young's modulus decrease [8]. However, in this paper residual stresses are not explicitly included in the numerical analysis, according to numerical models developed by Chan and Gardner [7] and Zhu and Young [12].

3. RESULTS AND DISCUSSION

According to EN 1993-1-1 [2], the value of member buckling resistance N_b is obtained by multiplying the cross section resistance N_c with the buckling reduction factor χ, defined as:

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \lambda^2}} \leq 1$$

where:

$\Phi = 0.5\,[1 + \alpha\,(\lambda - 0.2) + \lambda^2]$,

α is an imperfection factor,

λ is a nondimensional slenderness.

For cross sections of class 1, 2 or 3, a nondimensional slenderness is given by:

$$\lambda = \sqrt{\frac{A \cdot f_y}{N_{cr}}} = \frac{L_{cr}}{i \cdot \pi}\sqrt{\frac{f_y}{E}}$$

where:

L_{cr} is a buckling length for the considered buckling plane,

i is a radius of gyration for the corresponding axis,

A is a cross sectional area,

N_{cr} is an elastic critical buckling load.

The value of an imperfection factor depends on the flexural buckling curve. There are five buckling curves defined in EN 1993-1-1 [2], as presented in Figures 2 and 3. In the case of hollow sections, the choice of a buckling curve depends on the material yield strength and on the fabrication process. For hot-finished hollow sections of steel grade S235 to S420, a buckling curve is defined as *a*, while for cold-formed sections, it is *c*.

Results of flexural buckling analysis are presented through dependence between a buckling reduction factor, equal to a normalised compressive column resistance N_b/N_c, and a nondimensional slenderness. The value of a buckling resistance is obtained as an ultimate load reached during axial compression of a member, while other parameters as nondimensional slenderness and a cross section resistance are calculated, by using proper geometrical properties and material yield stress obtained from a stress-strain curve.

Figure 2 sums up all results of numerical simulations of flexural buckling behaviour from the application of five different material curves. For columns of nondimensional slenderness greater than 1.5, it could be observed that all spots lie in-between curves a and a_0. As the slenderness tends lower, the variation of results is greater. Therefore, for columns of the nondimensional slenderness lower that 0.5, results for cold-formed EHS lie above the curve c. Contrary, results for hot-finished specimens lie above the curve a. By increasing slenderness, buckling of cold-formed members fits higher curves. However, results for studied hot-finished EHS for all range of slenderness correspond to a and a_0 buckling curves.

It is noticed that results conducted by using material curves given by Quach and Young for flat and corner coupons do not significantly differ. However, the differences in flexural behaviour of members with applied cold-formed material properties of Quach and Young and of Zhu and Young are more noticeable. It could be explained by the different shape of material curves, which is observed by comparing a ratio between 0.2 % proof stress and a tensile strength. Although, it is outlined that material coupons tested by Zhu and Young are not taken from elliptical, but from oval sections, which makes an application of such input data in the specific problem of EHS flexural buckling questionable.

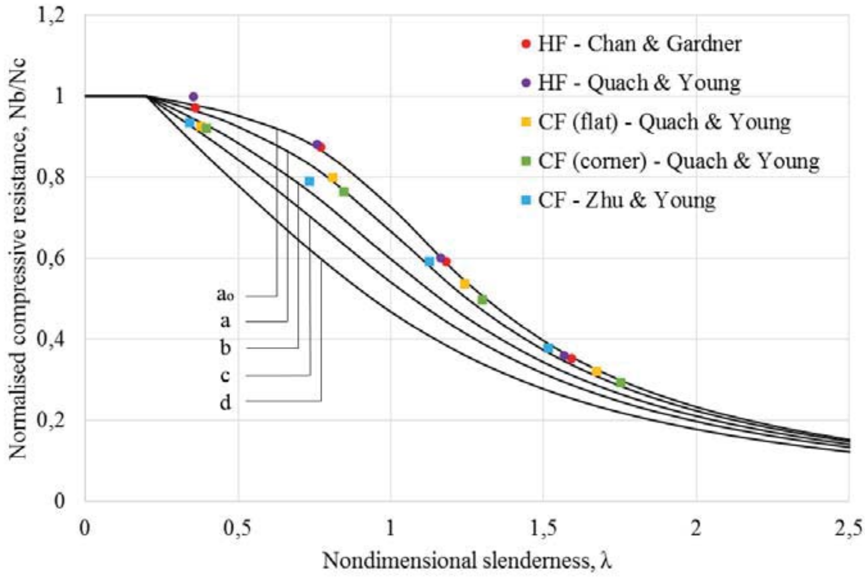

Figure 2 – Normalised FEA results and column buckling curves

It is worth noting that during analysis, it is observed that the influence of the applied local imperfection of 1/100 of plate thickness was negligible, even in the case of the shortest column model. As the section adopted for analysis is stocky and does not belong to the class 4, the outcome is not surprising.

