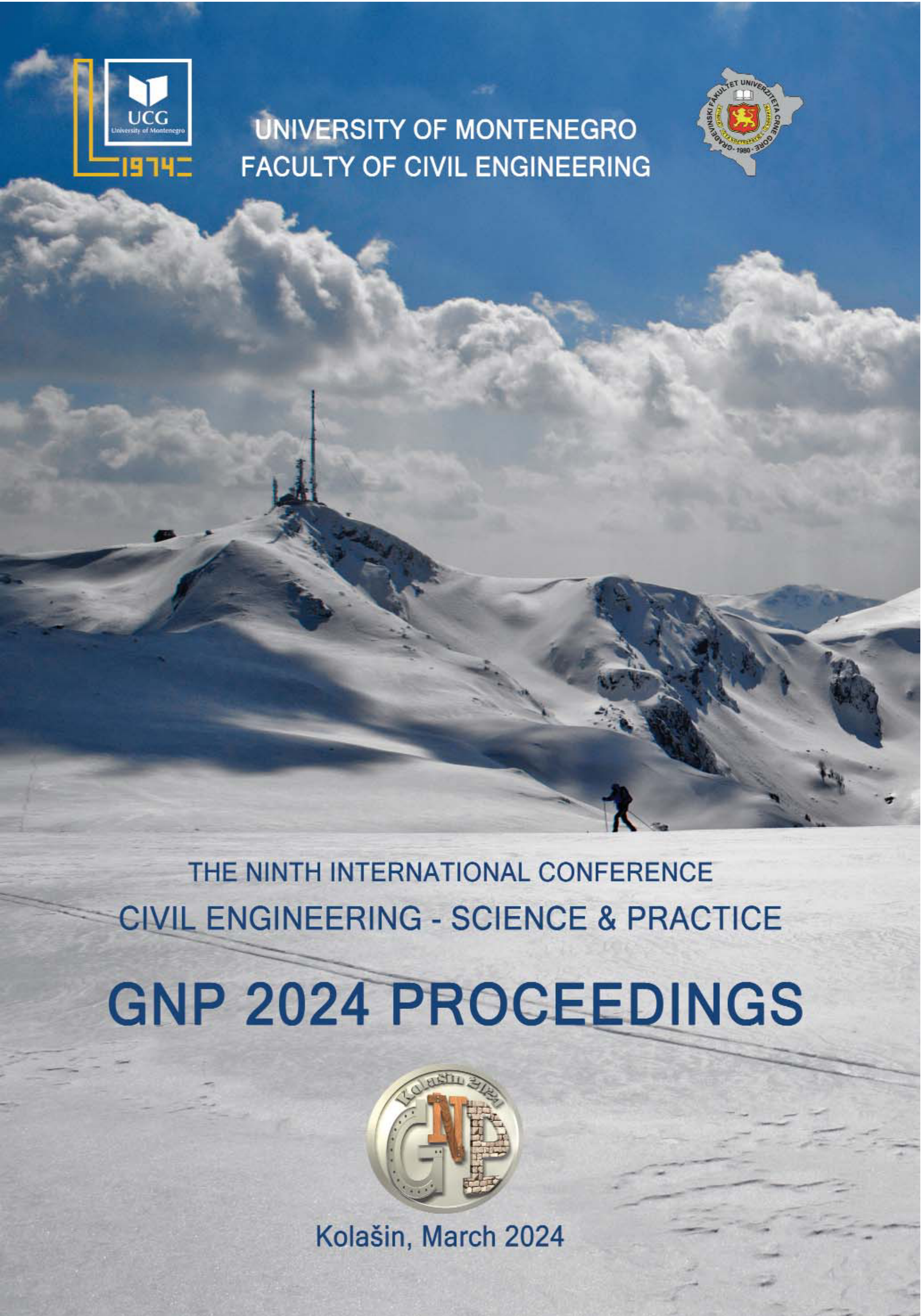

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DESIGN CROSS-SECTION RESISTANCES OF PERFORATED COLUMNS UNDER COMPRESSION

Abstract

Nowadays, numerous experimentally, numerically and analytically based research have been performed to evaluate the structural responses and ultimate capacity of beams with web openings, but mostly under bending. However, in practice, the application of steel cellular elements dominantly loaded by axial pressure is very common. With the lack of appropriate design approaches, we rely on engineering judgement, which can result in uneconomic, time-consuming, or unsafe solutions. To ensure the safety of a structure it is necessary to assess its structural resilience.

