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NUMERICAL STUDY ON BENDING BEHAVIOUR OF HOT-FINISHED AND COLD-FORMED ELLIPTICAL HOLLOW SECTIONS

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ABSTRACT

Elliptical hollow sections (EHS) are new products on the construction market. Their growing implementation in steel structures led to complementing design rules in the draft version of Eurocode EN 1993-1-1:2015. In this paper bending strength of elliptical hollow sections is being discussed, analysing cold-formed and hot-finished EHS profiles under pure bending. Numerical models include short members of diverse section slenderness with applied concentrated moments at the ends about either the major or the minor axis of inertia. Material nonlinear behaviour is included through experimental tensile test results adopted from previous researches. Influence of geometrical imperfections is incorporated in the analysis, however, imperfection amplitude variation has shown an insignificant effect on bending strength. For all analysed members, it is shown that numerically obtained ultimate moments are higher than bending strengths prescribed in EN 1993-1-1:2015. Differences in responses of hot-finished and cold-formed EHS are discussed. Comments on elliptical cross-section classification according to the design standard are made, as well as comments on the defined effective cross-sectional geometrical properties. Review of the set limiting slenderness for class 3 is suggested.

Keywords: *Elliptical hollow section; Bending resistance; Cross-section classification; Effective cross-sectional area; Numerical analysis;*

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1. INTRODUCTION

Until recently, three types of tubular sections were present on the construction market: square, rectangular and circular sections. However, in the past years, a new hollow section product has appeared - elliptical hollow section (EHS). There are more than a few examples of application of elliptical hollow sections as structural members, as following: columns of the Zeeman building at the University of Warwick (2003), columns of the Barajas airport building in Madrid (2004) and the Cork airport in Ireland (2006), supporting members for a glass façade in the Heathrow airport building in London (2007), arches of the pedestrian Society bridge in Scotland (2005) [1].

In the current Eurocode for the design of steel structures EN 1993-1-1:2005 [2], there are no design criteria defined for EHS structural elements. However, in the draft version of Eurocode EN 1993-1-1:2015 [3] which has not been published and enacted yet, there are added regulations about EHS profiles. Those design rules are mostly based on the studies that were conducted at Imperial College London, and that included a wide research on EHS behaviour under axial compression [4], bending [5], shear [6] and combined effects [7], that investigated elliptical cross-section classification [8] and stability problems of EHS members [9–11]. However, the mentioned studies were exclusively focused on hot-finished products.

Beside hot-finishing, hollow sections could be produced by a cold-forming or a hot-forming process. The process of cold-forming is conducted at ambient temperature by compressing and squeezing steel sheets through a set of rollers. In order to produce a tube section, steel sheets are afterwards welded alongside the edges. Commonly, elliptical shape is formed from the previously developed circular section that is additionally exposed to cold deformation. A hot-finishing process includes pretreatment equal to the cold-forming process, that is followed by additional heat treatment in a furnace. A hot-forming is the least common of three mentioned processes in tubular section industry and it includes the whole process of manufacturing at elevated temperatures, without applying cold deformations. Although hot-finished and hot-formed sections are often treated equally in design, recent research shows that their mechanical properties are different [12].

By now, not much research has been conducted on behaviour of cold-formed EHS members. In a few published papers, results on investigated material properties of cold-formed EHS, residual stresses and responses of a cross-section under pure axial compression have been presented [13,14]. 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, different behaviour of hot-finished and cold-formed structural members could be expected under various effects.

A comparative study on behaviour of hot-finished and cold-formed EHS columns under pure axial compression has been conducted by authors [15,16]. Results show that there is a difference in cold-formed and hot-finished member response in non-linear stress-strain domain. Results were compared to design criteria defined in Eurocode draft standard EN 1993-1-1:2015 [3] and in North American specification for the design of cold-formed structural members AISI-S100 [17], and it was shown that North American standard provides better predictions of both a stub column strength and a buckling column resistance than Eurocode. The limiting slenderness for pure compression for the class 3 according to EN 1993-1-1:2015 turned out to be underestimated, that led to the safe-sided results for design predictions of both cross-section compression strength and column buckling strength. Following the conclusions that were made, further research in this field is desirable, incorporating responses of EHS under different effects.

