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NOSIVOST POPREČNIH PRESEKA ELEMENATA OD NERĐAJUĆEG ČELIKA PREMA METODI KONTINUALNE ČVRSTOĆE

Rezime: Metoda kontinulane čvrstoće predstavlja savremen pristup u proračunu nosivosti poprečnih preseka elemenata od nerđajućeg čelika koji je poslednjih godina razvijen na Imperijal Koledžu u Londonu. Osnovu metode predstavljaju kontinualna veza između vitkosti i kapaciteta deformacije poprečnog preseka, nelinearna veza između napona i dilatacija i efekati ojačanja materijala usled hladne deformacije. U ovom radu su prikazana osnovna pravila proračuna nosivosti preseka prema Metodi kontinualne čvrstoće i, kroz numerički primer, izvršena komparativna analiza proračunske nosivosti pritisnutog preseka prema ovoj metodi i EN 1993-1-4.

Ključne reči: Nerđajući čelik, Metoda kontinualne čvrstoće, Nelinearnost, Izbočavanje, Nosivost.

STAINLESS STEEL CROSS-SECTION RESISTANCE ACCORDING TO CONTINUOUS STRENGTH METHOD

Abstract: Continuous strength method is a contemporary approach to calculation of resistance of stainless steel cross-sections which has been recently developed at the Imperial College of London. The basis of the method is the continuous relation between the slenderness and strain capacity of a cross-section, nonlinear relation between the stress and strain and the strengthening effects of cold forming. In the paper are presented the fundamental rules for calculation of cross-section resistance according to continuous strength method; the comparative analysis of design resistance of the compressed cross-section was conducted through a numerical example according to this method and EN 1993-1-4.

Key words: Stainless steel, Continuous strength method, Nonlinearity, Buckling, Resistance.

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1. INTRODUCTION

Stainless steel is a generic term for a wide range of steel alloys, of varying kind and quality, whose resistance to corrosion is achieved with a content of no less than 10,5% of chromium and no more than 1,2% of carbon. Its usage in civil engineering is synonymous with luxurious and attractive architecture, while its usage in conventional structures is still limited. The main reason is, above all, high cost of stainless steel in comparison with the traditional application of carbon steel. The most used materials in construction industry are austenitic and duplex steel. By observing the market demands and by continuously improving the production process in the previous decade the metallurgy industry initiated production of new, depleted alloys of stainless steels, ferrous and low-alloy duplex steels with low content of nickel, in this way simultaneously achieving the competitive cost and primary properties of stainless steel.

The basic specific properties of austenitic stainless steels are material nonlinearity, anisotropy and asymmetry, ductility and considerable strain hardening due to cold-formation [1]. The stress-strain curve is prominently nonlinear, there is not clearly yield point and plasticity plateau and has a low value of stress on the proportionality limit and it indicates gradual yielding of material. The absence of a sharply defined yield point necessitates the definition of an equivalent yield point, wherefore is adopted the value of stress at 0,2% plastic strain (0,2% proof stress). From the point of view of the cross-section resistance, the important characteristic of stainless steel is reflected in the improvement of mechanical properties due to cold-forming: rolling or press braking. This fact is very important if one considers that stainless steel is mostly used in civil engineering in the shape of cold-formed products. The response to plastic strain is the material strengthening effect which significantly increases the yield point and, slightly less, the tensile strength followed with a reduction in ductility and the formation of residual stresses.

The elastic buckling theory can, in case of elastic-plastic materials, be used only in the initial domain of elasticity. In case of nonlinear materials, such as the stainless steel, in the stress domain above the proportionality limit, the stiffness during loading is proportional to the tangent modulus, and at unloading it is proportional to the modulus of elasticity. For that reason in case of calculation of cross-section resistance where buckling occurs in the inelastic (nonlinear) stress domain above the proportionality limit, a well known expression for the elastic buckling stress cannot be implemented. In addition, implementation of a design concept which is based on the perfectly elastic-plastic material model such as carbon steel leads to conservative results. Considering the uncompetitive position of stainless steel in construction industry, correct analysis and usage of all of its characteristics is of essential importance for proposing the design recommendations.

