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Numerical Investigation of Flange Buckling Behavior of Steel Plate Girders with Corrugated Webs

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Abstract

Steel plate girders with trapezoidal corrugated webs have been used widely over the last years around the world in many roadways and railway steel bridges as they can introduce several important advantages compared with plate girders bridges with flat web. The study in this paper presents a numerical investigation of flange buckling behavior using the FE software ABAQUS and studies the effect of slenderness ratio of the flange and corrugated web on the bending moment capacity and the flexural behavior of trapezoidal corrugated web steel plate girders built-up from high-strength steel (HSSs). Firstly, the linear buckling analysis has been carried out to obtain the local flange buckling coefficient using the general equation of stresses and the stresses obtained from the numerical results, then the ultimate bending moment has been obtained from the nonlinear buckling analyses. The numerical results showed that the flange slenderness ratio and web slenderness ratio play a major role in controlling the bending moment capacity of corrugated web plate girders. Finally, some recommendations have been listed to help structural engineers to design corrugated web bridge girders efficiently.

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Keywords: Finite Element Analysis; Flange Buckling Behavior; High-Strength Steel; Bending Moment Resistance.

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1. INTRODUCTION

Corrugated web plate girders have been used for long years as main girders of steel bridges in a lot of countries around the world. The design capacity of these girders depends on two main capacities; the shear strength of the corrugated web, and the flexural capacity which depends on the upper and lower flanges in the I-shaped built-up cross section. The flexural strength of corrugated web steel girders is provided by the flanges of the girder and there is no contribution from the web has been found. In the corrugated web girders, there is no interaction between shear and flexural behavior. The bending strength of corrugated web I-girders is mainly depending on the local buckling of the compression flange which in turn depends on the flange outstand-to-thickness ratio. Previous studies [1] - [22] presented the bending strength and the local buckling behavior of flanges of corrugated web girders. The previous studies have some shortenings in the investigation of flexural behavior of corrugated web girders as they almost did not introduce any considerations or guidelines to help the structural engineer in the design of these types of girders, so this is the main objective of the current study.

2. FINITE ELEMENT MODELING (VALIDATION OF THE NUMERICAL MODEL)

Finite element (FE) analyses have been performed by the well-known FE software ABAQUS [23] for the evaluation of the flexural behavior of trapezoidal corrugated web girders built up with high-strength steel. Two analysis steps have been carried out to simulate the FE models. The first step is the linear elastic analysis carried out to get the critical compressive stress acting on the flanges in order to estimate the local flange buckling coefficient. The second step is the in-elastic buckling analysis to obtain the ultimate bending moment capacity. In

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order to study the flexural behavior of corrugated web girders, a new FE model has been validated based on the experimental results of Jáger et al. [17]. The girders were loaded by two concentrated loads to achieve the pure bending moment loading case. The girders were simply supported and laterally restrained to prevent the LTB failure type. The four-node shell element with reduced integrations (S4R) has been used to simulate the FE models. A mesh size of 25 mm has been used in current FE model to obtain accurate results and save the analysis time. The first positive eigenmode has been used to take the effect of initial geometric imperfections into account. In the current study, HSS material (S460) has been used with yield strength of 460 MPa. The elastic modulus of steel (E) was considered as 210 GPa, while the Poisson's ratio (υ) was taken as 0.3. As commonly used in the literature, the elastic-perfect plastic stress strain curve is used to simulate the HSS material [24], [25]. The geometry, the profile of web corrugation of 1TP1-1 and 4TP2-2 girders and material properties of the two validated girders are shown in **Table 1.**

TABLE 1: GEOMETRICAL AND MATERIAL PROPERTIES [17]

Models	t_f (mm)	b_f (mm)	t_w (mm)	Profile of web corrugation [17]					f_{yf} (MPa)	f_{yw} (MPa)
				b (mm)	d (mm)	c (mm)	h_r (mm)	α (°)		
1TP1-1	7.92	250	2.88	97	69	97	69	45	450	410
4TP2-2	7.82	250	2.93	145	103	145.5	103	45	488	366