This paper is focused on a finite element numerical study on the behaviour of hot-finished and cold-formed elliptical hollow sections under pure bending, about either the minor or the major principal axis. The analysis covers cross-sections of different slendernesses, and therefore, all four cross-section classes are included in the research. Results of the numerical analysis are compared to the design criteria defined in Eurocode draft standard EN 1993-1-1:2015 [3].

Experimental programme and corresponding numerical investigation on hot-finished EHS performed by Chan and Gardner [5] included bending tests on beams of the span 3 m and 4.5 m, with applied one-point and two-point load, respectively. However, a numerical simulation done as a part of this research, included short beam models with applied bending moments at the members' ends, in order to induce pure bending, avoid global stability problems and exclude effects of interaction with axial and shear forces. Numerical analysis is performed by using the software package Abaqus [18], based on the finite element analysis (FEA). Geometrical properties of the cross-sections are adopted according to EHS products that could be found on the market nowadays [19]. Material non-linear properties are included through experimental tensile test results published in previous researches [9,14,20].

2. OVERVIEW OF THE DESIGN RULES

According to Eurocode [2,3], bending strength of a cross-section should be determined by multiplying a plastic (W_{pl}), an elastic (W_{el}) or an effective section modulus (W_{eff}) with a yielding strength of the material. The selection of the appropriate section modulus depends on a cross-section class. The draft version of Eurocode EN 1993-1-1:2015 [3] states limiting proportions for EHS classification.

For obtaining cross-section slenderness, firstly an equivalent diameter D_e should be obtained. This parameter is defined depending on an effect present in a cross-section. For cross-sections in bending, D_e should be obtained as following:

- for bending about strong axis, when $h/b \leq 1.36$:

$$D_e = \frac{b^2}{h} \tag{1}$$

- for bending about strong axis, when $h/b > 1.36$:

$$D_e = 0.4\frac{h^2}{b} \tag{2}$$

- for bending about weak axis:

$$D_e = \frac{h^2}{b} \tag{3}$$

where h and b are overall dimensions of a cross-section ($h > b$).

These equations for obtaining an equivalent diameter have been derived according to the point in the elliptical hollow section where local buckling initiates in the elastic range [8]. For bending about the minor axis, local buckling happens at the place of the maximum radius of curvature of EHS, that corresponds to the point with the maximum compressive stress. However, for bending about the major axis, it is necessary to obtain a critical radius of curvature, which depends on an aspect ratio of a cross-section. Theoretical solution for EHS with $h/b = 2$ predicts that buckling occurs at a distance of $0.21h$ from the extreme fibre in compression, however, experimental results showed that this point is on $0.11h$ [8]. On the other side, for EHS with lower h/b ratio, buckling would start at the place with the maximum compressive stress. Accounting theoretical and experimental findings, for bending about the strong axis, two expressions for obtaining D_e are given for two ranges of h/b.

Cross-section slenderness that is compared with limiting slenderness for obtaining a cross-section class, is defined as a ratio D_e/t, where t is a wall thickness. For sections in bending, limiting slendernesses for classes 1, 2 and 3, are given as $\lambda_1 = 50\varepsilon^2$, $\lambda_2 = 70\varepsilon^2$ and $\lambda_3 = 140\varepsilon^2$, $\varepsilon^2 = 235/f_y$, respectively. The same slenderness limits are set for circular cross-sections. Here, modification in design rules between the draft version [3] and the current Eurocode [2] is observed, as according to the later one, limiting slenderness for class 3 is considerably lower – $90\varepsilon^2$.

Also, EN 1993-1-1:2015 [3] defines an effective section modulus for EHS of the slenderness lower than $240\varepsilon^2$, as:

$$W_{eff} = W_{el}\sqrt[4]{\frac{140\varepsilon^2}{d_e/h}} \tag{4}$$

For EHS with slenderness exceeding $240\varepsilon^2$, instructions given EN 1993-1-6 [21] should be followed.

