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INFLUENCE OF GEOMETRICAL AND STRUCTURAL IMPERFECTIONS ON THE BEHAVIOR OF STEEL PLATE GIRDERS

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Abstract. *The girders or parts of the girders are not ideally flat in terms of their geometry. The deviations that occur are defined as geometric imperfections. Also, in the material from which the girder is made, a certain deviation may occur during factory production or for some other reason, which is known as structural imperfection. This paper presents the analysis of the behavior of plate girders (welded steel I girders), with and without material stiffening and loaded with patch loading. The results were obtained by numerical simulation in the ANSYS for models with included geometric imperfections. The model was performed in accordance with the recommendations for different behavior curves of materials from Eurocode 3. The limit load obtained by numerical simulation corresponded to the experimental results from the literature. Stress values for girders with and without geometric imperfections for the same load value were compared.*

Key words: *geometric imperfections, structural imperfection, plate girder, steel girder*

1. INTRODUCTION

The behavior of plate girders (welded steel I girders) under the patch load is very complex. The complexity of this problem lies in the fact that, on the one hand, there is a localized buckling of the girder in the web. On the other hand the load due to buckling does not match the limit load.

In practice, this case is encountered during the assembly of bridges, the process of launching the bridge to its final position over temporary or permanent supports. The influences which occur may exceed the load of the structure in certain points due to the patch loading. As no complete theoretical solution to this problem has not been found yet, there is a need for a more detailed analysis. With that kind of problems, in order to perform

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their design, it is necessary to consider the geometry of the girders and the characteristics of the materials from which they are made. The way to its solution requires a combination of experimental research and numerical analysis, to which special attention is paid in this paper. Especially in cases of numerical simulations where numerical models are formed, it is very important to include imperfections of girders.

When analyzing the behavior of plate steel girders, in the beginning, the models were composed of ideally flat plates. It is clear that real constructions are not ideally flat, but that they have initial imperfections before applying the load. These irregularities have become an unavoidable part of the analysis and it has been shown that in some cases their impact is not negligible.

The importance of this problem is also shown by the fact that in the European regulations EN1993-1-5 in Annex C [1], as well as ENV 1993-1-1 [2], recommendations are given for the method of setting the initial imperfections. Cases of research on the influence of real imperfections on the size of the limit load are represented in the literature in a smaller number. Within the commentary of EN1993-1-5, a suggestion was given that studies of the impact of real imperfections should be continued in order to improve the calculation recommendations. Girder analysis was performed in the ANSYS program. Girders without longitudinal stiffener and girders with longitudinal stiffener near the loaded upper flange were tested. We analyzed the influence of the length of the uniformly distributed load on the loaded flange, and in the plane of the web, known as patch loading and the behavior of the girder in the nonlinear domain, as well as the ultimate load which was manifested as progressive increase of registered deformations of flanges and the web and strains without further increase of force. Tests were performed using numerical simulations and they relate to the behavior of the girder model and the values of the ultimate load for different material models in the plastic domain with the aim of choosing the one that gives the closest results to the real model. Also, in terms of stress analysis, the results of girders with and without geometric imperfections were compared.

Geometric imperfections mainly occur during the construction and operation of the structure. Globally, imperfections are divided into geometric imperfections, ie. imperfections concerning girder geometry and structural imperfection, ie. imperfections related to material imperfections. When determining the ultimate load capacity of steel plate structures by numerical analysis, in case the reduction factor is not taken, the initial imperfections must be included. However, no matter how precisely the imperfections are defined, they represent only a replacement for the real imperfections of the girder. Accordingly, it is clear that there are certain differences in the results of numerical simulations in relation to the results obtained by experimental research. In this regard, it is impossible to precisely define the inhomogeneity of the material, the effect of the load or the definition of boundary conditions, but appropriate substitutions must be found in the formation of the numerical model.

2. IMPERFECTIONS OF GIRDERS

This section will provide an overview of girder analysis involving imperfections and a brief overview of this issue that can be found in the literature.

2.1. Geometric imperfections of girders

The initial deformations are predicted to include the corresponding model imperfections. Their choice is such that due to the load, the least resistance of buckling is obtained. Imperfections can also be divided into: local imperfections within which individual elements are analyzed and global imperfections that apply to the entire structure.

According to the method of setting the initial geometric imperfection, they can be divided into real imperfections, imperfections according to their own modes, equivalent geometric imperfections and imperfections according to the fracture shape.