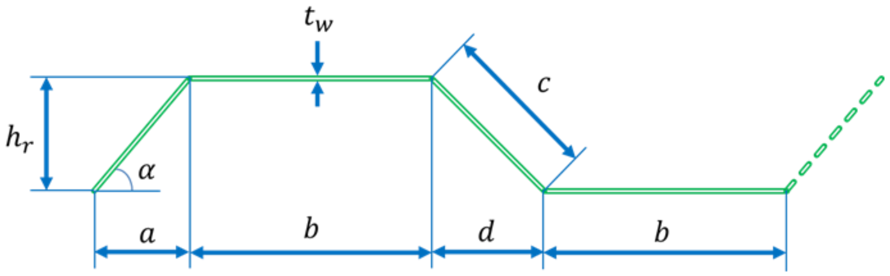

Fig.1. Notation of corrugated web profile.

The notation of web profile is shown in Figure 1. The complete details of the developed FEM and the cross-section details of the corrugated web girders are shown in Figure 2. A comparison between the load-deflection curves predicted by the FEM against the experimental results are shown in Figure 3.

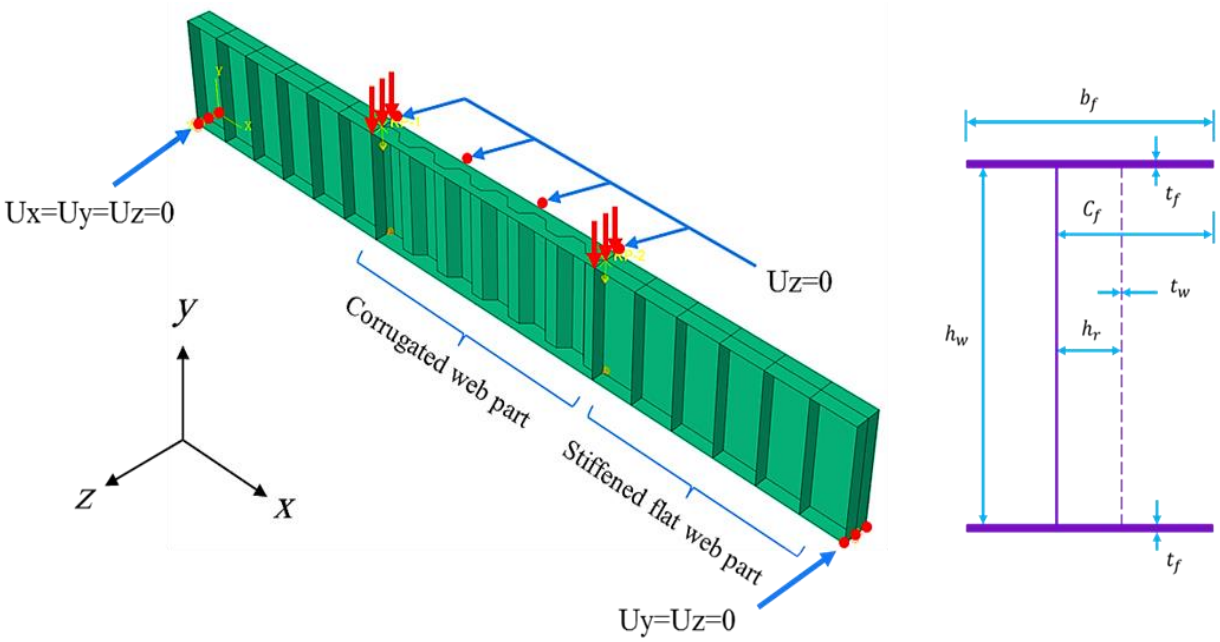

Fig. 2. 3D-FEM details for the simulated CWPGs and notation of cross section.

TABLE 2. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL FAILURE LOADS OF THE VALIDATED GIRDERS

No.	Specimen	2F (Exp.) kN	2F (Num.) kN	Difference %
1	1TP1-1	200.5	198.7	0.9
2	4TP2-2	156.3	166.2	6.3

Where F is the concentrated load.