3. NUMERICAL ANALYSIS

The study presented in this paper includes the geometry of elliptical hollow sections corresponding to hot-finished sections manufactured by Tata Steel [19] of the overall dimensions 150x75 mm. For achieving different cross-section slenderness, wall thickness is varied through analysis – it is applied as 2, 3, 4 and 5 mm. The member length is set to 450 mm. Concentrated moments are applied at both ends of the member, in order to achieve a uniform bending moment along the member length. Boundary conditions with all displacements constrained are applied at the member ends, with only rotation allowed about the minor, i.e. the major principal axis, depending weather bending about the minor or the major axis is analysed.

Numerical simulations are performed in the finite-element software package Abaqus [18]. Finite elements implemented in numerical models are shell elements S4R with reduced integration and six degrees of freedom per node. Uniform mesh density is chosen with a finite element size of 5 mm, as presented in Fig. 1.a, adopted according to the mesh convergence study. All edge nodes at member ends are connected by coupling to the reference point at the cross-section centroid at each member end, to which boundary conditions are applied, as shown in Fig. 1.b.

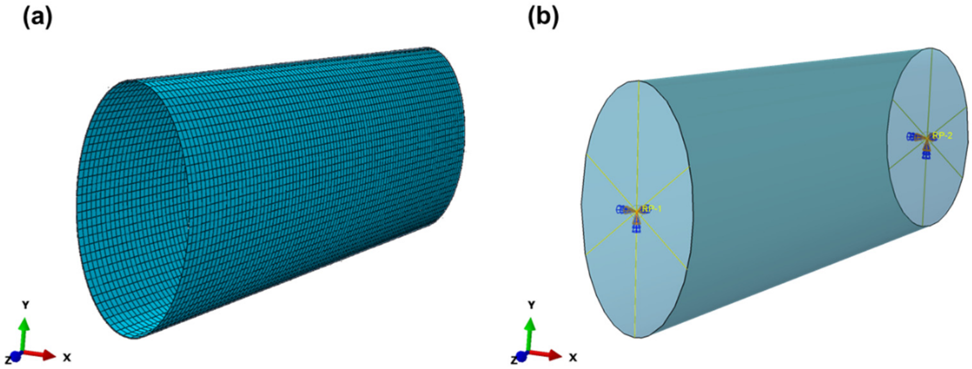

Fig. 1. Numerical model of a short beam: (a) FE mesh, (b) boundary conditions

In the first step of numerical simulation, Eigenvalue analysis is conducted in order to obtain buckling modes, afterwards used as initial deformed shapes of a member. Secondly, the static analysis with modified Riks method is performed, accounting material and geometrical non-linearities, in order to obtain a bending strength of a cross-section.

Local geometric imperfections are incorporated in the numerical model by setting adequate imperfection amplitude to the first buckling mode. According to the recommendations given in EN 1993-1-5 [22], the advised value of geometric imperfection amplitude for numerical simulation is 80% of fabrication tolerance. A fabrication tolerance for wall thickness of CHS is given depending on a section diameter D and a wall thickness t: for $D \leq 406.4$ mm and $t \leq 5$ mm, the maximum imperfection should not exceed 10% of the thickness [23,24]. In order to validate numerical models of three-point and four-point bending tests performed on hot-finished EHS beams, Chan and Gardner [5] applied different amplitudes of local imperfections: $t/10$, $t/100$ and $t/500$. Though, it was observed that sensitivity to imperfections was low. In the analysis conducted in this research, initial local imperfections are applied as 1/100 and 1/10 of the section wall thickness, but the influence on the ultimate bending strength of a cross-section has been negligible (1% difference at maximum).

Material properties of cold-formed and hot-finished steel sections are taken into account through the results of tensile coupon tests that were conducted in experimental investigations of elliptical and oval hollow sections. Quach and Young [14] obtained stress-strain curves for material coupons taken from different parts along a section 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 were observed. Contrary, material properties of cold-formed sections were not uniform throughout elliptical perimeter – corner coupons had greater yield stress and tensile strength, but lower ductility. This is due to the manufacturing process, as curved parts of the section had been subjected to local cold bending and undergo plastic deformations. In the research of hot-finished EHS done by Chan and Gardner [9], only coupons from the flattest portion of the section were tested. Similarly, when cold-formed oval hollow sections were investigated by Zhu and Young [20], only mechanical properties of flat coupons were obtained. The summation of all stress-strain curves implemented in numerical models in this research is presented in Fig. 2 and in the following list:

- hot-finished coupon tested by Chan and Gardner [9];
- hot-finished coupon tested by Quach and Young [14];
- cold-formed coupon from the most curved part of the section tested by Quach and Young [14];
- cold-formed coupon from the flattest part of the section tested by Quach and Young [14];
- cold-formed coupon from the flat part of oval hollow section tested by Zhu and Young [20].

