ДГКМ
ДРУШТВО НА ГРАДЕЖНИТЕ КОНСТРУКТОРИ НА МАКЕДОНИЈА

Партизански одреди 24,
П.Фах 560, 1001 Скопје
Северна Македонија

MASE
MACEDONIAN ASSOCIATION OF STRUCTURAL ENGINEERS

Partizanski odredi 24,
P. Box 560, 1001 Skopje
North Macedonia

SS - 5

mase@gf.ukim.edu.mk
http://mase.gf.ukim.edu.mk

INFLUENCE OF STIFFENER AND FLANGE ON ELASTIC CRITICAL LOAD OF I-GIRDERS SUBJECTED TO PATCH LOADING

Milica KOPRIVICA[1], Aleksandar ĆERANIĆ[2], Saša KOVAČEVIĆ[3], Ratko SALATIĆ[4], Nenad MARKOVIĆ[5]

ABSTRACT

The paper considers the influence of patch load length, flange thickness, and stiffener's characteristics on the behaviour of steel plate girders subjected to patch loading in terms of elastic stability. The aim is to show the dependence of the elastic critical load on the mentioned parameters, through the buckling coefficients of the isolated web plate and steel I-girders subjected to patch loading.

The girder without transverse stiffeners in the load application zone, but with longitudinal stiffener was analyzed. The buckling coefficients of clamped plate and I-girder are compared, and suggestions for improving the EN1993-1-5 patch loading resistance model are presented. The paper gives a brief overview of the ultimate load capacity of longitudinaly stiffened I-girders. Numerical results are compared with the results of current standards EN1993-1-5.

The aim of this research is to single out the characteristics of the girders that have the greatest impact on the elastic critical load. It is necessary to come up with new expressions for the calculation of the buckling coefficient through more detailed and comprehensive analyzes. It is shown that the influence of stiffener and flange cannot be neglected because both parameters are important.

Keywords: Elastic critical load; Buckling coefficient; Patch loading; Plate girders.

---

[1] MSc, Teaching assistant, Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia, tel: +38164 4612663, e-mail: mbendic@grf.bg.ac.rs

[2] MSc, Spenncon AS, Stabells gate 9, Hønefoss, Norway, ceranicaleksandar@gmail.com

[3] Dr, Department of Civil and Environmental Engineering, Imperial College London, London, SW7 2AZ, UK, s.kovacevic@imperial.ac.uk

[4] Dr, Professor, Faculty of Civil Engineering, University of Belgrade, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia, ratko.salatic@gmail.com

[5] Dr, Matice srpske 62, 11000 Belgrade, Serbia, markovic.nenad2018@gmail.com

1. INTRODUCTION

The stability problems and ultimate load behaviour of steel plate girders have been attracting attention in recent decades. Behaviour of the steel I-girder without vertical stiffener in the zone of load introduction, under the localized load (patch load) on the flange in the plane of the web is one of the studied problems. This problem has got the importance with a general trend to avoid vertical stiffeners (except at supports), also for moving loads, e.g., crane girders loaded by crane wheels and during the incremental launching of multi-span steel bridges over temporary or permanent supports. In order to describe the problem of I-girder's behaviour, it is necessary to analyze various parameters as flange thickness, stiffener thickness and width, the distance between the loaded flange and the stiffener, patch load length, web thickness, relative flexural rigidity of the stiffener. Mentioned parameters and their relationships in different ways affect the behaviour of the I-girder. It is necessary to observe each of them independently and analyze their contribution. Computer programs based on the finite element method have enabled a wide range of numerical simulations – numerical experiments.