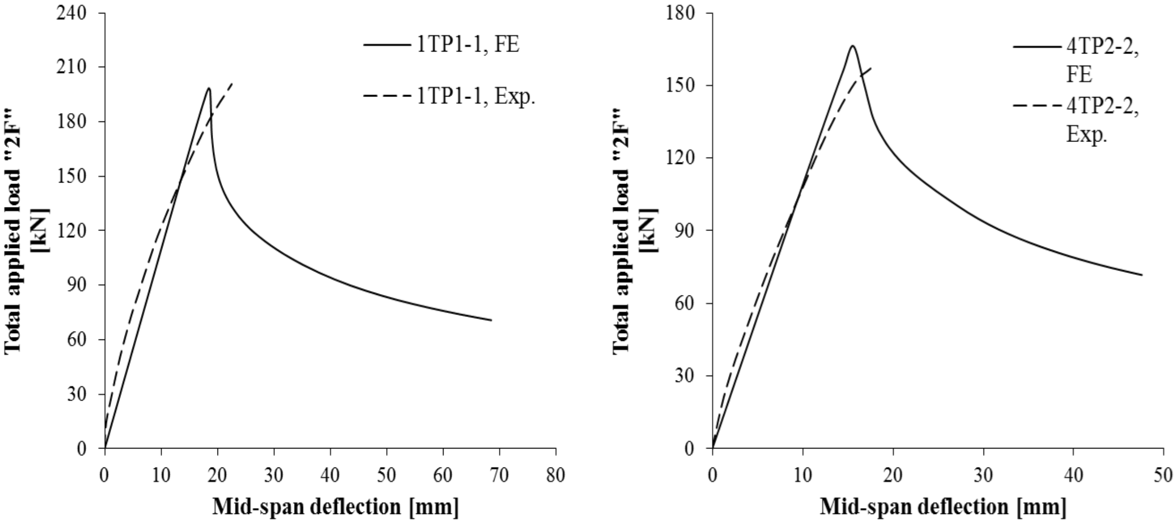

Fig. 3. Comparison between the load-deflection curves predicted by the FEM against the experimental results [17].

3. PROPOSED NUMERICAL STUDY

In this study, two important parameters have been investigated to indicate the effect of these parameters on the flexural behavior of trapezoidal corrugated web plate girders built up from HSSs. The first parameter is the flange slenderness ratio (C_f/t_f), the second is the slenderness ratio of the corrugated web (h_w/t_w). The FE models have been subjected to uniform bending moment using two applied concentrated loads as shown in Figure 2. The ranges of the analyzed parameters in the investigated numerical models have been presented as follows:

- C_f/t_f ranges from 10.5 to 17.125
- t_f/t_w ranges from 1 to 8
- h_w/t_w ranges from 75 to 600
- b, c ranges from 50mm to 350mm
- t_w ranges from 2mm to 16mm

where $b_f = 300$ mm, $t_f = 16$ mm, $h_w = 1200$ mm, and $\alpha = 45°$.

4. RESULTS AND DISCUSSION

The corrugated web steel plate girders have been failed by local flange buckling failure type. Table 3 shows the FE models analyzed in the current parametric study and the ultimate bending moments of the models. The numerical local buckling coefficient of the flange ($k_{\sigma,\mathrm{num}}$) has been calculated using the equation of critical stress obtained from the results of the numerical models (see Equation (1)).

$$k_{\sigma,num} = \frac{\sigma_{cr,FEM}\,12(1-\nu^2)}{\pi^2\,E}\left(\frac{C_f}{t_f}\right)^2 \tag{1}$$

where $\sigma_{cr,FEM.}$ is the critical compressive stress of the flange.

The effect of the flange slenderness ratio on the bending moment resistance of corrugated web girders is presented in Figure 4. Increasing the flange slenderness ratio more than 14ε (class 4 limit of EC3 [26] for classifying the flange of built up I-section) leads to decrease in the bending moment resistance, Where $\varepsilon = \sqrt{236/f_y}$; fy is the flange's material yield stress in MPa.