An overview of the existing experimental study on compressed I-section short columns with web openings, assessment of the impact of openings' size and shape on cross-section deformation and resistance capacity under pure compression was performed. To accomplish an adequate and easy-to-use design method for hot rolled perforated columns, the design procedures stated in: (i) draft version of new European code prEN 1993-1-13, (ii) the Direct Strength Method (DSM) in American standard AISI S100-16 and (iii) the Continuous Strength Method (CSM) in prEN 1993-1-4 were evaluated based on experimental data, and the obtained outcomes are briefly presented in this paper. Although none of these design methods include all aspects of observed case – hot rolled perforated elements under compression (Eurocode has a strict limit of axial force, CSM and DSM primarily refer to cold-formed steel sections and do not recognize the existence of openings at all), they turned out to be quite accurate. The corresponding results were obtained by modifying those procedures, so they better reflect a case of interest. Thus, DSM method didn't need any modifications, and CSM had the most.

Keywords

Web openings, compression, cross-section resistance, design method.

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1. INTRODUCTION

One of the greatest advantages of perforated structural elements is the ability to run service lines directly through the web openings. This helps to reduce floors depth and optimize the utilization of both space and steel material. Common choices for the opening shape include circular, rectangular, hexagonal and sinusoidal designs. They have a wide range of application in both composite and non-composite structures, they can appear as parts of portal frames, as simply supported member etc.

Although the web openings reduce the shear and compressive capacity of such elements (alters the stress distribution within the member), with proper design, construction and positioning of the opening, and verification models, including the load conditions, full structural efficiency of the web opening in steel elements can be achieved.

The axial capacity of cellular columns is evidently lower compared to sections without opening (with gross cross-section area). Initially, the effect of introducing web openings appears to have more significant impact on columns than on beams. This is because the web contribution to the cross-section bending capacity is lower than its contribution to the cross-section capacity under axial load. However, in the case of slender columns, where buckling resistance is less favourable than axial resistance, web openings enable full cross-section axial capacity by increasing the moment of inertia and critical buckling load.

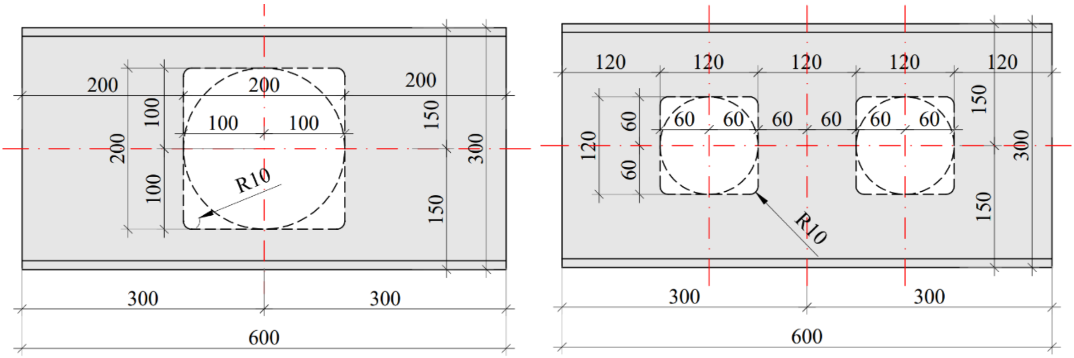
In this paper, assessment of different design procedures for cross-section resistance was performed and it is defined to accomplish an adequate and easy-to-use verification model for dominant axial pressure.

1.1. DESIGN OF BEAMS WITH WEB OPENINGS

Until today, the behaviour of steel perforated members under bending have been extensively investigated. Some results are implemented in new generation of Eurocode and refer to defining cross-section deformation and strength capacity of perforated members with various opening shapes (prEN 1993-1-13 [1]), but with an explicit limitation of compression force that can appear. Otherwise, American standard AISI S100-16 [2] gives design rules for cold formed perforated sections under compression. However, the design efficiency characteristics of hot rolled columns with web openings have not yet been disclosed.

1.2. EXPERIMENTAL RESREACH ON PERFORATED MEMBERS UNDER COMPRESSION

Experimental responses of compressed I-section short columns with web openings [3] reports the experimental study on compressed perforated members to determine their susceptibility to local buckling. Assessment of the impact of openings' size and shape on cross-section deformation capacity was carried out. A total of four different specimens were tested: specimen with one isolated circular opening ("ICO1x200"), specimen with two close-spaced circular openings ("ICO2x120") and specimens with equivalent square openings ("ISO1x200" and "ISO2x120"), see Figure 1. The numbers 120 and 200 given in name of specimens refer to the opening dimension (diameter in case of circular opening and width in case of square opening). The cross-section that was used is IPE300 with the yield strength of 328MPa (obtained from standard tensile test).