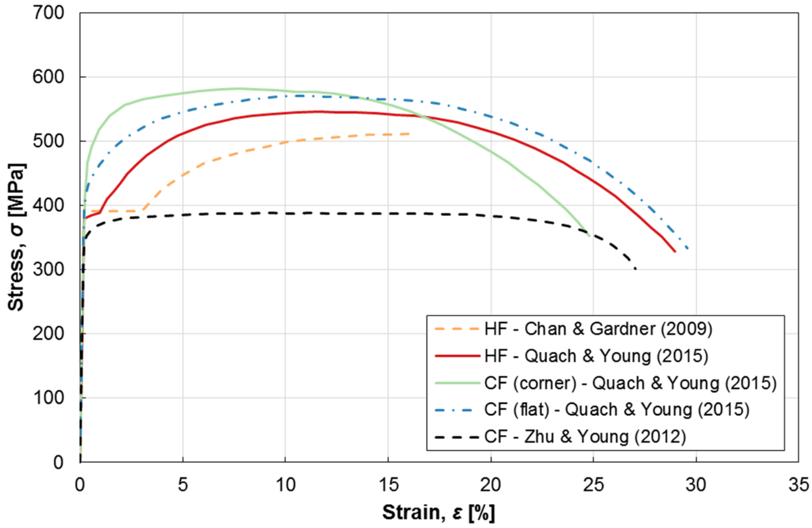

Fig. 2. Stress-strain curves of EHS material

It can be observed from Fig. 2 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. The behaviour of hot-finished steel fits better the behaviour of basic steel material. Contrary, a cold-forming process causes a change in the stress-strain relationship of the basic material. However, even for the presented two hot-finished EHS, the length of the yield plateau differs. This is due to the difference in the manufacturing process after cold-rolling, as hot-finished sections tested by Chan and Gardner were exposed to the temperature of 900 ^{0}C, while for EHS tested by Quach and Young, heat treatment was performed at the temperature of approximately 750 ^{0}C.

In order to incorporate material properties into the numerical model, except defining Young's modulus and Poisson's ratio in the elastic domain, it is necessary to define true stress and true plastic strain for describing plastic behaviour of the material. It is done according to the following relations as specified in Abaqus user's manual [18]: $\sigma_{true} = \sigma(1+\varepsilon)$ and $\varepsilon_{true,pl} = \ln(1+\varepsilon) - \sigma_{true}/E$, where E is Young's modulus.

During a production process of hollow sections, cold-formed members 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 [12]. Measurement of residual stresses in elliptical hollow sections was done by Law and Gardner for hot-finished members [10], by Chen and Young for cold-formed members [13] and by Quach and Young for both hot-finished and cold-formed EHS [14]. The residual stress in a longitudinal direction could influence the ultimate strength of a cross-section. Experimental results show that longitudinal residual stresses in hot-finished hollow sections are significantly smaller than those in cold-formed hollow sections, rating 10–15% of the material yield strength. Therefore, it is expected that they have an insignificant influence on structural behaviour and thus excluded from the numerical analysis obtained by Chan and Gardner [5]. In the case of cold-formed sections, the maximum bending residual stress can reach approximately 75% of the material 0.2% proof stress, while the maximum membrane residual stress is about 25% of the 0.2% proof stress. Although bending residual stress has a high amplitude, numerical investigations showed that it does not affect the ultimate strength of a cross-section [13]. For that reason, the residual stresses are not explicitly included in the numerical analysis of this research, neither of hot-finished nor of cold-formed members.

4. RESULTS AND DISCUSSION

By modelling a short beam with applied moments at the ends, a uniform bending moment is achieved alongside the member, while shear and axial forces, as well as global buckling effects, are excluded. In Fig. 3, there are presented failure modes obtained for buckling about the major and the minor principal axis, for a member of the cross-section EHS 150x75x3 mm, with the applied hot-finished material model given by Quach and Young. Similar shape failure modes have been observed for the other analysed cross-sections.