The decrease in the bending moment resistance depends on the flange to web thickness ratio. At lower ratios of flange to web thickness ratio ($t_f/t_w < 2$), the bending moment resistance is not significantly affected by the flange slenderness ratio as the connection between the corrugated web and the compression flange was considered to be fixed. At higher ratios of flange to web thickness ratio ($t_f/t_w \geq 2$), the flange slenderness ratio has a significant effect on the bending moment resistance as the fixation between the corrugated web and the flange has been decreased gradually by decreasing the thickness of the corrugated web.

Table 3. Full detailed dimensions of the current FE models

Model	h_w	t_w	b_f	t_f	b	c	$\alpha(°)$	d	h_r	L	$k_{\sigma,\mathrm{num}}$	M_{ult} (kN.m)
G1	1200	16	300	16	50	50	45	35	35	3060	1.432	*3101.61*
G2	1200	12	300	16	50	50	45	35	35	3060	1.2611	*2825.55*
G3	1200	8	300	16	50	50	45	35	35	3060	1.0878	*2675.9*
G4	1200	6	300	16	50	50	45	35	35	3060	0.9962	*2638.28*
G5	1200	5	300	16	50	50	45	35	35	3060	0.9486	*2623.57*
G6	1200	4	300	16	50	50	45	35	35	3060	0.8995	*2613.65*
G7	1200	3	300	16	50	50	45	35	35	3060	0.8457	*2609.26*
G8	1200	2	300	16	50	50	45	35	35	3060	0.7826	*2596.557*
G9	1200	16	300	16	150	150	45	106	106	3072	1.6171	*2662.34*
G10	1200	12	300	16	150	150	45	106	106	3072	1.3942	*2589.2*
G11	1200	8	300	16	150	150	45	106	106	3072	1.1247	*2464.42*
G12	1200	6	300	16	150	150	45	106	106	3072	0.9941	*2385.2*
G13	1200	5	300	16	150	150	45	106	106	3072	0.935	*2293.98*
G14	1200	4	300	16	150	150	45	106	106	3072	0.8805	*2267.28*
G15	1200	3	300	16	150	150	45	106	106	3072	0.8291	*2219.86*
G16	1200	2	300	16	150	150	45	106	106	3072	0.7755	*2203.47*
G17	1200	16	300	16	250	250	45	177	177	2989	1.4777	*2672.4*
G18	1200	12	300	16	250	250	45	177	177	2989	1.2057	*2538.21*
G19	1200	8	300	16	250	250	45	177	177	2989	0.8808	*2310.33*
G20	1200	6	300	16	250	250	45	177	177	2989	0.7405	*2119.85*
G21	1200	5	300	16	250	250	45	177	177	2989	0.6825	*1968.85*
G22	1200	4	300	16	250	250	45	177	177	2989	0.6328	*1998.26*
G23	1200	3	300	16	250	250	45	177	177	2989	0.5896	*1945.04*
G24	1200	2	300	16	250	250	45	177	177	2989	0.5473	*1897.59*
G25	1200	16	300	16	350	350	45	248	248	2990	1.4493	*2668.98*
G26	1200	12	300	16	350	350	45	248	248	2990	1.1483	*2526.53*
G27	1200	8	300	16	350	350	45	248	248	2990	0.7688	*2142.65*
G28	1200	6	300	16	350	350	45	248	248	2990	0.6156	*1934.4*
G29	1200	5	300	16	350	350	45	248	248	2990	0.5564	*1868.09*
G30	1200	4	300	16	350	350	45	248	248	2990	0.509	*1805.48*
G31	1200	3	300	16	350	350	45	248	248	2990	0.4715	*1747.31*
G32	1200	2	300	16	350	350	45	248	248	2990	0.4387	*1691.26*
G33	1200	16	300	16	85	85	45	60	60	3045	1.5732	*2799.26*
G34	1200	12	300	16	85	85	45	60	60	3045	1.4311	*2681.78*
G35	1200	8	300	16	85	85	45	60	60	3045	1.2799	*2606.06*
G36	1200	6	300	16	85	85	45	60	60	3045	1.1962	*2583.24*
G37	1200	5	300	16	85	85	45	60	60	3045	1.1503	*2559.09*
G38	1200	4	300	16	85	85	45	60	60	3045	1.0994	*2557.59*
G39	1200	3	300	16	85	85	45	60	60	3045	1.0384	*2543.42*
G40	1200	2	300	16	85	85	45	60	60	3045	0.958	*2523.49*