2.1.1. Real imperfections

The setting of imperfections in this way is used in the testing of concrete carriers or during serial production. Setting imperfection in this way is used in testing specific girders or during series production. In numerical modeling, this type of imperfection is usually replaced by some other imperfections, which are easier to model. In this paper, real imperfections on numerical models are given. There is not much data in the literature about systematic measurements of initial deformations, that is, real imperfections used in the experiments, which was an additional incentive for the authors of this paper to research.

Speaking about the experiences of researchers who assigned real initial imperfections on their numerical test models, specifically in [3], the girder in the ABAQUS software package was modeled. The shape of the precise girder geometry was obtained using a 3D measuring device. The measured web geometry was transferred to the model for numerical analysis, while it was estimated that the measured geometry of the flanges, i.e. its imperfections should be neglected, so the flanges of the model are taken as ideally flat. It was concluded that the results of girders with real imperfections lead to a satisfactory ultimate load compared to the experimental results. In addition to the real imperfections, the structural imperfections of the girder were also included.

2.1.2. Imperfections according to buckling modes

This type of imperfection is defined on a mathematical-numerical basis, by analyzing the bending of the girder at its eigenvalues. After determining the eigenmodes, the shape of the eigenmodes is assigned to the geometry of the girder model. Such girder geometry should be considered as the initial geometry with appropriate boundary conditions.

One of the first researchers to include the influence of initial imperfections in his research of patch-loaded girders was Bergfelt [4]. He concludes that if the shape of the initial imperfection of the girder is similar to the shape of its own buckling mode, then the ultimate bearing capacity is lower than if this is not the case. The amplitude, the shape of its own mode, the slenderness of the element and the type of stiffening of the web to flange should be taken into account.

Graciano [5] analyzed the girders loaded with patch loading by setting the initial imperfections according to eigenmodes in the ANSIS software package. The models were previously tested experimentally. The cases for the first three basic buckling modes shapes of the girder were examined (Fig. 1), as well as for the case of the sum of the first three buckling modes.

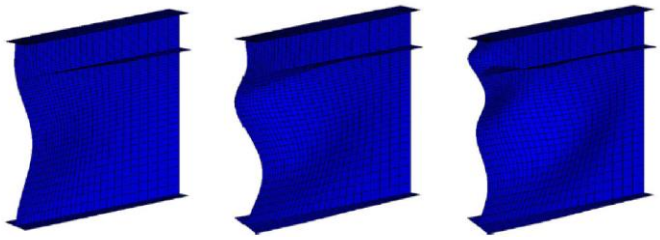


Fig. 1 The first three buckling modes respectively [5]

The conclusion of this research is that the shape of the initial imperfection that results in the lowest strength for a girder differs for each size of imperfection and stiffener location. It is also pointed out that the initial imperfections for girders under patch loading can be modeled using a shape similar to the first eigenmode or sine wave in order to obtain satisfactory results.

In the EN 1993-1-5, Annex C [1], it is proposed that Geometric imperfections may be based on the shape of the critical plate buckling modes with amplitudes given in the National Annex, as well as to recommend 80% of the geometric fabrication tolerances. In the case of greater distances of transverse stiffness, in global imperfections for longitudinal stiffening the eigenmodes consist of two or more half-waves. Therefore, care should be taken that the assumed imperfections have a certain number of half-waves, because the relevant form of imperfection is the one that gives the least ultimate load.

In the work of Chacon [3], the girder geometry, based on its eigenmodes, is given in accordance with the regulations EN1993-1-5, with an amplitude w = 80% of the factory tolerance. Structural initial imperfections were also taken in all girders. Four types of girders with different initial geometries were examined (girder length was varied). It was concluded that satisfactory results were obtained according to the first two eigenmodes, while setting the shape of higher eigenmodes does not give less resistance as provided in EN 1993-1-5.

2.1.3. Equivalent geometric imperfections

The initial geometric imperfections of a girder that are represented in the form of a mathematical function, for example a sine function, and follow the form of real geometric imperfections, are called equivalent imperfections. European regulations [1], [2] provide rules for assigning geometric imperfections. Equivalent imperfections can be used in all cases where no more precise analysis is performed. The table with recommended values of amplitudes and shapes of imperfections in relation to the width and length of the support already exist. It is also noted that equivalent geometric imperfections can be replaced by appropriate fictitious forces.

In the work of Granath [6], satisfactory results were obtained by assigning equivalent imperfections (in the form of a sinusoidal function similar to the form of the first buckling mode) for the girders without stiffening.

