ДГКС ASES | E-7
Kongres 2026
Congress 2026

doi: 10.67563/ASESCONF2026051S

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TORSION AND WARPING CONSTANT FOR STEEL I BEAMS WITH BATTEN PLATES

Summary: A reliable calculation method for torsion constant (I_T) and warping constant (I_w) of I section with batten plates is presented. As welding of the batten plates transforms the cross section from an open to a two-cell closed one, the associated torsion theory becomes rather complex. St. Venant torsion theory of thin-walled closed sections is extended to multi-cell sections and an expression for I_T is derived. In a similar manner, Vlasov non-uniform torsion theory was used for deriving an expression for I_w. Special consideration was paid to the behavior and shear flow of the web and the influence of the fillet between the flange and the web on the torsional properties. The validity of the made assumptions and the derived expressions was verified using the finite element method. Set of tabulated values of I_T and I_w for all IPE sections with different batten plates thicknesses is provided.

Keywords: torsion constant, warping constant, I section with batten plates

TORZIONI MOMENT INERCIJE I KONSTANTA KRIVLJENJA ZA ČELIČNE I GREDE SA VEZNIM LIMOVIMA

Rezime: Predstavljen je pouzdan metod proračuna torzionog momenta inercije (I_T) i konstante krivljenja (I_w) za I preseke se veznim limovima. Kako se zavarivanjem veznih limova poprečni presek transformiše iz otvorenog u zatvoreni presek sa dve ćelije, prateća teorija torzije postaje prilično složena. Sen-Venanova teorija torzije tankozidnih zatvorenih preseka proširena je na višećelijske preseke i izveden je izraz za I_T. Na sličan način, primenjena je teorija ograničene torzije prema Vlasovu za dobijanje izraza za I_w. Posebna pažnja je posvećenja toku smicinja i uticaju unutrašnjeg rebra kao i uticaju zaobljenja između nožica i rebra na torziona svojstva. Validnost usvojenih pretpostavki i izvedenih izraza verifikovana je primenom metode konačnih elemenata. Priložen je i skup tabelarno prikazanih vrednosti za I_T i I_w za sve IPE profile sa različitim debljinama veznih limova

Ključne reči: torzioni moment inercije, konstanta krivljenja, I presjek sa veznim limovima

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1. INTRODUCTION

One recent method for increasing lateral torsional buckling (LTB) resistance of steel I beams is the use of batten plates. Batten plates of appropriate width and thickness are welded to the flanges of I beams thus forming a set of closed cross section beam segments.

Although, recent research [1], [2], [3] shows promising results in the use of batten plates as a way of mitigating the negative effects of LTB there is still a long way to go before they can be reliably and easily used in practice.

From an analytical point of view the stated problem is rather complex and coupled with difficulties. Batten plates not only reinforce the I beam and increase its stiffness but also fundamentally change its behavior. In closed cross section segments and their vicinity warping torsion theory for open cross sections can no longer be used thus warping torsion theory for closed cross section must be applied. Furthermore, the presence of batten plates changes the typology of a cross section, from an open one to a closed two-cell one.

Typology change of the cross section further complicates the problem, especially in the context of torsion theory. Basic section properties like St. Venant torsion constant I_T and warping constant I_w become rather difficult to obtain.

The aim of this paper is to try to overcome the outlined problem and to derive an analytical solution for I_T and I_w for beams with batten plates.

First the problem of St. Venant torsion of multi-cell cross sections will be explored. Governing differential equations will be presented and an analytical solution for I_T will be derived. In the second part of the paper similar approach will be used for determining the warping constant I_w. The validity of the made assumptions and derived expressions is verified using the finite element method (using both ANSYS and IDEA StatiCA software). Set of tabulated values of I_T and I_w for all IPE sections with different batten plates thicknesses are provided.

Special consideration is paid to the behavior and shear flow of the web and on the influence of the fillet between the flange and the web on torsion properties.