2. THE CONTINUOUS STRENGTH METHOD

Concept of cross-section classification (or the effective width concept) is a method which allows defining the resistance of a cross-section in function of the yield point as the maximum value of stress which can be reached in the cross-section. This method ignores the significant strain hardening of stainless steels, which may produce conservative results, especially for stocky cross-sections whose resistance is determined by the higher values of stress in comparison with the yield point.

The Continuous Strength Method (CSM) [2],[3] represents a contemporary method for design of cross-sectional resistance, which was created as a result of extensive experimental and analytical studies for the stainless steel members loaded by compression and bending. The nature of the stress-strain relationship for stainless steel, and absence of a clear yield point, means that the maximum value of stress at which failure of the cross-section occurred is not determined by the stress at which yielding starts. According to this method, the stress at which a cross-section buckles (local buckling stress) represents the only physical limit in the continuous improvement of mechanical properties of a material which follows the increase of the strain. Such approach permits a more precise analysis of local buckling effects in calculation of stainless steel cross-section resistance in comparison with the traditional concept of effective width.

Elastic buckling stress can be determined by applying available numerical methods CUFSM [4]. Alternatively, according to the recommendations given in EN 1993-1-4 [5], the smallest value of critical stress of an individual part of cross-section can be assumed as the elastic buckling stress which results in the following equation for cross-section slenderness:

$$\bar{\lambda}_p = \sqrt{\frac{f_{0,2}}{\sigma_{\mathrm{cr,p,min}}}} = \frac{\bar{b}/t}{28{,}4\varepsilon\sqrt{k_\sigma}} \tag{1}$$

where:

$\sigma_{\mathrm{cr,p,min}}$ is the smallest value of critical stress of an individual part of cross-section,

$\bar{b}$ is the width of the considered part of cross-section,

t is the corresponding wall thickness of the cross-section part,

$\varepsilon = [(235/f_{0,2})(E/210000)]^{0,5}$,

k_σ is the buckling coefficient which depends on the support conditions and distribution of stress.

Deformation capacity of the cross-section is expressed in a normalized form, and for the stocky cross-sections it is the relation of the strain corresponding to the value of ultimate load at which buckling occurs, $\varepsilon_{\mathrm{csm}}$, and the elastic part of strain at 0,2% proof stress, $\varepsilon_{0,2,\mathrm{el}}$.

By implementing linear regression method in the analysis of experimental data obtained by testing compressed stub columns it was shown that the area in which the relations of the ultimate load and the section yield load, $N_u/Af_{0,2}$ highter than unity, is determined by the limit value of the cross-section slenderness:

$$\bar{\lambda}_p = 0{,}68 \tag{2}$$

This value determines the limit between the slender cross-sections that fail due to local buckling in the elastic domain of stress and the non-slender cross-sections where local buckling occurs in the inelastic domain, after reaching the yield point. A similar value is observed in equivalent analyses of the structural elements made of carbon steel and aluminum alloys.

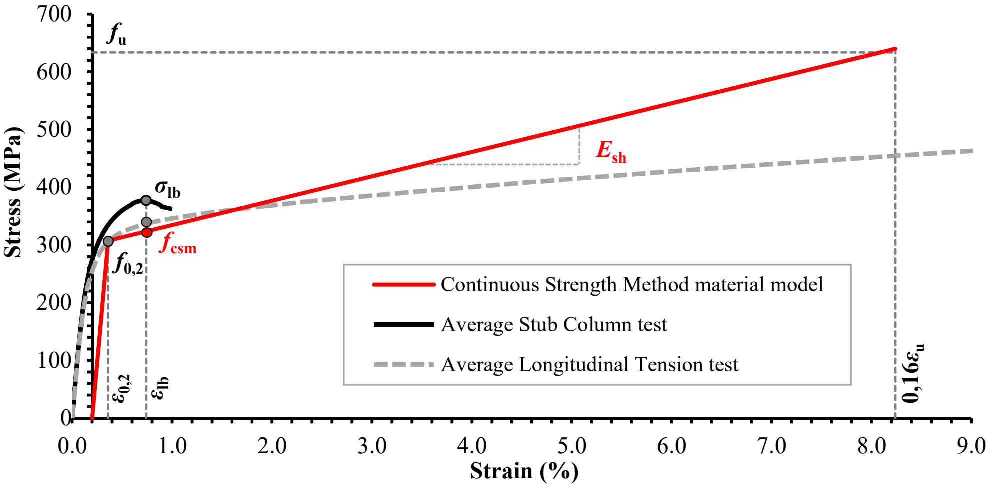

Figure 1 – Material model according to Continuous Strength Method [3]