Note: All dimensions are in mm.

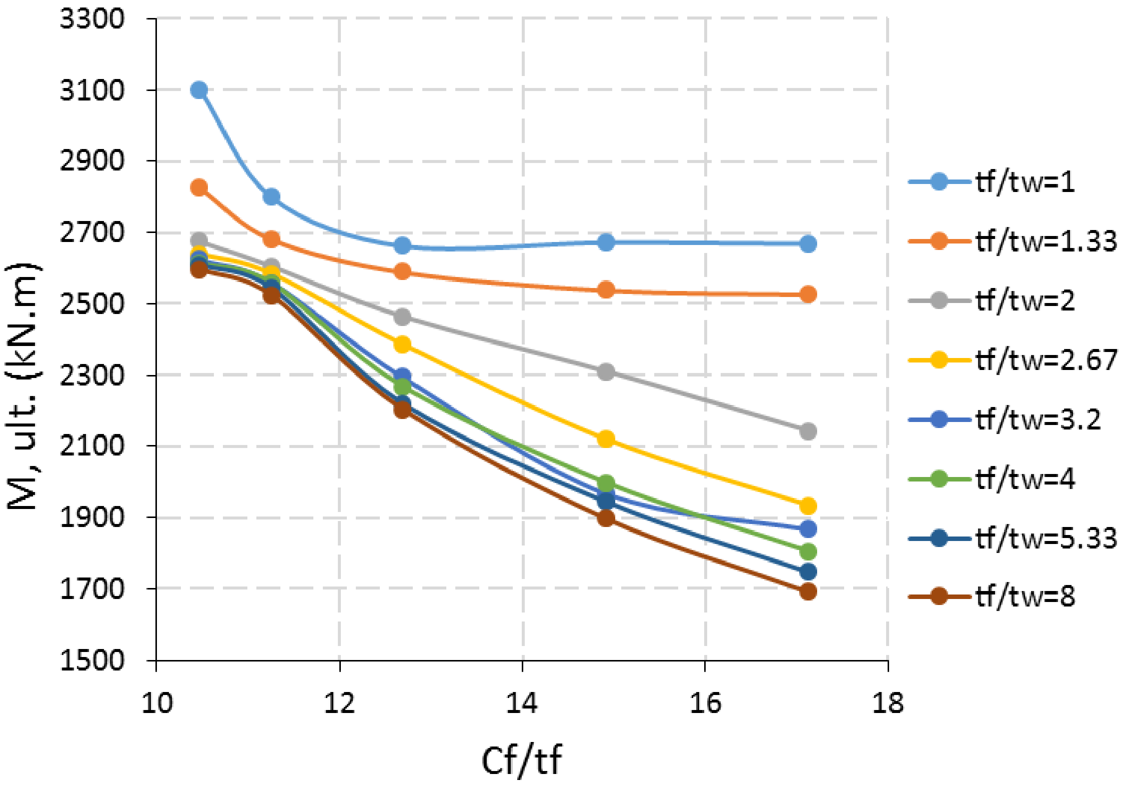

Fig. 4. Effect of flange slenderness ratio on the ultimate bending moment capacity.