In [7], equivalent imperfections of the sinusoidal function were used. Although these imperfections did not represent the most unfavorable case for predicting the lowest resistance, satisfactory results were obtained. The conclusion was: the shape of imperfections becomes relevant only for non - square plates, while for square plates the difference in imperfections according to their eigenmode and equivalent imperfections in the form of sinusoidal function becomes negligible.

In [8], the imperfections given on the basis of the buckling shape that was previously obtained experimentally are considered. With such given imperfections, the lower ultimate strength was obtained in comparison with other cases of imperfections. The authors suggested that this be included in the regulations as a better way of setting imperfections.

2.2. Structural imperfections

Structural (material) imperfections of the carrier refer in most cases to imperfections of materials that occurred during factory production or for other reasons. These imperfections are residual (residual) stresses in the material. These stresses occur during the welding of the girders, which reduces their load-bearing capacity [9]. Structural imperfections must be taken so as to cause the most unfavorable case of buckling, which is achieved by including residual stresses in the model in FEM. EN 1993-1-5 highlights the use of a combination of structural imperfections with one of the geometric imperfections. Residual stresses can sometimes be considered as fictitious, additional initial deformations [1].

In paper [3], it is stated that each residual stress is atypical and that each specific case can cause different implications. It is stated that the introduction of patterns for residual stresses gives somewhat more precise results, but that their influence does not play a decisive role.

Simplified patterns for residual stresses, proposed by the Swedish regulations for steel girders, were used in [10] and [11].

Note that the presence of geometric and material nonlinearity must be observed simultaneously.

3. Geometric Characteristics of the Girder and Numerical Model

Within this paper, a numerical model was formed which confirmed the results of N. Marković's experiment, taken from the literature [12]. The model included the geometric characteristics of the girders with imperfections, and during the testing, within the material characteristics, several different σ-ε curves were taken, which correspond to the tested material samples from which the experimental models were made [13]. The geometry of the girder model with all dimensions is shown in Fig. 2. Four girders of the same dimensions were tested, two are without longitudinal stiffening, and two with longitudinal stiffening. The girder span is s=500 mm, web depth h=500, web thickness t_w=4 mm, flange with b_{fl}=120 mm, flange thickness t_{fl}=8 mm, stiffening depth h_{st}=30 mm, stiffening thickness t_{st}=8 mm, distance from the upper flange to the longitudinal stiffener h_1=100 mm. The length of application of the load l differed. Two girders lengths of patch load is l=50 mm and for the other two is l=150 mm. Web panel aspect ratio is s/h=1.

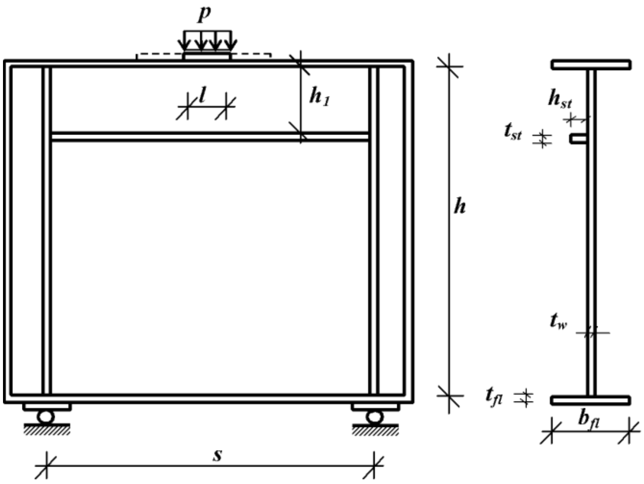


Fig. 2 Model of girder [14]

The aim of this research is, among other things, to examine the influence of real geometric imperfections of the girder web on the stress state, so that the girder models for computer simulations were taken as girders without and girders with imperfections.

Defining the initial shape of the girder for a numerical model was based on the precise geometry of the examined experimental model. In the experimental models, the initial geometric imperfections of the web were measured at a number of points (Fig. 3) with a measuring device. Imperfections of flange and stiffeners were not considered. Numerical models were formed and their geometry corresponded to the girders from the experiment. Figure 4 shows the shape of the initial geometric imperfections before applying the load. The values are given with magnification to highlight imperfections.