In case of stocky cross-sections where the value of the ultimate load N_u exceeds the value of the cross-section yield load ($N_{0,2}= Af_{0,2}$), the relation of the end shortening at the ultimate load δ_u and the length of the stub column L, is defined as strain occurring at "failure" of the cross-section ε_{lb} due to inelastic local buckling. Strain ε_{csm} is determined by subtracting the plastic part of the strain at the 0,2% proof stress from the total value of the local buckling strain ε_{lb}:

$$\varepsilon_{csm} = \varepsilon_{lb} - 0{,}002 = \delta_u / L - 0{,}002;\ N_u \geq N_{0,2};\ \bar{\lambda}_p \leq 0{,}68 \tag{3}$$

All the available results of experimental research of stub columns and bending beams, combined with the equivalent results of carbon steels members were analyzed in order to generate the design curve which defines the relationship between the normalized value of deformation capacity $\varepsilon_{csm}/\varepsilon_{0,2,el}$ and slenderness of the cross-section $\bar{\lambda}_p$. By using the regression analysis and setting the condition that the design curve must pass through the identification limit between the slender and non-slender (stocky) cross-sections, i.e. through the point (0,68;1,0) the following equation was obtained:

$$\frac{\varepsilon_{csm}}{\varepsilon_{0,2,el}} = \frac{0{,}25}{\bar{\lambda}_p^{\,3{,}6}} \tag{4}$$

Where the value of the strain $\varepsilon_{0,2}$ is determined by the expression:

$$\varepsilon_{0,2,\mathrm{el}} = \frac{f_{0,2}}{E} \tag{5}$$

Two upper bounds regarding the deformation capacity of the cross-sections were adopted, resulting from the conditions of required ductility of the material given in EN 1993-1-1[6] and of the adopted stress-strain material model:

$$\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_{0,2,\mathrm{el}}} \le min\left(15; \frac{0{,}1\varepsilon_{\mathrm{u}}}{\varepsilon_{0,2}}\right) \tag{6}$$

The first versions of the Continuous Strength Method were based on the Ramberg-Osgood material model [7] which resulted in relatively complex calculation equations. The research indicated that by adopting a simplified material mode, the calculation obtain the form which more acceptable for implementation in the technical regulations and in design codes. For that reason, the elastic, linear hardening material model was adopted. For the initial point of this model, the value corresponding to the plastic part of total strain, of 0,2% was adopted, which, combined with the defined strain capacity of the cross-section $\varepsilon_{\mathrm{csm}}$ which provides an accurate assessment of the stress value. The slope of the elastic domain of this model was determined by the value of the modulus of elasticity $E = f_{0,2}/\varepsilon_{0,2,\mathrm{el}}$. The slope of the strengthened domain of E_{sh} was determined by the slope of the straight line which passes through the point which corresponds to the yield point $(\varepsilon_{0,2,\mathrm{el}}, f_{0,2})$ and the end points determined by the coordinates $(0{,}16\varepsilon_{\mathrm{u}}, f_{\mathrm{u}})$:

$$E_{\mathrm{sh}} = \frac{f_{\mathrm{u}} - f_{0,2}}{0{,}16\varepsilon_{\mathrm{u}} - \varepsilon_{0,2,\mathrm{el}}} \tag{7}$$

where f_{u} and ε_{u} are the ultimate tensile strength and corresponding strain value.

Strain ε_{u} can be determined by the application of the equation provided in the Annex C EN1993-1-4 [5]:

$$\varepsilon_{\mathrm{u}} = 1 - \frac{f_{0,2}}{f_{\mathrm{u}}} \tag{8}$$

After the deformation capacity of the cross-section has been determined by using equation (4), the limit value of the stress can be determined by applying the proposed analytical material model:

$$f_{\mathrm{csm}} = f_{0.2} + E_{\mathrm{sh}}\varepsilon_{0,2,\mathrm{el}}\left(\frac{\varepsilon_{\mathrm{csm}}}{\varepsilon_{0,2,\mathrm{el}}} - 1\right) \tag{9}$$

Finally, the design resistance of the compressed cross-section, whose slenderness is lower than 0,68, can be determined using the equation:

$$N_{\mathrm{c,Rd}} = N_{\mathrm{csm,Rd}} = \frac{Af_{\mathrm{csm}}}{\gamma_{\mathrm{M0}}} \tag{10}$$

where A is the cross-section area and γ_{M0} is the material partial safety factor according to EN1993-1-4 [5].