(a) specimen with one isolated circular/square opening

(b) specimen with two close-spaced circular/square openings

Figure 1. Test specimens [3]

Tests have shown the failure mode of the specimens was local buckling triggered by the weakening of the section web by the openings at the interface between the elastic and plastic stress regions (see Figure 2 that compares local buckling failure mode around web openings of the test specimen ISO2x120 and its equivalent FE model). It was also found that the ultimate resistances of specimens with circular openings are higher than those measured for the corresponding specimens with square openings. Moreover, in the case of circular openings specimens, the measured axial strains around openings are higher than the strains at the web post, indicating the shear transfer around the openings.

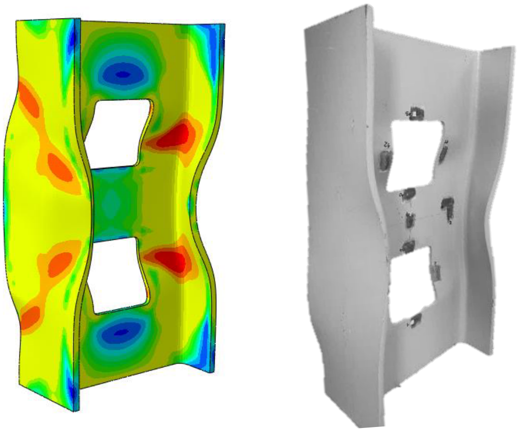


Figure 2. Failure mode of ISO2x120

Obtained results were used for evaluation of different design predictive models for cross-section resistance as shown below.

2. EVALUATION OF DESIGN PREDICTIVE MODELS FOR CROSS-SECTION RESISTANCE

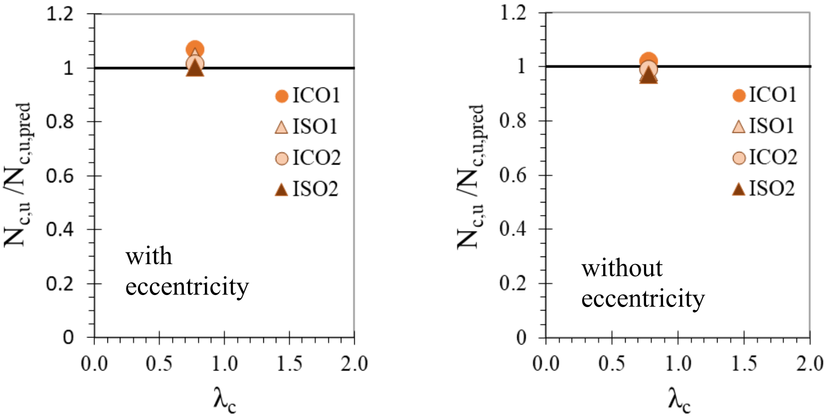
The accuracy of the codified design approaches for cross-section resistance given in draft version prEN 1993-1-13[1] and American standard AISI S100-16 [2] was estimated by comparing experimental ultimate axial loads with corresponding predicted capacities. Also, CSM method [4,5] that now features in draft European standard prEN 1993–1-4 [6] was considered even though it doesn't recognize the existence of openings at all.

The distinctions between the considered methods are graphically emphasized in Figures 3 - 5 where the experimental-to-predicted cross-section resistance ratios $N_{c,u}/N_{c,u,pred}$ ($N_{c,u}$ is experimental resistance of the cross-section whereas $N_{c,u,pred}$ is design resistance) are plotted against the full cross-section slenderness λ_c. The predicted design values were calculated using the nominal cross-section dimensions of described specimens and yield strength obtained from standard tensile test.

2.1. CROSS-SECTION RESISTANCE ACCORDING TO PREN 1993-1-13

In accordance with prEN 1993-1-13 [1], local buckling is accounted for using the concept of cross-section classification and Effective Width Method (EWM) based on an elastic-plastic material model, such as in the current code in use EN 1993-1-1 [7]. The cross-section class is determined by the classification of all cross-section elements, comparing their slenderness (width-to-thickness ratio) with the limit values prescribed in the code. The EWM focuses on the isolated plate elements that comprise a cross-section and accounts for the reduction of compressive cross-section capacity due to local buckling through a reduction of plate element width. [3]

In the case of perforated webs, cross-section should be classified at each web opening and web post. At the opening, both flanges and web are classified as outstand elements [3].