The development of Eurocodes - European standards, for the design of civil engineering structures has brought a new approach to harmonize solutions of the patch load problem with other stability problems. The buckling coefficient of the steel plate girders obtained using the procedures given in the Eurocode EN1993-1-5 [1] leads often to conservative values of the ultimate load. An attempt is made in this paper to give some improvements to that procedure and to pay attention to parameters that have been neglected, and their impact is significant. Special efforts are needed to combine different impacts of isolated parameters and provide solutions that will describe the problem of steel plate buckling better than existing regulations. Eurocode EN1993-1-5 [1] provides a simplified expression for the buckling coefficient in the calculation of the elastic critical load P_{cr} – Eq. (1). For a longitudinally stiffened plate girder under patch load applied on the top flange, between two vertical stiffeners on a distance a, the buckling coefficient should be obtained using Eq. (2) and Eq. (3):

$$P_{cr} = 0.9 k_F E \frac{tw^3}{h_w} \tag{1}$$

$$k_F = 6 + 2\left(\frac{h_w}{a}\right)^2 + \left[5.44\frac{b_1}{a} - 0.21\right]\cdot\sqrt{\gamma_s} \tag{2}$$

$$\gamma_s = 10.9\frac{I_{sl1}}{h_w \cdot t_w{}^3} \leq 13\cdot\left[\frac{a}{h_w}\right]^3 + 210\left[0.3 - \frac{b_1}{h_w}\right] \tag{3}$$

where I_{sl1} - second moments of area of the stiffener closest to the loaded flange including contributory parts of the web

Generally, the moment of inertia of the longitudinal stiffener is calculated for a cross section according to Eurocode EN1993-1-5 [1] with respect to its centroidal axis parallel with the web plane. The effective cross section consists of the stiffener itself and an effective portion of the web plate having a width of $15\varepsilon t_w$ on each side of the stiffener.

As it could be observed, the given expression in Eq. (2) does not take into account the length of an applied patch load and influence of the flange.

The following notations are used in this paper to describe the problem of longitudinally stiffened steel plate girders subjected to the patch loading, to compare the results, and to derive conclusions: h_w – web depth, t_w – web thickness, t_f – flange thickness, b_f – flange width, t_s – stiffener thickness, b_s – stiffener width, a – distance between vertical stiffeners, b_1 – depth of the loaded subpanel taken as the clear distance between the loaded flange and the stiffener, s_s – patch load length, ν – Poisson's ratio, E – modulus of elasticity, k_F – buckling coefficient, γ_s - relative flexural rigidity of the stiffener.

Previous, preliminary studies [2] have shown the influence of flange and stiffener on the elastic critical load, but their contribution was not separated. The obtained results for longitudinally stiffened girders were limited because only stiffeners whose thickness is equal to the thickness of the flange were observed. The buckling coefficients of I-girders and isolated plates corresponding to the web of I-girders were compared. Improved expressions for calculating the buckling coefficient were given, and the shortcomings of the Eurocode EN1993-1-5 [1] were pointed out [2].

In this paper, the influence of load length s_s, flange thickness t_f and longitudinal stiffener's dimensions (b_s, t_s) on the elastic critical load of the I-girder is given. In particular, the isolated web of the girder and I-girders are analyzed. The results were compared with the expressions in the Eurocode EN1993-1-5. Following numerical analysis is based on the finite element method. The commercial software Abaqus [3] was used in this research to obtain the elastic critical buckling load. All further conclusions refer to precisely defined material and geometric characteristics.

2. NUMERICAL SIMULATIONS

The purpose of this paper is to show the influence of longitudinal stiffeners on the elastic critical load of an isolated web plate (that was modelled as a plate clamped along all edges) and I-girder, using FE analysis. Finite element model is based on experimental studies [4]. The plate and I-girder with a web panel aspect ratio $a/h_w = 1$ and plate (web) thickness of 4 mm (schematically presented in Fig. 1) were investigated. Since it has been shown in previous studies [5] that the clamped plate (hereinafter referred to as CC plates) best suits the behaviour of the girder **(**better than the simply supported plates and plates simply supported on the vertical and clamped on the horizontal edges), the boundary conditions are set as follows: degrees of freedom 2 and 5 are only constrained in the vertical edges, degree of freedom 4 in the horizontal edges, while degree of freedom 3 is constrained in all edges. The length of an applied uniform load s_s, flange and stiffener thickness (t_f, t_s) were varied.