2. ST. VENANT TORSION THEORY FOR A TWO-CELL THIN-WALLED CLOSED CROSS SECTION

Using the equilibrium condition along the *x* axis in a two-cell closed cross section, the following equation can be written:

$$T_1 - T_2 - T_{12} = 0 \rightarrow T_{12} = T_1 - T_2 \tag{1}$$

where,
T_1 – is the shear flow in cell 1,
T_2 – is the shear flow in cell 2.

Equation (1) states that the shear flow in the common wall between the cells is equal to the difference between adjoining cells shear flow. This statement enables the decomposition of the two-cell cross section into individual ones as shown in Figure 1.

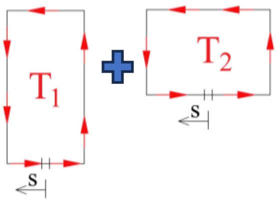

Figure 1: Decomposition of the two-cell closed cross section

Torque in each cell can be calculated using the first Bredt formula:

$M_{T1} = 2T_1A_{m1}$ and $M_{T2} = 2T_2A_{m2}$ (2)

where

$A_{m,i}$ – is the area of the cross section enclosed by the skeleton line.

The only unknowns are shear flows T_1 and T_2. If they are known, torsion constant I_T can be calculated.

Shear flows T_1 and T_2 can be determined using compatibility conditions. The twists of cells 1 and 2 must be equal to the twist of the entire cross section.

Introducing ψ_1 and ψ_2 as torsion functions ($\psi_i = \frac{T_i}{G\frac{d\varphi_i}{dx}}$), a linear two by two system of equations (3) is obtained, from which torsion functions ψ_1 and ψ_2 can be calculated

$$\left.\begin{aligned} \psi_1 \oint_1 \frac{1}{t(s)}\, ds - \psi_2 \oint_1^2 \frac{1}{t(s)}\, ds &= 2A_{m,1} \\ \psi_2 \oint_2 \frac{1}{t(s)}\, ds - \psi_1 \oint_2^1 \frac{1}{t(s)}\, ds &= 2A_{m,2} \end{aligned}\right\} \tag{3}$$

Knowing the values for ψ_1 and ψ_2 the torsion constant of a two-cell closed cross section can be calculated using the Equation (4).

$$I_T = \frac{\sum_{i=1}^{n} T_i A_{m,i}}{G\frac{d\varphi}{dx}} = 2\psi_1 A_{m,1} + 2\psi_2 A_{m,2} \tag{4}$$

3. WARPING TORSION THEORY FOR A TWO-CELL THIN-WALLED CLOSED CROSS SECTION

Imagine that in an arbitrary point of a closed cross section a longitudinal cut of the skeleton line is made. Because of that cut a relative axial displacement Δu_1 of the points on the opposite side of the cut appears.

This relative axial displacement i.e warping ($u(s)$) can be determined as the sum of warping of the cross section treated like an open one ($u_o(s)$) and the warping due to shear flow i.e. shear strain γ_{xs} ($u_s(s)$), Eq (5).

$$u(s) = u_o(s) + u_s(s) \tag{5}$$

Axial displacement of the points along the skeleton line of an open cross section is defined by the Equation (6).

$$u_o(s) = -\frac{d\varphi}{dx} \int_0^s r_t ds \tag{6}$$

Relative axial displacement of the points on the opposite side of the cut is:

$$\Delta u_{10} = -\frac{d\varphi}{dx} \oint_s r_t\, ds = -\frac{d\varphi}{dx} A_m \tag{7}$$

Axial displacement of the points along the skeleton line due to Bredt shear is defined by the Equation (8).

$$u_s(s) = \int_0^s \frac{T_s}{G\, t(s)} ds \tag{8}$$

The compatibility condition stating that no relative axial displacement of the points on the opposite side of the cut occurs (Δu_1 = 0) can be used to determine the unknown shear flow.

$$\Delta u_{11}\, T_s + \Delta u_{10} = 0 \tag{9}$$

By solving the Equation (9), the unknown shear flow is determined, Eq (10).