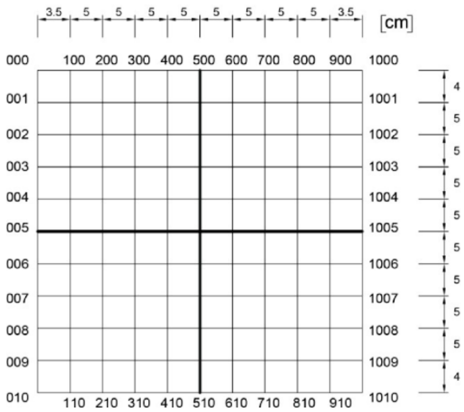


Fig. 3 Points on the web where the initial imperfections are given [15]

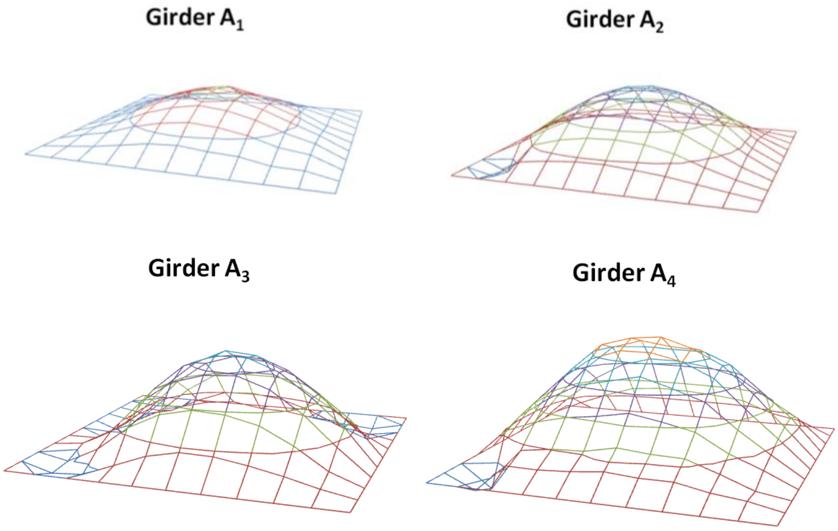


Fig. 4 Initial imperfections of the webs before loading for all type of girders

To obtain relevant data, for a numerical model, it is of great importance to represent the exact behavior of the material. Precise tests of the material properties of the girders were performed and the obtained results were used to form nonlinear models of materials used in numerical analysis.

According to European standards, in cases where material data are not available, the yield stress is assumed theoretically as a horizontal line to the achieved yield stress or its slope is defined with the value E / 10000, where E is the modulus of elasticity of that material.

Another case is the approximation of the E / 100 slope curve where the reinforcement of the material is considered and, in the case of a more realistic representation, it is possible to approximate the real curve in such a way as to obtain a multilinear curve that will best show the material characteristics. All variants of curves will be used in this paper. Bilinear curves with tangent modulus Et = E / 10000, Et = E / 100 will be used as well as a multilinear curve corresponding to the actual σ-ε material curve (Fig. 5).

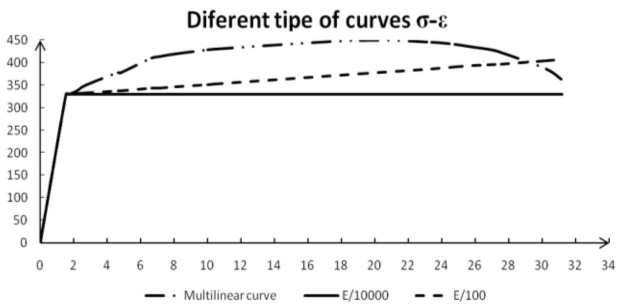


Fig. 5 σ-ε curves used in numerical model

The boundary conditions of the girder are defined so that the girder in the static sense is simply supported. In numerical analysis, the own weight of the girder is included in the calculation. The load of the girder is given as an equally distributed load over the entire width of the flange, and with certain lengths *l* on the upper flange. The girder load was applied through the load plate as in the experiment, and it was permitted to move only in vertical direction.