(a) *(b)*

Figure 3. Cross-section capacity according to prEN 1993-1-13 [1]

Design resistance capacity of a cross-section with web openings under pressure is determined by modifying the expressions (8.8) and (8.9) stated in prEN 1993-1-13 [1]:

$$N_{T,Ed}=\frac{1}{\frac{1}{N_{b,Rd}}+\frac{0.4w_{Vier,add}}{M_{T,Rd}}} \tag{1}$$

where:

$M_{T,Rd}$ is the bending resistance of cross section of the compressed Tee section in the plane of the web at mid-length of the opening.

$N_{b,Rd}$ is the design value of the buckling resistance of the compressed Tee for buckling in the plane of the web, determined for a buckling length of 0,5 a_{eff} (coefficient depending on opening shape)

$w_{Vier,add}$ is the relative deflection across the opening at the serviceability limit state

The cross-section resistance is defined as buckling resistance of the compressed Tee sections in web plane, considering bending moments due to Vierendeel bending effects and axial force. It should be noted that resistance calculated by Eq (1) is related to one Tee element (for cross-section capacity it should be multiplied by 2). One effect that this procedure accounts for is also an eccentricity $w_{Vier,add}$, see Eq (1). As we observe only axial load without global moment it makes sense not to take at all, but otherwise, existence of force eccentricity is more realistic than pure compression. Therefore, both cases were considered and respectively shown in Figure 3a and Figure 3b.

2.2. CROSS-SECTION RESISTANCE ACCORDING TO DIRECT STRENGTH METHOD

In contrast to the effective width method, which focuses on the individual elements that comprise a cross section, the key to the DSM in AISI S100-16 [2] is that member strength can be defined in terms of the elastic instabilities for the gross cross-section and the actions that causes the section to yield. A significant difference between the EWM and the DSM is the replacement of plate-buckling stress with cross-section local bucking stress, ensuring that equilibrium and compatibility around the cross section are maintained.

According to DSM, nominal axial strength resistance P_{nl} is determined using Eq (2) or Eq (3), depending on λ_l value:

$$P_{nl}=P_{ne} \qquad \text{for} \quad \lambda_l \leq 0.776 \tag{2}$$

$$P_{nl}=\left[1\text{-}0.15\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4}\right]\left(\frac{P_{crl}}{P_{ne}}\right)^{0.4} P_{ne} \qquad \text{for} \quad \lambda_l > 0.776 \tag{3}$$

where:

$$\lambda_l=\sqrt{P_{ne}/P_{crl}} \tag{4}$$

P_{ne} is global column strength as defined in Section E2 of standard AISI S100-16 [2]

P_{crl} is critical elastic local column buckling load, determined in accordance with Appendix 2 of standard AISI S100-16 [2]

The comparative study was performed without any assumptions in the subject design procedure. The results are presented graphically in Figure 4.

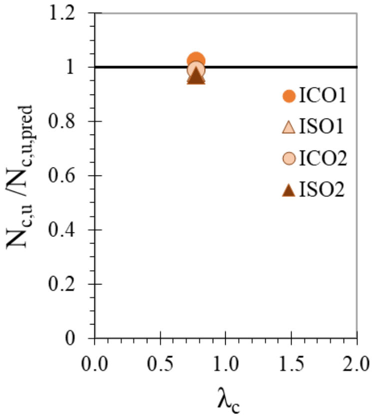


Figure 4. Cross-section capacity according to DSM, AISI S100-16 [2]

2.3. CROSS-SECTION RESISTANCE ACCORDING TO CONTINUOUS STRENGTH METHOD

The CSM [4,5] is an approach developed for the calculation of cross-section resistance capacity which is based on defining the maximum deformation that the section can achieve ε_{csm} in function of its stiffness λ_p, and defining the material model that better describes behaviour of steel elements (continuous relationship between the cross-section's deformation capacity and the full cross-section slenderness). In contrast to the design procedures in prEN 1991-1-13 [1] and EN 1993-1-1 [7] which are based on EWM, the CSM accounts for the interaction between individual parts of the cross-section (flanges and web) as well as the hardening of steel material.