$$T_s = \frac{d\varphi}{dx}\frac{2A_m G}{\oint_s \frac{ds}{t(s)}} = \frac{d\varphi}{dx}\,\psi\, G \tag{10}$$

with

$$\psi = \frac{2A_m}{\oint_s \frac{ds}{t(s)}}$$

Axial displacement of the points along the skeleton line of the thin-walled closed cross section can now be determined, Eq (11).

$$u(s) = u_o(s) + u_s(s) \rightarrow u(s) = -\frac{d\varphi}{dx}\left(\int_0^s r_t ds - \psi \int_0^s \frac{ds}{t(s)}\right) \tag{11}$$

The term in the brackets actually represents the unit warping i.e. sectorial coordinate of a thin-walled closed cross section, Eq (12).

$$\omega_1 = \omega_0 - \omega_s = \int_0^s r_t ds - \psi \int_0^s \frac{ds}{t(s)} \tag{12}$$

Above-described method could also be used for determining the sectorial coordinate of an *n*-cell cross section.

Thin-walled closed cross section with *n* cells can be regarded as an *n* times statically indeterminate system where the primary unknowns are the shear flows T_{si}. By using compatibility conditions ($\Delta u_i = 0$), a linear system of equations (13) is obtained.

$$\left\{\begin{Bmatrix} \oint_1^1 \frac{1}{t(s)}\, ds & -\oint_1^2 \frac{1}{t(s)}\, ds & \dots & -\oint_1^n \frac{1}{t(s)}\, ds \\ -\oint_2^1 \frac{1}{t(s)}\, ds & \oint_2^1 \frac{1}{t(s)}\, ds & \dots & -\oint_2^n \frac{1}{t(s)}\, ds \\ \vdots & \dots & \ddots & \vdots \\ -\oint_n^1 \frac{1}{t(s)}\, ds & -\oint_n^2 \frac{1}{t(s)}\, ds & \dots & \oint_n^1 \frac{1}{t(s)}\, ds \end{Bmatrix} \begin{Bmatrix} \psi_1 \\ \psi_2 \\ \vdots \\ \psi_n \end{Bmatrix} = \begin{Bmatrix} 2A_{m,1} \\ 2A_{m,2} \\ \vdots \\ 2A_{m,n} \end{Bmatrix}\right\} \tag{13}$$

The solution of this system yields the unknown functions ψ_i for each cell. In the same manner as for the one cell cross section, the sectorial coordinate can be calculated using Equation (14).

$$\omega_1 = \omega_0 - \omega_s = \int_0^s r_t ds - \sum_{i=1}^n \psi_i \int_0^s \frac{ds}{t(s)} \tag{14}$$

In the shared cell walls, for example between cells j and j+1, both corresponding torsion functions should be used.

On the basis of the calculated sectorial coordinate using normalization equations, the principal sectorial coordinate ($\overline{\omega}$) can be determined. Once the principal sectorial coordinate $\overline{\omega}$ is determined, the warping constant of the cross section can be calculated using expression (15).

$$I_w = \int_A \overline{\omega}^2 dA \tag{15}$$

4. TORSIONAL SECTION PROPERTIES OF I SECTION WITH BATTEN PLATES

Using the laid-out procedures in the previous chapters of the paper, a closed form expression for I_T and I_w for I sections with batten plates will now be derived.

4.1. TORSION CONSTANT I_T

The analysed example is shown in Figure 2.

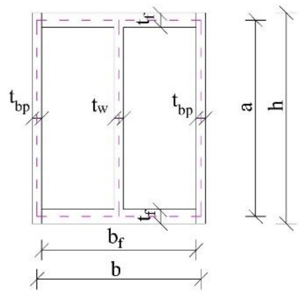

Figure 2: I section with batten plates

Flange thickness is t_f, web thickness is t_w while the batten plates thickness is denoted as t_{bp}. The width of the flanges is b_f and the height of the cross section is h.

Dimensions a and b are defined as follows:

$$b = b_f + t_{bp}$$
$$a = h - t_f \tag{16}$$
$$2A_{m,1} = 2A_{m,2} = ab$$

In order to derive an expression for I_T, at first the system of equations (3) should be solved for the unknown torsion functions ψ_1 and ψ_2.