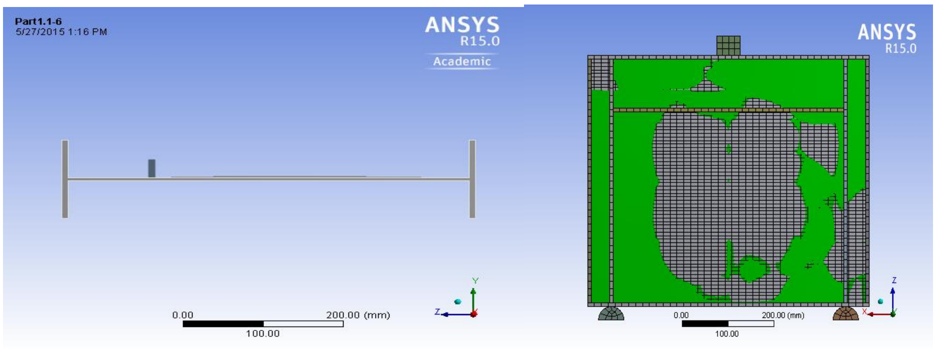


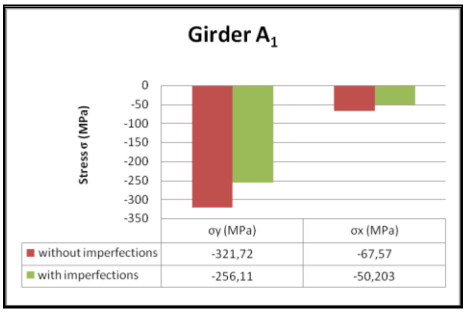
Fig. 6 Numerical model with initial imperfections

Based on the geometry of the girder, the numerical model of the girder was discretized by dividing it into finites element mesh. From the database of elements of the software package ANSYS Workbench 15, elements of the SOLID type were selected. A finite element size of 15mm was adopted.

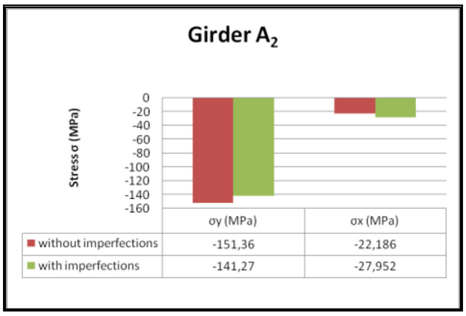
Figure 6 shows a beam with a finite element mesh before loading and on which geometric imperfections are clearly visible.

4. Results and Discussions

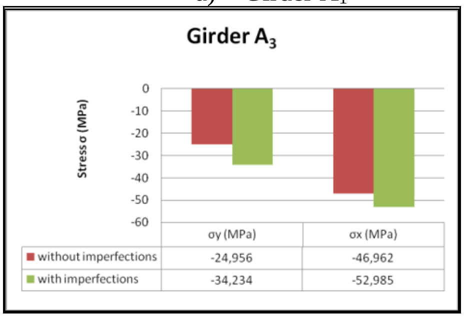
The actual models for numerical simulation of girder behavior allow inclusion of initial deformations-imperfections into the calculation on the basis of the actual girder model. In the numerical simulations of the model, the form, character and course of the deformation process as well as the buckling were identical as in the experiments with actual models, for each concrete sample [15]. Based on that, this numerical models can be used for further analysis. Figure 7 shows the stress diagrams σ_x and σ_y for girders without imperfections and for girders with real imperfections for all types of girders A_1, A_2, A_3 and A_4. The influence of real imperfections in numerical simulation on stress values σ_x and σ_y at one of the measuring points for the same load value is presented (100 kN).



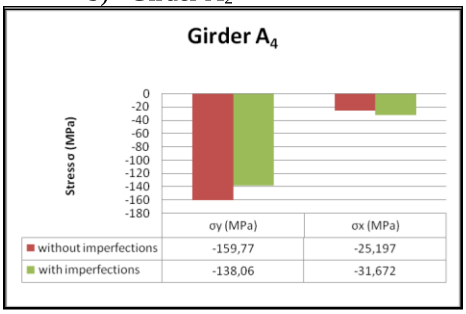
a) Girder A_1



b) Girder A_2



c) Girder A_3



d) Girder A_4

Fig. 7 Influence of real imperfections in numerical models of girders on stress values σ_x and σ_y for force of 100 kN [15]

One of the main goals of this modeling is to monitor the ultimate bearing capacity of the girder. The obtained values were compared with the ultimate load obtained experimentally. Table 1 shows the ultimate load values in kN for all four types of girders (A1, A2, A3 and A4) obtained experimentally (experiment), as well as obtained by numerical simulation for different values of curved σ-ε materials (multilinear curve, E/10000 and E/100).

The difference between the ultimate load of numerical models and the ultimate load obtained experimentally is shown as a percentage. The last column shows the mean value of the deviation expressed as a percentage for each of the given behaviors of the material curves.