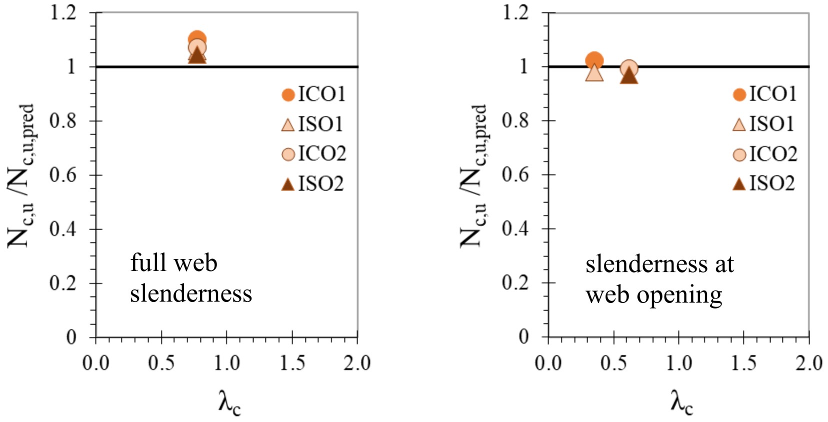
The CSM cross-section resistance under compression $N_{csm,\,Rd}$ is calculated by multiplying the gross cross-section area A with the CSM limiting stress f_{csm}, where f_{csm} is determined based on the material model defined with Eq (6).

$$N_{csm,Rd} = \frac{A \cdot f_{csm}}{\gamma_{M0}} \tag{5}$$

$$f_{csm} = \begin{cases} E\varepsilon_{csm} & \text{for} \quad \varepsilon_{csm} \leq \varepsilon_y \\ f_y & \text{for} \quad \varepsilon_y < \varepsilon_{csm} \leq \varepsilon_{sh} \\ f_y + E_{sh}(\varepsilon_{csm} - \varepsilon_{sh}) & \text{for} \quad \varepsilon_{sh} < \varepsilon_{csm} \leq C_1 \cdot \varepsilon_u \end{cases} \tag{6}$$

E_{sh}, ε_{sh} and ε_{csm} are calculated as a function of cross-section stiffness λ_p and material characteristics f_u and f_y according to [4,5].

In its original form, cross-section stiffness λ_p is taken as a stiffness of the slenderest cross-section element. Because CSM method doesn't recognize existence of web openings, it is not clear whether to consider elements of both gross and net cross-section, or only at the web opening (the differences are emphasised in Figure 5a and Figure 5b).



(a) *(b)*

Figure 5. Cross-section capacity according to CSM [4,5]

2.4. SUMMARY

The accuracy of the design approaches for cross-section resistance given in prEN 1993-1-13 [1], DSM [2] and CSM method [4,5] was estimated by comparing the generated experimental ultimate loads with corresponding unfactored predicted strengths. In order to provide an indication of the variation in aforementioned design procedures, the summary of the obtained results is reported in Table 1. The comparisons are presented in terms of the ratio of experimental-to-predicted cross-section resistance ($N_{c,u}/N_{c,u,pred}$). In order to quantify the effect of web openings on the cross-section resistance, the table also includes the ratio of experimental-to-cross-section resistance in case there is no web openings $N_{c,u,gross}$ (cross-section resistance in that case is equal to product of gross cross-section area and yield strength).

Table 1. Comparisons of experimental with design cross-section resistances

Specimens	$N_{c,u} / N_{c,u,gross}$	$N_{c,u} / N_{c,u,pred}$				
		prEN 1993-1-13 (EWM)		AISI S100-16 (DSM)	CSM	
		with eccentricity	without eccentricity	/	Full web slenderness	Slenderness at web opening
ICO1x200	0.75	1.07	1.02	1.02	1.10	1.02
ISO1x200	0.72	1.04	0.98	0.98	1.06	0.98
ICO2x120	0.83	1.02	0.99	0.99	1.07	0.99
ISO2x120	0.82	1.00	0.97	0.97	1.05	0.97
Mean value	0.78	1.03	0.99	0.99	1.07	0.99

It can be seen that decreasing the opening size leads to a higher predictive resistance of column cross-section than it actually is (according to experiment), and the question is what are upper and lower limits of opening size for which these methods give reliable and acceptable results. Also, when applying all three methods, the experimental-to-design resistance ratio is lower in the case of rectangular opening; thus, based on our experimental data, neither method recognizes the influence of the opening shape on the ultimate resistance capacity.

3. CONCLUSIONS

DSM stated in AISI S100-16 [2] in its basic form gives a good estimate of the resistance capacity of these elements. prEN 1993-1-13 [1] and CSM method [4,5] gave the similar results, but with appropriate modifications. Even without changes, cross-section resistances calculated by the provisions of the European standard and the CSM method [4,5] gives results that are more on the safety side, but in some cases up to 10% which raises the question of the economy of their application as such. However, their applicability to cross-sections of different slenderness and in cases of different slenderness ratios of the elements at the openings and outside the openings can be estimated only after extensive parametric analysis.

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