For a more general solution of this system of equations, the so-called flexibility coefficients δ_{ij} [4] will be introduced:

$$\delta_{11} = \oint_1 \frac{1}{t(s)}\, ds = \frac{b}{t_f} + \frac{a}{t_{bp}} + \frac{a}{t_w}, \qquad \delta_{22} = \oint_2 \frac{1}{t(s)}\, ds = \frac{b}{t_f} + \frac{a}{t_{bp}} + \frac{a}{t_w}$$

$$\delta_{12} = \delta_{21} = \oint_1^2 \frac{1}{t(s)}\, ds = \frac{a}{t_w} \qquad \text{and} \qquad \delta_{10} = \delta_{20} = 2A_{m,1}$$

If the system of equations (3) is solved for the analysed example, it will result by equal torsion functions ψ_1 and ψ_2:

$$\psi_1 = \psi_2 = \frac{\delta_{10}}{\delta_{11} - \delta_{12}} \tag{17}$$

Substituting Equation (17) into (4), the expression for torsion constant I_T can be determined:

$$I_T = 2\psi_1 A_{m,1} + 2\psi_2 A_{m,2} = 4\psi_1 A_{m,1} = 2\frac{{\delta_{10}}^2}{\delta_{11} - \delta_{12}} \tag{18}$$

If the previously calculated values for flexibility coefficients are replaced in Equation (18), the expression for the torsion constant of a I section with batten plates is finally obtained:

$$I_T = \frac{2(ab)^2}{\frac{b}{t_f} + \frac{a}{t_{bp}}} \tag{19}$$

By inspecting the derived expression for I_T, several important observations can be made. Firstly, due to the symmetry of the cells the torsional functions for cell 1 and 2 are equal. Therefore, the net shear flow in the web is zero. The section behaves like a one-cell closed section with dimensions a and b. Web doesn't contribute at all to the torsional stiffness.

Strictly speaking the web will contribute to the torsion constant by a small amount due to the fact that shear stresses are not constant across the thickness of the cell walls

The modified torsion constant that takes into account the variation of shear stresses across the thickness of the walls, according to [5] is given by Equation (20).

$$I_T^* = I_{T,Bredt} + I_{T,open} = \frac{2(ab)^2}{\frac{b}{t_f} + \frac{a}{t_{bp}}} + \frac{1}{3}\oint_s t(s)^3 ds \tag{20}$$

4.2. WARPING CONSTANT I_W

An expression for the warping constant for I section with batten plates is somewhat more difficult to derive. Fortunately, some simplifications can be made. Firstly, as considered section is doubly symmetric, the shear centre (S_c) coincides with the centroid. Furthermore, as the web centreline is in the axis of symmetry, no warping of the web occurs. This enables the simplification of the analysed problem to the derivation of the warping constant for a one-cell closed thin-walled section.

Lastly, no normalization of the sectorial coordinate is necessary as the location of the shear centre is known and that the warping in point *0* must be zero.

The principal sectorial coordinate can be calculated using expression (21).

$$\overline{\omega_1} = \overline{\omega_0} - \overline{\omega_s} = \int_0^s r_t ds - \psi \int_0^s \frac{ds}{t(s)} \tag{21}$$

The warping of the cross section treated as an open one ($\overline{\omega_0}$) and the warping of the cross section due to continuous shear flow $\overline{\omega_s}$ for the analysed example is shown in Figure 3.