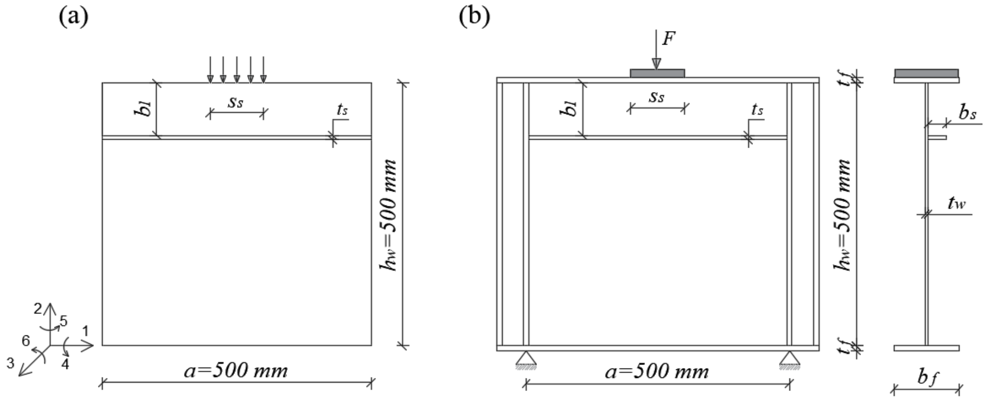

Fig. 1. (a) Plate under patch load; (b) I-girders under patch load

The flange width of the I-girder was set to 120 mm, while the flange thickness was set to 8, 16, and 24 mm. The depth of the loaded subpanel taken as the clear distance between the loaded flange and the stiffener b_1 was set to 100 mm. Three different longitudinal stiffeners were used. The thickness of the longitudinal stiffener was varied (t_s=t_w, 2t_w, 3t_w). The width b_s was varied to achieve the maximum impact of stiffener on the ultimate load capacity based on convergence analysis at the ultimate limit state for each thickness t_s. The longitudinal stiffener’s dimensions that have been considered are 52x4 mm, 58x8 mm, 50x12 mm (b_s x t_s). The lengths of an applied uniform load s_s were 0, 50, 100, 150, 200, 250 mm. The material considered was homogenous with an elastic modulus of 205 GPa and Poisson’s ratio of 0.3.

A general-purpose four-node quadrilateral shell element with reduced integration and six degrees of freedom per node (S4R) from the Abaqus element library was used for the FE analysis. All numerical runs were performed with a 5 mm finite element mesh size.

3. RESULTS AND DISCUSSION

As a result of the numerical analysis of an isolated web plate and I-girder values of the critical loads P_{cr} were obtained for different flange and stiffener dimensions. The buckling coefficients k_F were calculated from P_{cr} using Eq. (1). This makes it possible to independently observe the influence of stiffener and flange. Results are compared with the propositions of Eurocode EN1993-1-5.

3.1. Buckling coefficient of the isolated web plate as a function of patch load length and dimensions of the stiffener

Table 1 shows the buckling coefficients k_F of isolated clamped web plates. The values are given as the function of ratio s_s/h_w, and dimensions of stiffener b_s and t_s, for three different longitudinal stiffeners (52x4, 58x8, 50x12) whose dimensions are determined from the ultimate load analysis. The relative flexural rigidity of the stiffener γ_s is adopted according to the terms given to the Eurocode EN1993-1-5 (Eq. 2, Eq. 3). The boundary conditions corresponding to the clamped plate were chosen for analysis.