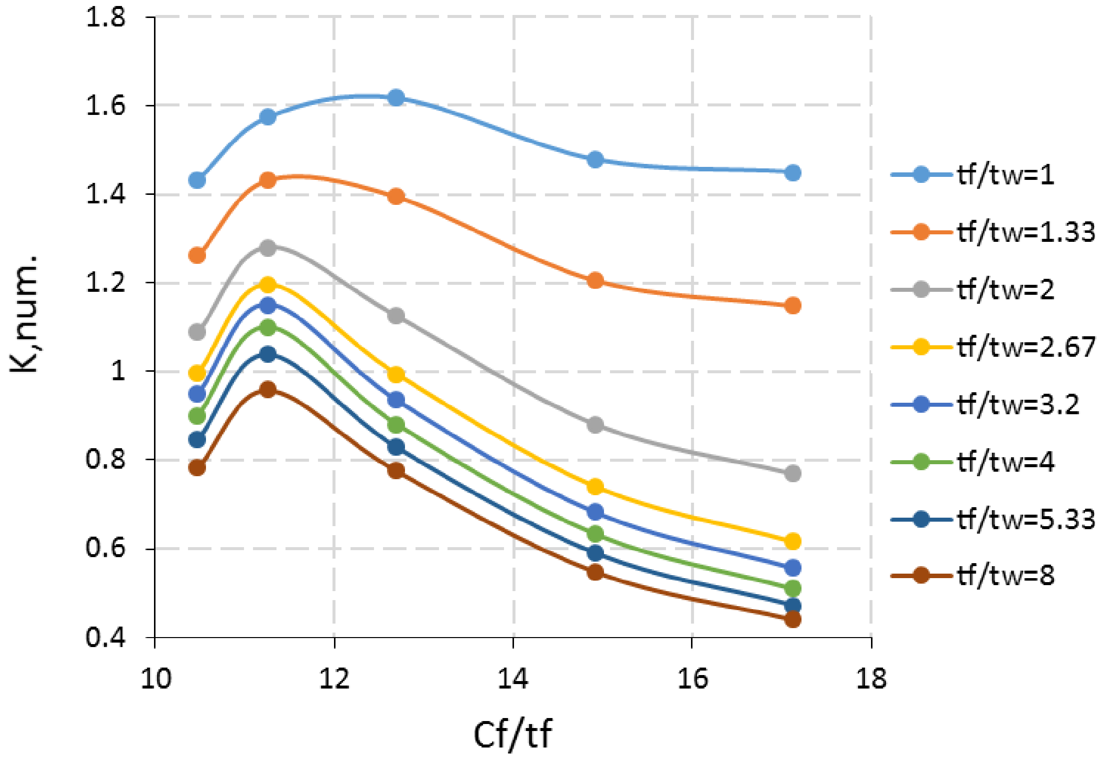

Fig. 5. Effect of flange slenderness ratio on the local buckling coefficient.

The local flange buckling coefficient has been influenced by the flange slenderness ratio as shown in Figure 5. Increasing the slenderness ratio of the flange increases the flange buckling coefficient until slenderness ratio equal 11. At higher slenderness ratios more than 11, the buckling coefficient decreases gradually.

Figure 6 presents the effect of the slenderness ratio of the trapezoidal corrugated web on the buckling coefficient of the compression flange. The increase in web slenderness ratio decreases the buckling coefficient as the function of the corrugated web in corrugated web plate girders is the supporting of the compression flange from failing by local flange buckling. The decrease in the coefficient of buckling continued until web slenderness ratio equals to 200. A marginal effect of web slenderness ratio has been noticed at web slenderness ratios higher than 200.