In Figure 3, results are shown which are obtained by using material properties of hot-finished EHS from Chan's and Gardner's research. For comparison, experimental results of column tests of flexural buckling about major and minor axis of inertia, published by Chan and Gardner [7], are also presented. By numerical simulation performed in this investigation it is not intended to verify any experimental results, as there are no input data for such analysis. Due to the lack of an exact measured initial geometrical imperfections along elliptical perimeter and column length, as well as due to the other effects during testing, there is variation in presented test and numerical results. However, in both cases there is a trend of following the highest buckling curves.

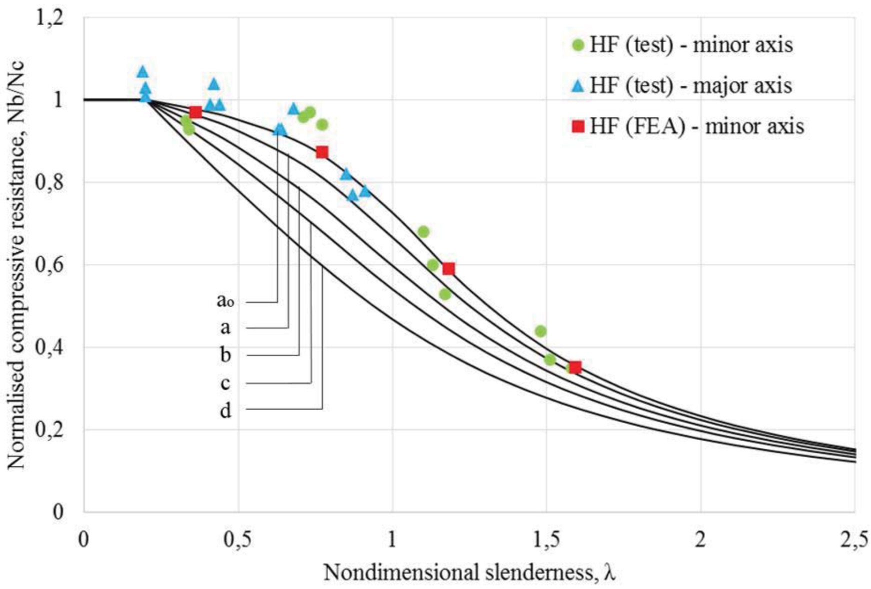

Figure 3 – Normalised FEA results and test results for hot-finished EHS [7]

Chan and Gardner [7] recommended that buckling curves defined for SHS, RHS and CHS hot-finished columns for buckling about both major and minor axis could also be applied to EHS columns. As all spots presenting buckling of investigated hot-finished members about minor axis lie above the buckling curve defined for hollow sections, the obtained results suit to the mentioned proposal of Chan and Gardner. Talking about cold-formed sections, the same conclusion could be made for columns of a lower slenderness. However, one should be aware of the example of slender columns where such propositions lead to safe-sided results in design.

4. CONCLUSIONS

This paper presents numerical evaluation of flexural buckling of elliptical hollow sections. Column models of hot-finished and cold-formed sections are made. Overall and local imperfections are included in simulation with amplitudes of 1/1000 of member length and 1/100 of plate thickness, respectively. Material properties are applied through results of tensile coupon tests presented in other researches of EHS. Only buckling about minor axis of inertia is analysed.

Obtained numerical results for hot-finished and cold-formed members are compared. In the range of higher slenderness, when buckling happens in the elastic stress domain before reaching the yielding stress, similar behaviour is observed for cross sections produces in both ways. Contrary, for a lower slenderness, cold-formed members tend to lower buckling curves than hot-finished ones. It is concluded that compressive capacities of columns are highly dependent on their material properties, especially in non-linear stress-strain domain.

Comparing buckling curves given in EN 1993-1-1 to the numerical results for EHS, it is noticed that in the lower slenderness area, results fit curves *a* and *c*, which are defined for hot-finished and cold-formed hollow sections of the specified steel grades. However, in the higher slenderness region, buckling of all models correspond to the curve *a*. Therefore, if adopting the same curve for all cold-formed members, design predictions might be conservative.

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