Table 1. Buckling coefficient k_F of isolated clamped web plates, as a function of patch load length s_s [mm] and stiffener dimensions b_s x t_s [mm]

	Unstiffened plate	*Stiffened plate* $b_s \times t_s$ *[mm x mm]*		
s_s/h_w	*0*	*52 x 4* $\gamma_s=53.46$	*58 x 8* $\gamma_s=118.56$	*50 x 12* $\gamma_s=107.24$
0	8.00	12.34	13.42	14.05
0.1	8.10	12.54	13.60	14.23
0.2	8.35	12.76	13.78	14.33
0.3	8.74	13.26	14.26	14.87
0.4	9.26	13.89	14.88	15.50
0.5	9.91	14.75	15.74	16.37

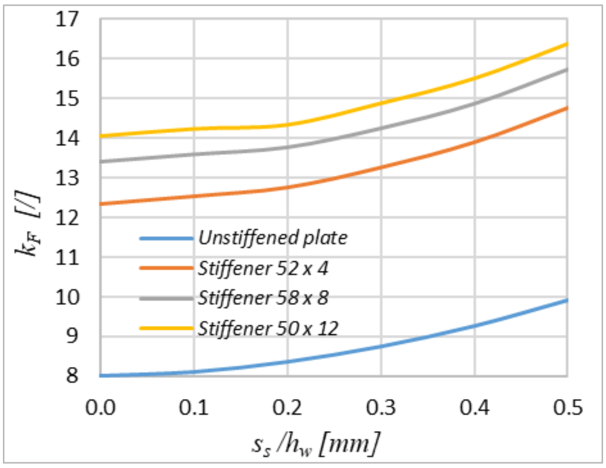

Fig. 2. Graphical interpretation of the buckling coefficient for different patch load lengths s_s and stiffener dimensions b_s x t_s [mm]

Figure 2. shows that the buckling coefficient increases with the patch load length, especially for higher patch load length. All three stiffeners contribute significantly to the coefficient k_F, and thus to the values of the elastic critical load.

3.2. Buckling coefficient of I-girders as a function of patch load length and thickness of the flange and dimensions of the stiffener

The following Tables 2, 3 and 4 show the values of the buckling coefficient k_F of the isolated web plates and the I-girders. Each table refers to a different value of flange thickness t_f. The following notations are used in the tables: *SP* refers to the stiffened plate, and *SG* refers to the stiffened I-girders. In the column labelled *EC* are the k_F coefficients obtained using Eq. (2). *St1*, *St2*, and *St3* denote the stiffeners of the following dimensions: 52x4, 58x8 and 50x12 (b_s x t_s), respectively. The buckling coefficient increases with increasing ratio s_s/h_w for all observed plates and girders regardless of stiffeners. If we observe stiffened girders, based on the presented results, it is noticed that the stiffener thickness t_s is a parameter that affects the results more than the stiffener width b_s, but the influence of the flange is essential and should not be neglected.

Table 2. Comparison of the buckling coefficient for CC plates and I-girders obtained by Eurocode EN1993-1-5 and numerically – t_f =8 mm

s_s / h_w	SP,St_1	SG,St_1	EC,St_1	SP,St_2	SG,St_2	EC,St_2	SP,St_3	SG,St_3	EC,St_3
0	12.34	12.71	14.42	13.42	13.94	17.56	14.05	14.63	17.09
0.1	12.54	12.94	14.42	13.60	14.15	17.56	14.23	14.83	17.09
0.2	12.76	13.41	14.42	13.78	14.60	17.56	14.33	15.27	17.09
0.3	13.26	14.08	14.42	14.26	15.27	17.56	14.87	15.95	17.09
0.4	13.89	14.99	14.42	14.88	16.20	17.56	15.50	16.89	17.09
0.5	14.75	16.18	14.42	15.74	17.42	17.56	16.37	18.12	17.09