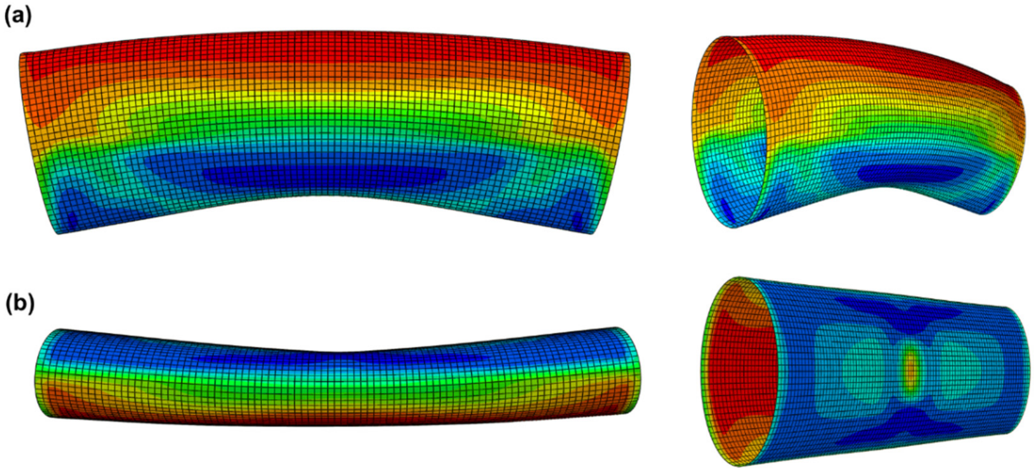

Fig. 3. Failure modes due to pure bending about: (a) the major axis, (b) the minor axis

As noticed in Fig. 3, for buckling about the minor axis, local buckling appears in the area of the cross-section with the maximum compressive stress, that corresponds to the flattest part of EHS. For buckling about the major axis, the exact location of the bulge cannot be easily defined from the presented pictures. Therefore, EHS with marked spots with the maximum out-of-plane deformation are presented in Fig. 4. Cross-sections are given for the initial deformation at the beginning of the loading (step 1) and at the point of reaching the ultimate bending moment (step 2). For buckling about the major axis, maximum out-of-plane deformation moves upward between these two steps. In the beginning, at a distance of approximately 30 mm from the extreme fibre in compression, it corresponds to the theoretical solution that predicts initiation of the elastic critical buckling at a distance of $0.21h$ from the extreme fibre in compression. The result does not match the one experimentally obtained by Chan and Gardner, that located buckling initiation at a distance of $0.11h$ [8]. For buckling about the minor axis, during the whole loading process, maximum deformation is located at the flattest point of the cross-section, as previously described.

In Fig. 5, there are given numerically obtained values of ultimate moments for analysed cross-sections for bending about the minor and the major principal axis, M_u, normalised with a bending strength according to EN 1993-1-1:2015, M_{EN}. The results are plotted against $D_e/(t \cdot \varepsilon^2)$ and slenderness limits for classes 1, 2 and 3 are marked with dashed lines. The prescribed values of limiting slenderness are discussed further in this section. However, it is noted that the slenderness limit for class 1 is not analysed in this paper. As the difference between cross-sections of class 1 and 2 regards rotation capacity of a member, in order to investigate this effect, a post-ultimate behaviour of the element should be analysed.

As it could be noticed, all ratios M_u/M_{EN} presented in Fig. 5 are larger than 1.0. In other words, for the analysed set of data, recommendations given in the draft version of Eurocode 3 are safe-sided.