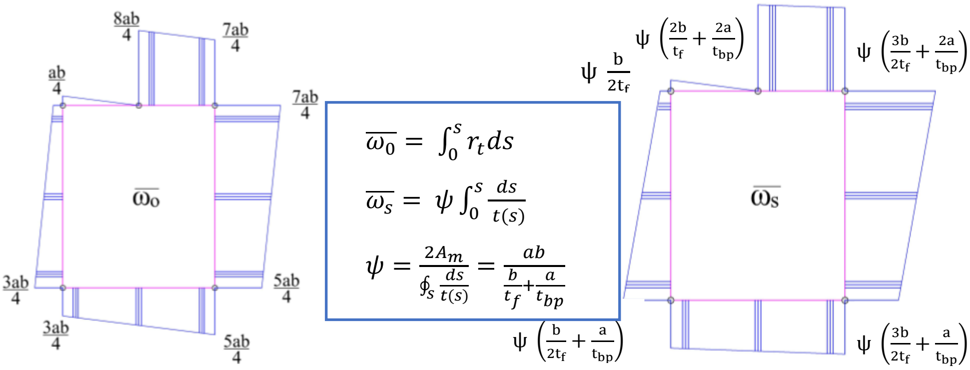

Figure 3: Sectorial coordinate $\overline{\omega_0}$ and $\overline{\omega_s}$

Now, that the $\overline{\omega_0}$ and $\overline{\omega_s}$ have been determined, the principal sectorial coordinate $\overline{\omega_1}$ can be calculated using equation (21). Obtained results are shown in Figure 4. Parameter β is defined as follows.

$$\beta = \frac{\frac{t_f}{t_{bp}} - \frac{b}{a}}{\frac{t_f}{t_{bp}} + \frac{b}{a}} \tag{22}$$

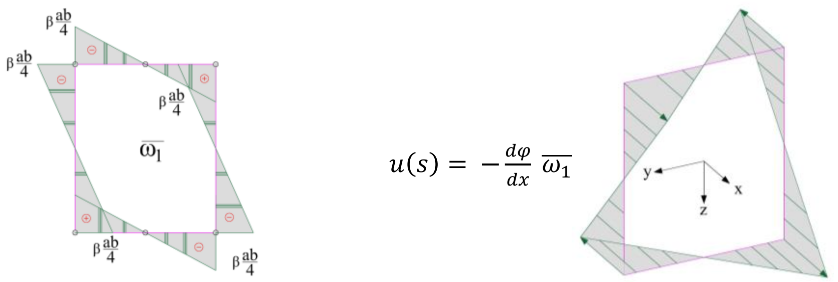

Figure 4: a) Principal sectorial coordinate $\overline{\omega_1}$, b) warping of the contour

Once the principal sectorial coordinate is calculated, the warping constant I_w is easily determined. Using Equation (15) and Vereshchagin's rule for a triangle times triangle diagram, the expression for the warping constant for an I section with batten plates is finally derived.

$$I_w = \frac{1}{24} (ab\beta)^2 (bt_f + at_{bp}) \tag{23}$$

Warping is not constant across the thickness of the section walls. Besides contour warping (warping of the points along the skeleton line, Eq (23)), there is also warping of the points across the thickness of the section walls, so called thickness warping.

In the calculation of the warping constant I_w of the section, according to [6], thickness warping could be included by adding it to the contour warping, Eq (24).

$$I_w^{*} = I_{w,c} + I_{w,t} \approx \frac{1}{24}(ab\beta)^2\left(bt_f + at_{bp}\right) + \sum_{i=1}^{n} \frac{t_i^3 s_i^3}{144} \tag{24}$$

Equation (24) is of an approximate nature because it doesn't resolve the problem of the discontinuity of thickness warping at wall junctions.

5. VERIFICATION OF THE PROPOSED EXPRESSIONS

Proposed expressions for I_T and I_w (equations (20) and (24)) are derived using several simplifications and assumptions. The fillet between the web and the flange of an I section is neglected while the non-uniformity of shear stress across the thickness of the walls and thickness warping are taken into account in a simplified manner.

In this section of the paper these assumptions and consequently their influence on the torsion properties I_T and I_w are investigated using finite element method. According to [7] only by using the finite element method accurate values for I_T and I_w for rolled I sections can be obtained. With this in mind, a 2D model of an I section with batten plates is created in ANSYS and IDEA StatiCA software. In ANSYS software, in order to assess the influence of the fillet and for easier comparation to the proposed expressions, two separate models are created, one with the fillet and one without.