Table 3. Comparison of the buckling coefficient for CC plates and I-girders obtained by Eurocode EN1993-1-5 and numerically – t_f =16 mm

s_s / h_w	SP,St_1	SG,St_1	EC,St_1	SP,St_2	SG,St_2	EC,St_2	SP,St_3	SG,St_3	EC,St_3
0	12.34	14.10	14.42	13.42	15.33	17.56	14.05	16.06	17.09
0.1	12.54	14.42	14.42	13.60	15.64	17.56	14.23	16.37	17.09
0.2	12.76	15.06	14.42	13.78	16.29	17.56	14.33	17.02	17.09
0.3	13.26	15.97	14.42	14.26	17.21	17.56	14.87	17.96	17.09
0.4	13.89	17.20	14.42	14.88	18.48	17.56	15.50	19.25	17.09
0.5	14.75	18.84	14.42	15.74	20.18	17.56	16.37	20.99	17.09

Table 4. Comparison of the buckling coefficient for CC plates and I-girders obtained by Eurocode EN1993-1-5 and numerically – t_f =24 mm

s_s / h_w	SP,St_1	SG,St_1	EC,St_1	SP,St_2	SG,St_2	EC,St_2	SP,St_3	SG,St_3	EC,St_3
0	12.34	15.18	14.42	13.42	16.38	17.56	14.05	17.12	17.09
0.1	12.54	15.56	14.42	13.60	16.77	17.56	14.23	17.51	17.09
0.2	12.76	16.40	14.42	13.78	17.62	17.56	14.33	18.38	17.09
0.3	13.26	17.57	14.42	14.26	18.83	17.56	14.87	19.61	17.09
0.4	13.89	19.19	14.42	14.88	20.50	17.56	15.50	21.32	17.09
0.5	14.75	21.43	14.42	15.74	22.83	17.56	16.37	23.70	17.09

The results of the Eurocode EN1993-1-5 are more conservative for greater values of flange thickness, patch load length s_s, and stiffener thickness. Interestingly, the increase of k_F for I-girder related to corresponding CC plate for certain patch load lengths is independent of the stiffener's dimensions but increases with flange dimensions. E.g, for the I-girder with flange thickness t_f= 8 mm, this maximum magnification is 10%, for t_f= 16 mm the maximum increase is 28%, and for t_f= 24 mm it reaches a value of 45%, for all three stiffeners.

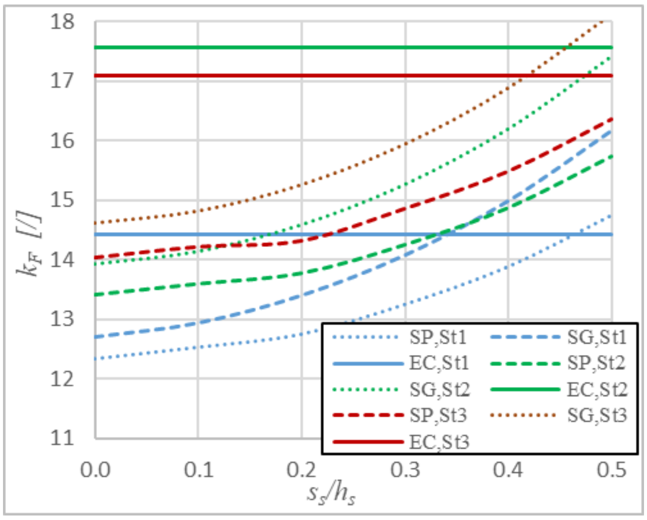

Fig. 3. Graphical interpretation of the buckling coefficient of I-girders for different ratio $s_{s/}\ h_w$ and dimensions of flange and stiffener