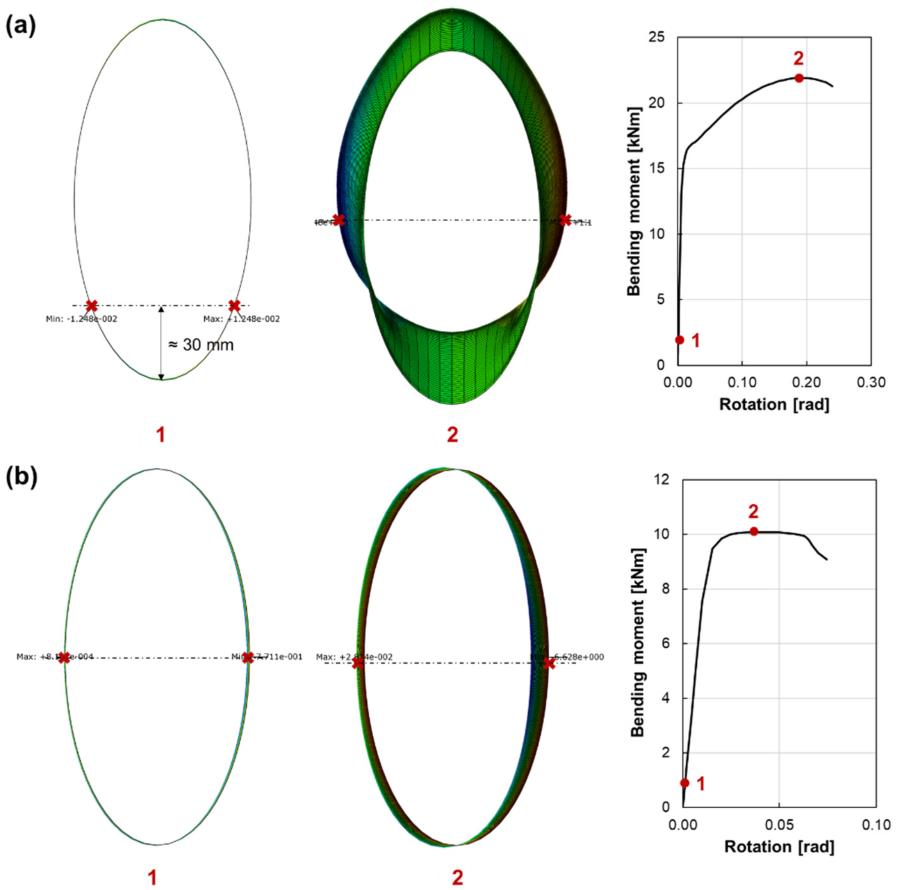

Fig. 4. Deformed shapes of EHS due to pure bending about: (a) the major axis, (b) the minor axis

For bending about the major axis and cross-sections of class 1 and 2, ratios M_u/M_{EN} lie between 1.0 and 1.5 and considerable dissipation in results is present depending on the applied material model. However, it is interesting to note that a distinct difference in behaviour between a group of hot-finished EHS and a group of cold-formed EHS is not observed. For the cross-sections of class 3, a greater difference between the bending strength prescribed by the design code and the ultimate moment determined by numerical analysis is present. Also, significant differences in the response of models with applied cold-formed and hot-finished stress-strain curves are present, with the exception of the cold-formed material model given by Zhu and Young for an oval hollow section. As the geometry of an oval section is different than EHS, results obtained with this material model should be taken with caution, considering a discrepancy of material stress-strain relationship along perimeters of these two cross-section types. For chosen geometries of a cross-section, none EHS are of class 4.