Cross section is discretized by a maximum number of elements allowed by the software thus capturing the effects of thickness warping and non-uniform shear stresses. Typical 2D model and the results of the analysis are shown in Figure 5.

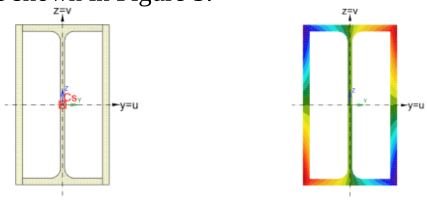

Figure 5: Typical 2D model and the distribution of the sectorial coordinate

Sectorial coordinate is integrated over the entire area of the section (not only along the skeleton line) thus capturing thickness warping and contribution of fillets more precisely.

Second objective of this analysis is to quantify the batten plates influence on torsion properties I_T and I_w. For the test sample all IPE sections are considered. Investigated batten plates thickness are 8 mm and 10 mm.table

Torsional properties I_T and I_w calculated using the proposed expressions (equations (20) and (24), for all analysed cases are shown in Table 1.

The results in Table 1 clearly indicate the positive effect of batten plates on torsional properties I_T and I_w of IPE sections. Torsion constant I_T is increased in the range from 200 times up to nearly 500 times. The effect of batten plates on the warping constant I_w is also pronounced but significantly less than for I_T. As the section height is increased the effectiveness of batten plates diminishes. For very large section heights (IPE 550 and IPE 600) the batten plates appear to have an adverse effect. Although these findings may seem counterintuitive i.e. that the open cross section, for a certain height, warps less than the equivalent closed one, this is indeed the case for a certain a/b ratio.

For a > 3b, $I_{w,closed}$ is larger than $I_{w,open}$. This indicates that very narrow closed cross sections have a larger tendency to warp compared to the equivalent open sections.

Table 1: Torsional properties I_T and I_w for IPE sections with batten plates, determined by Eqs (20) and (24)

Section	Without batten plates		I_T with batten plates (cm^4)		I_w with batten plates (cm^6)		$\frac{I_{T,bp,10}}{I_T}$	$\frac{I_{w,bp,10}}{I_w}$
	I_T (cm^4)	I_w (cm^6)	t_{bp} 8 mm	t_{bp} 10 mm	t_{bp} 8 mm	t_{bp} 10 mm		
IPE 80	0.6727	115.1	168.54	197.94	5.09	31.00	294.2	0.27
IPE 100	1.153	342.1	313.27	367.98	8.70	31.21	319.1	0.09
IPE 120	1.689	872	528.14	621.63	57.49	23.94	368.0	0.03
IPE 140	2.401	1951	825.99	974.43	255.21	61.80	405.8	0.03
IPE 160	3.530	3889	1215.96	1436.7	758.69	245.77	407.02	0.06
IPE 180	4.723	7322	1722.00	2039.4	1948.91	831.23	431.8	0.11
IPE 200	6.846	12746	2346.72	2783.8	4171.61	2089.90	406.6	0.16
IPE 220	8.982	22310	3173.51	3772.1	8614.02	4912.19	419.9	0.22
IPE 240	12.74	36680	4168.29	4961.5	15935.0	9862.16	389.4	0.27
IPE 270	15.71	69469	5958.62	7091.0	32251.8	20973.4	451.3	0.30
IPE 300	19.75	124260	8231.20	9800.7	61837.7	42169.2	496.2	0.34
IPE 330	27.59	196090	10554.4	12616	115055	84752.4	457.2	0.43
IPE 360	37.08	309370	13351.3	16036	210854	166597	432.4	0.54
IPE 400	50.41	482890	17018.4	20521	378962	315203	407.0	0.65
IPE 450	66.05	780970	21931.1	26578	714463	626648	402.4	0.80
IPE 500	88.62	1235400	27668.2	33688	1272000	1163216	380.1	0.94
IPE 550	121.7	1861500	34152.4	41725	2087229	1963310	342.8	1.05
IPE 600	164.6	2814700	41629.3	51048	3374592	3257269	310.1	1.16

Torsional properties I_T and I_w determined using IDEA StatiCA and ANSYS software are shown in Table 2. Only batten plates with the thickness of 10 mm are investigated.