3.3. Comparison of the ultimate loads numerically obtained and from Eurocode

Table 2-Comparison of the ultimate loads for various approaches, t_f=8 mm

t_f [mm]	s_s	P_{cr}^{FEA}	P_{cr}^{EC}	F_u^{FEA}	F_u^{EC}	F_u^{EC}/F_u^{FEA}	$F_u^{EC}{}_{corr}$	$F_u^{EC}{}_{corr}/F_u^{FEA}$	$F_u^{EC}{}_{corr}/F_u^{EC}$
bs x ts	[mm]	[kN]	[kN]	[kN]	[kN]	[-]	[kN]	[-]	[-]
8 52 x 4	0	301	310	137	135	0.99	133	0.98	0.99
	100	318	310	211	168	0.80	170	0.81	1.01
	200	356	310	301	196	0.65	210	0.70	1.07
8 58 x 8	0	331	310	143	135	0.95	140	0.98	1.03
	100	346	310	223	168	0.75	178	0.80	1.06
	200	384	310	336	196	0.58	218	0.65	1.11
8 50 x 12	0	347	310	147	135	0.92	143	0.97	1.06
	100	362	310	230	168	0.73	182	0.79	1.08
	200	400	310	355	196	0.55	222	0.63	1.14

Table 6 - Comparison of the ultimate loads for various approaches, t_f=16 mm

t_f [mm]	s_s	P_{cr}^{FEA}	P_{cr}^{EC}	F_u^{FEA}	F_u^{EC}	F_u^{EC}/F_u^{FEA}	$F_u^{EC}{}_{corr}$	$F_u^{EC}{}_{corr}/F_u^{FEA}$	$F_u^{EC}{}_{corr}/F_u^{EC}$
bs x ts	[mm]	[kN]	[kN]	[kN]	[kN]	[-]	[kN]	[-]	[-]
16 52 x 4	0	334	310	202	160	0.79	167	0.82	1.04
	100	357	310	268	189	0.70	203	0.76	1.07
	200	408	310	357	214	0.60	245	0.69	1.15
16 58 x 8	0	364	310	213	160	0.75	174	0.82	1.08
	100	386	310	287	189	0.66	211	0.74	1.12
	200	438	310	402	214	0.53	254	0.63	1.19
16 50 x 12	0	381	310	220	160	0.73	178	0.81	1.11
	100	404	310	298	189	0.63	216	0.72	1.14
	200	457	310	421	214	0.51	260	0.62	1.21

Table 7 - Comparison of the ultimate loads for various approaches, t_f=24 mm

t_f [mm] bs x ts	s_s [mm]	P_{cr}^{FEA} [kN]	P_{cr}^{EC} [kN]	F_u^{FEA} [kN]	F_u^{EC} [kN]	F_u^{EC}/F_u^{FEA} [-]	$F_u^{EC}{}_{corr}$ [kN]	$F_u^{EC}{}_{corr}/F_u^{FEA}$ [-]	$F_u^{EC}{}_{corr}/F_u^{EC}$ [-]
24 52 x 4	0	360	310	265	186	0.70	201	0.76	1.08
	100	389	310	326	211	0.65	237	0.73	1.12
	200	455	310	428	224	0.52	271	0.63	1.21
24 58 x 8	0	389	310	279	186	0.67	208	0.75	1.12
	100	418	310	348	211	0.61	245	0.71	1.16
	200	486	310	474	224	0.47	280	0.59	1.25
24 50 x 12	0	406	310	289	186	0.64	213	0.74	1.14
	100	436	310	361	211	0.59	251	0.69	1.19
	200	506	310	513	224	0.44	286	0.56	1.28

Tables 5, 6, and 7 compare the elastic critical load and ultimate loads of steel plate I-girders as a function of patch load length and stiffener dimensions, for three different flange thicknesses which are numerically obtained and from Eurocode. The results refer to the girders of the characteristics given in Part 2 - Numerical simulations.