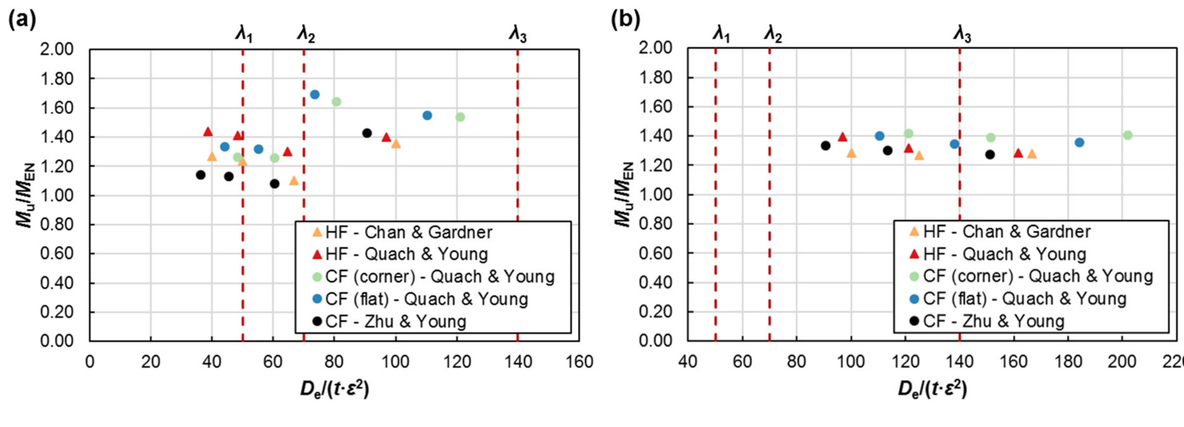

Fig. 5. Comparison of numerically obtained ultimate moments with design bending strengths: (a) bending about the major axis, (b) bending about the minor axis

In the case of bending about the minor axis, all analysed cross-sections are of class 3 and 4. All ratios M_u/M_{EN} are concentrated approximately between 1.2 and 1.4, for both classes. Comparing to bending about the strong axis, smaller dissipation of results is present and all models show a similar response, without strongly expressed differences depending on the assigned material model.

According to the described results, Fig. 6 and Fig. 7 are plotted to compare ultimate strengths with a plastic moment capacity, M_{pl}, and an elastic moment capacity, M_{el}, respectively. Comparing results for bending about the strong axis given in Fig. 6.a and Fig. 7.a for the range of EHS of class 3, a notable difference between M_u/M_{pl} and M_u/M_{el}, up to almost 50%, is observed. Although for cold-formed material models given by Quach and Young, plastic moment capacity gives safe-sided predictions of the bending strength, it is not the case with analysed hot-finished EHS. Therefore, it could be concluded that choosing a cross-section slenderness limit is delicate and should be followed by a wide parametric analysis including both various material models and cross-section geometry.

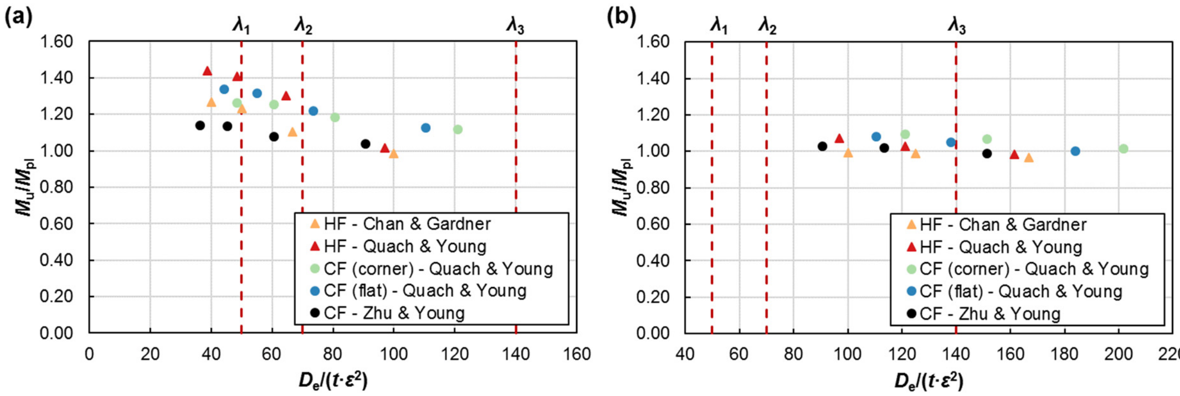

Fig. 6. Comparison of numerically obtained ultimate moments with plastic moment capacity: (a) bending about the major axis, (b) bending about the minor axis