Figure 1 shows the average stress-strain curves obtained by tensile testing of material properties and by stub column tests [8], and the elastic, linear hardening material model with a graphical interpretation of the limiting stress f_{csm} according to CSM [3].

The influence of cold forming on the improvement of mechanical properties of material of the stainless steel structures was not analytically included in the existing Eurocode EN 1993-1-4 [5]. In the recent several years, the research on the specimens of press-braked and cold-rolled elements were performed and equations to predict the 0,2% proof stress and tensile stress, in the impact zones of the cross-section, were developed. Rossi et al. [9] proposed an innovative predictive analytical model to evaluate the enhanced 0,2% proof stress in the flat section and the corner region of cold formed section which was based on the determination of the plastic strains caused during the continuous procedure of cold forming of basic steel material. The authors provided the equation which, in the function of the cross-section area of corner region and the gross cross-section area, determines the average value of enhanced 0,2% proof stress for the entire cold formed cross-section. In this way, the effects of strength enhancement in the material were taken into consideration, and a more accurate prediction of cross-section resistance is provided.

2.1. Numerical example

A numerical example of the calculation of design resistance of compressed press-braked C section according to the CSM [3] is presented in this section. The stub column specimens, whose design calculations is shown here, were tested in the Materials and Structures laboratory at the Faculty of Civil Engineering, University of Belgrade [8].

Cross-section geometric and mechanical properties:

$h = 100\,\text{mm} \quad b = 40\,\text{mm} \quad t = 4\,\text{mm} \quad r_i = 8\,\text{mm} \quad A = 653{,}7\,\text{mm}^2$

$E = 192202\,\text{N/mm}^2 \quad f_{0,2} = 307{,}3\,\text{N/mm}^2 \quad f_u = 633{,}6\,\text{N/mm}^2 \quad \varepsilon_u = 0{,}515 \quad \varepsilon_{0,2,el} = 0{,}0016$

Cross-section slenderness: $\bar{\lambda}_p = \dfrac{92/4}{28{,}4 \cdot 0{,}837\sqrt{4}} = 0{,}484$

Cross-section deformation capacity: $\dfrac{\varepsilon_{csm}}{\varepsilon_{0,2,el}} = \dfrac{0{,}25}{0{,}484^{3,6}} = 3{,}407$

Strain-hardening slope: $E_{sh} = \dfrac{633{,}6 - 307{,}3}{0{,}16 \cdot 0{,}515 - 0{,}0016} = 4038{,}4\,\text{N/mm}^2$

Limiting stress: $f_{csm} = 307{,}3 + 4038{,}4 \cdot 0{,}0016 \cdot (3{,}407 - 1) = 322{,}8\,\text{N/mm}^2$

Cross-section resistance according to CSM: $N_{u,csm} = 322{,}8 \cdot 653{,}7 = 211\,\text{kN}$

Cross-section ressistance according to EN 1993-1-4: $N_{u,EC} = 200{,}9\,\text{kN}$

Test ultimate load: $N_{u,test} = 247{,}6\,\text{kN}$

When the values of the cross-section resistance according to CSM and Eurocode are compared with the test value, it can be concluded that CSM [3] provided a considerably better prediction of the cross-section resistance in comparison with the recommendations provided in the standing EN 1993-1-4 [5].

3. CONCLUSIONS

The continuous strength method [2],[3] represents an alternative approach in the calculation of stainless steel cross-section resistance with the generally accepted cross-section classification approach (or limit slenderness). Its application is limited to the stocky cross-sections where local buckling occurs in the inelastic stress domain and whose slenderness is $\overline{\lambda}_{\mathrm{p}} \leq 0{,}68$. All the research up to date indicated that this method provides a high percent of agreement of design and experimental values of cross-section resistance, so the professional public expects it to be introduced in the new, revised version of Eurocode EN 1993-1-4 [5].

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