Table 1 Ultimate load values for all types of girders and deviation in relation to experimental results

	A_1	A_2	A_3	A_4	%
Experiment	165	215	183	255	Mean value
Multilinear curve	178,174	216,9275	188,5	274	
%	7,98%	0,90%	3,01%	7,45%	4,84%
E/10000	172	235,406	176,962	299,407	
%	4,24%	9,49%	-3,30%	17,41%	8,61%
E/100	180,5	238,637	185,5	302,438	
%	9,39%	10,99%	1,37%	18,60%	10,09%

Table 2 shows the increase in ultimate load with increasing patch loading length from 50 mm to 150 mm for non-stiffening girders (A_1 and A_2) and with stiffening (A_3 and A_4). The results obtained experimentally and numerically by simulation were compared and presented in percentages.

Table 2 Influence of "patch loading" on ultimate load

	Without stiffener	*With stiffener*
	A_1 and A_2	A_3 and A_4
Experiment	23,26 %	31,20 %
Multilinear curve	17,86 %	59,66 %
E/10000	26,93 %	40,90 %
E/100	24,36 %	38,67 %
Mean value	22,56 %	43,56 %

Table 3 shows the effect of longitudinal stiffening on the ultimate load capacity for girders with load length l = 50 mm (A_1 is without stiffening and A_3 is with stiffening) and load length l = 150 mm (A_2 is without stiffening and A_4 is with stiffening).

Table 3 Influence of longitudinal stiffening on the increase of ultimate load capacity

Load length	*l=50 mm*	*l=150 mm*
	A_1 and A_3	A_2 and A_4
Experiment	9,84 %	15,69 %
Multilinear curve	5,8 %	20,83 %
E/10000	2,88 %	21,38 %
E/100	2,77 %	21,10 %
Mean value	2,99 %	22,10 %

5. CONCLUSIONS

The behavior of plate girders under the patch loading is very complex and depends on various parameters. The appearance of plasticization occurs already after 50% of the ultimate load. The deformations that occur then do not have to be significant. The Plastification develops on the most loaded part of the web, first, only on the surface and then spreads along the thickness of the web. This behavior depends on many parameters, and it can be quite complex due to the variable stress field.

The influence of geometric imperfections of the web in the girders (without flange and stiffening imperfections) was included and a comparison with girders without imperfections was performed within the numerical simulation, in order to monitor the development of stresses.

Stress values for the same load values for the observed girders were obtained. The obtained results were compared for girders with geometric imperfections of the webs on one side and girders without geometric imperfections on the other side. In Figure 7 we can see that by including imperfections in the calculation, deviations in stress values occur. It is necessary to keep in mind that within our model, the effects of imperfections of flanges and stiffening, possible deviations in defining the boundary conditions that correspond to the real girder, etc. were not taken into account.

The ultimate load for all types of girders were calculated and the obtained values were compared with the experimental results (shown in Table 1). The values for different σ-ε curves in accordance with European regulations were calculated separately. In all cases of the given material behavior diagrams, the results are satisfactory. The best agreement with the experimental results was given by the material behavior curve corresponding to the multilinear curve of real material and this deviation averages 4.84%.

With the increase of patch load length, there was an increase in the ultimate load capacity in both stiffened and unstiffened girders, with included imperfections (see Tab. 2). The presence of longitudinal stiffeners also increases the ultimate load capacity, which is shown in Table 3.

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UTICAJ GEOMETRIJSKIH I STRUKTURNIH NESAVRŠENOSTI NA PONAŠANJE ČELIČNIH PLOČASTIH NOSAČA

Nosači ili delovi nosača nisu idealno ravni u pogledu svoje geometrije. Nesavršenosti koje se javljaju definišu se kao geometrijske imperfekcije. Takođe, u materijalu od kojeg je napravljen nosač može doći do određenog odstupanja tokom fabričke proizvodnje ili iz nekog drugog razloga, što je poznato kao imperfekcija materijala. Ovaj rad predstavlja slučaj pločastih nosača (zavareni čelični I nosači) sa i bez ukrućenja i opterećenih patch loading-om. Dobijeni su rezultati numeričkom simulacijom u programu ANSYS za modele sa uračunatim geometrijskim imperfekcijama. Formiranje modela izvršeno je u skladu sa preporukama za različite krive ponašanja materijala iz Evrokoda 3. Granično opterećenje dobijeno numeričkom simulacijom odgovaralo je eksperimentalnim rezultatima iz literature. Upoređene su vrednosti napona za nosače sa i bez geometrijskih imperfekcija za istu vrednost opterećenja.

Ključne reči: *geometrijske imperfekcije, imperfekcije materijala, pločasti nosač, čelični nosač*