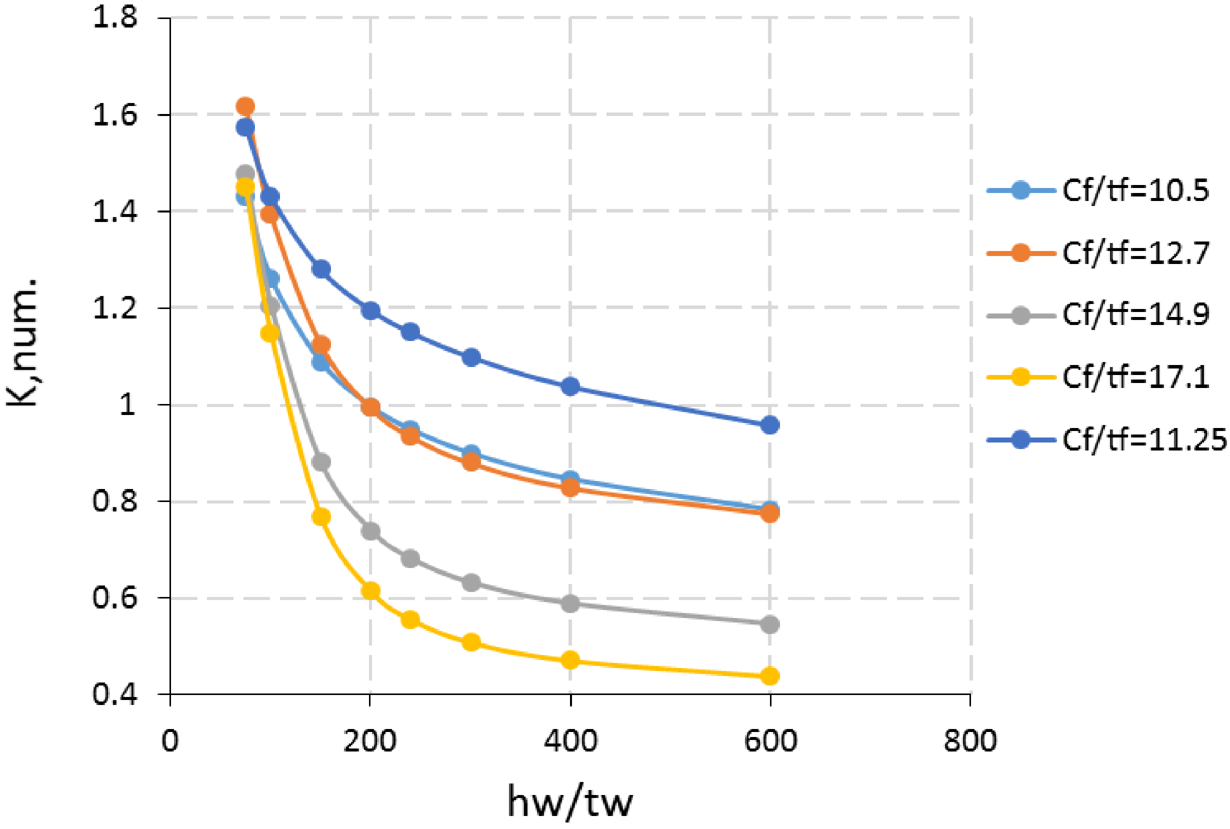

Fig. 6. Effect of corrugated web slenderness ratio on the local buckling coefficient.

5. CONCLUSIONS

To shed the light on the flexural behavior of the corrugated web plate girders built up from HSSs, the current study presented a new developed FE model to investigate the flexural behavior of corrugated web girders. The following conclusions are drawn:

1. The numerical results showed that the flange slenderness ratio and web slenderness ratio play a major role in controlling the flexural behavior of corrugated web plate girders.
2. In order to get an effective design for the corrugated web girders failing by local flange buckling, the flange slenderness ratio should follow the flange classifying equation of the EC3:
3. $\frac{c_f}{t_f} \leq 14.\sqrt{\frac{235}{f_y}}$ (Class 4 classifying equation).
4. The higher buckling coefficient values have been obtained at web slenderness ratios lower than 200. At web slenderness ratio higher than 200, the local buckling coefficient is not much affected by the web slenderness ratio.
5. At flange to web thickness ratio $(t_f/t_w) \geq 2$, the flange slenderness ratio has a significant effect on the ultimate bending moment resistance, while at flange to web thickness ratio $(t_f/t_w) < 2$, the flange slenderness ratio has a marginal effect on the ultimate bending moment.

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