Value P_{cr}^{FEA} represents the elastic critical load of I-girders obtained numerically using finite element method-FEA. P_{cr}^{EC} refers to the elastic critical load of steel I-girder which corresponds to the procedure applied in Eurocode EN1993-5. The values of ultimate load : F_u^{EC} (ultimate load according to the procedure applied in Eurocode EN1993-5) and F_u^{FEA} (numerically obtained ultimate load), are compared. Based on the presented results, it can be concluded that Eurocode procedures are significantly conservative in terms of calculating the ultimate load. There is a need to improve these results.

The corrected values of the ultimate load marked as $F_u^{EC}{}_{corr}$ were obtained according to the procedure given in Eurocode EN1993-5, but with the values of the elastic critical load obtained numerically- P_{cr}^{FEA}. Improvements are more noticeable for girders with a larger flange thickness, for longer localized load length - s_s, and for larger stiffener dimensions. By introducing the numerically obtained elastic critical load into the Eurocode expressions, an improvement of up to 14, 21, 28% was achieved for flange thicknesses of 8, 16, 24 mm, respectively.

4. CONCLUSIONS

In previous studies, which were preliminary, the results related to non-stiffened and stiffened girders, were presented [2]. However, the stiffened girders were limited to a series of girders whose flange and stiffeners thicknesses were equal. In order to be able to observe the impact of stiffener independently of the flange, there was a need for new numerical parametric analysis. In this paper, the results for the buckling coefficient k_F, for three different stiffeners are processed. For three series of girders with 8, 16 and 24 mm flange thicknesses, the stiffeners with the same dimensions were adopted – 52x4, 58x8, 50x12 mm. Coefficients k_F are shown for isolated web plates and I-girders, which provides conclusions on the impact of flange on elastic critical load. The results showed that the influence of stiffener dimensions on the elastic critical load is significant. The influence of stiffener thickness t_s is more pronounced in relation to width b_s. The values of the buckling coefficients change as a function of the patch load length in all considered cases. There is a need to include the influences of the considered characteristics of the flange, stiffness and s_s length in the expressions for the coefficient k_F. Existing standards do not take into account the patch load length, and often give results that are markedly different from numerical ones. The aim of this research is to single out the characteristics of the girders that have the greatest impact on the elastic critical load. It is necessary to come up with new expressions for the calculation of the buckling coefficient through more detailed and comprehensive analyzes. It is shown that the influence of stiffener and flange cannot be neglected because both parameters are important.

REFERENCES

[1] Eurocode 3 (EC3): Design of steel structures. Part 1–5: General rules–Supplementary rules for planar plated structures without transverse loading. EN1993-1-5; 2006

[2] Bendić M. et al.: Elastic critical load of stiffened I-girders subjected to patch loading, 8th International conference Contemporary achievements in civil engineering, Subotica, Serbia, 2021, 153-161, 2021

[3] Abaqus Simulia. Dassault Systemes. 2016.

[4] Marković N.: Izbočavanje limenih nosača pod dejstvom lokalnog opteresenja, Doktorska disertacija (Ph.D. Thesis in Serbian), Univerzitet u Beogradu, Gradevinski fakultet u Beogradu, 2003.

[5] Jakovljević I., Kovačević S., Marković N.: Elastic critical load of plates and plate girders subjected to patch load, Building materials and structures, 2018, 55-67

[6] Bendić M. et al.: Elastic critical load of I-girders subjected to patch loading. In Proceedings of the Symposium of the Association of Structural Engineers of Serbia – ASES, Aranđelovac, Serbia, May 13-15, 2021.

[7] Ćeranić A., Kovačević S., Marković N. Influence of patch load length and flange stiffness on the ultimate strength of steel plate girders, The seventh International Conference Civil Engineering - Science & Practice, GNP 2020 Proceedings – Kolašin, Montenegro, 10-14 March 2020, 55-62.

[8] Ćeranić A. et al.: Influence of longitudinal stiffeners on behaviour and ultimate resistance of plate girders subjected to patch loading, Conference Civil Engineering - Science & Practice, GNP 2020 Proceedings – Kolašin, Montenegro, 2022.