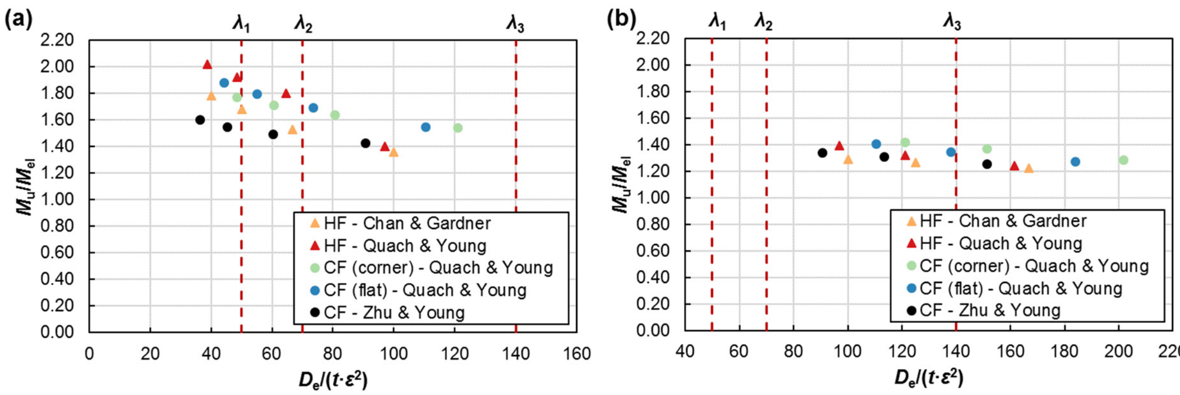

Fig. 7. Comparison of numerically obtained ultimate moments with elastic moment capacity: (a) bending about the major axis, (b) bending about the minor axis

Results for bending about the weak axis are presented in Fig. 6.b and Fig. 7.b. Firstly, comparing to bending about the major axis, a smaller difference between M_u/M_{pl} and M_u/M_{el}, of approximately 30%, is noticed. If plastic moment capacity was adopted for EHS of class 3, unsafe predictions in cross-section resistance would be made, according to some analysed models. When cross-sections of class 4 are discussed, a comparison between Fig. 5.b and Fig. 7.b should be made. In the former one, M_{EN} is calculated accounting effective section modulus. In both cases, the ratio between ultimate moment and elastic, i.e. effective moment capacity is above 1.2 and does not exceed 1.4. For that reason, a shift of the limiting slenderness for class 3 should be considered, accounting possible effects of different cross-section aspect ratios and conducting proper parametric analysis. It is interesting to note that a difference between M_{eff} and M_{el} arises with cross-section slenderness, that is the consequence of the effective section modulus definition according to EN 1993-1-1:2015, given in Eq. 4, that includes the fourth root of the normalised slenderness.

5. CONCLUSIONS

Numerical study on bending strength of hot-finished and cold-formed elliptical hollow sections is presented in this paper. Models of short EHS members with applied bending moments at the ends are developed. Pure bending about the major and the minor principal axis is studied. Material stress-strain curves are applied through the results of tensile coupon tests published in other researches of EHS. Local geometrical imperfections are incorporated in simulations, although varied imperfection amplitude of 1/100 and 1/10 of a plate thickness did not show a significant effect on the results.

The obtained bending strengths for the analysed hot-finished and cold-formed members are presented and compared to design criteria defined in the draft version of Eurocode for design of steel structures EN 1993-1-1:2015 [3]. For all analysed members, it is shown that the obtained ultimate moment is higher than the bending strength calculated according to the design standard. Therefore, design recommendations could be considered as safe-sided, although one should be aware of the considerable underestimation in the bending resistance that is in some cases present in EHS design. The peak underestimation occurs for sections of class 3 that bend about the strong axis, followed by dissimilar responses of cold-formed and hot-finished EHS. However, the use of plastic moment capacity in these cases does not give appropriate results, suggesting that the application of elastic theory is preferable. For the tested range of cross-section slenderness, reduction of a section modulus due to buckling in the elastic domain, characteristic for cross-sections of class 4, is not considerable comparing to elastic section modulus. However, for analysed EHS it is shown that even the application of the later one gives safe-sided results, although slenderness limit for class 3 is increased in the draft standard, in comparison to the limit prescribed for CHS in the current Eurocode EN 1993-1-1:2005 [2]. A potential shift of the slenderness limit for class 3 should be considered.

In further studies, it is suggested to extend the set of data and include elliptical hollow sections of all classes for both bending about the minor and the major principal axis. For making general conclusions regarding appropriate design rules for bending resistance of EHS, it is necessary to perform wide parametric analysis, covering a range of cross-section geometrical properties, but also applying appropriate material models, covering different manufacturing processes.

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