By inspecting the results presented in Table 2, several observations can be made. First of all, the values for I_T obtained using Equation (20) are in good agreement with the values obtained using FEM software. Small differences ranging from 2.4% to 6.8% are due to the influence of the fillet between the flange and the web.

The situation with the warping constant I_w is very different. The discrepancies between the results are rather large, especially for smaller sections. There are two main reasons for such results. The first reason is the parameter β and thickness warping. As β is getting smaller, the thickness warping becomes more pronounced. For very small values of β, thickness warping practically dominates (see.g. section IPE 120). Although thickness warping, in some manner, is included in Equation (24) it can only be considered as an approximation due to unresolved discontinuities at the junctions. Depending on the t_f/t_{bp} ratio, Equation (24) tends to either overpredict or underpredict the influence of thickness warping.The second important factor that effects the value for I_w significantly is the fillet between the flange and the web. The effect of fillet on warping constant is dual in nature. For small section profiles the filet has a positive effect on the warping constant. As the height of the cross section is increased, this positive effect diminishes and becomes adverse.

Table 2: Torsional properties I_T and I_w for IPE sections with batten plates, determined using IDEA StatiCa and ANSYS software

I_T and I_w determined using eq 20 and eq. 24				**I_T and I_w determined using IDEA StatiCA**		**I_T and I_w determined using ANSYS**		$\frac{I_{T,bp,10}}{I_{T,ANSYS}}$	$\frac{I_{w,bp,10}}{I_{w,ANSYS}}$
$I_{T,bp,10}$ (cm^4)	β_{10}	$I_{w,t,bp,10}$ (cm^6	$I_{w,bp,10}$ (cm^6)	$I_{T,bp,10}$ (cm^4)	$I_{w,bp,10}$ (cm^6)	$I_{T,bp,10}$ (cm^4)	$I_{w,bp,10}$ (cm^6)		
197.94	0.1802	6.32	31.00	212.68	18.801	212.48	18.843	0.93	1.65
367.98	-0.0947	12.75	31.21	393.96	15.509	393.93	15.556	0.93	2.01
621.63	-0.0162	22.69	23.94	658.18	28.767	659.04	29.315	0.94	0.82
974.43	0.0505	37.06	61.80	1023.5	126.76	1023.7	127.48	0.95	0.48
1436.78	0.1021	56.82	245.77	1507.1	469.54	1508	472.32	0.95	0.52
2039.48	0.1533	83.26	831.23	2127.1	1314	2129	1322.4	0.96	0.63
2783.85	0.1934	117.46	2089.90	2829.1	2751.4	2909.6	3240.5	0.96	0.64
3772.15	0.2355	162.15	4912.19	3923.3	6862.7	3925	6876	0.96	0.71
4961.58	0.2688	218.34	9862.16	5162.7	13643	5166.3	13666	0.96	0.72
7091.05	0.2926	323.49	20973.4	7348.3	27493	7357.2	27605	0.96	0.76
9800.71	0.3185	466.16	42169.2	10120	52865	10143	53264	0.97	0.79
12616.47	0.3660	647.18	84752.4	12810	98225	13057	105550	0.97	0.80
16036.25	0.4203	896.67	166597	16503	196630	16545	198070	0.97	0.84
20521.43	0.4661	1291.30	315203	21105	368950	21166	371910	0.97	0.85
26578.41	0.5213	1968.27	626648.	27254	711930	27359	719470	0.97	0.87
33688.82	0.5733	2937.12	1163216	34465	1291700	34604	1305600	0.97	0.89
41725.01	0.6128	4289.68	1963310	42658	2168600	42817	2189100	0.97	0.90
51048.13	0.6551	6236.48	3257269	52109	3542400	52309	3575800	0.98	0.91

6. CONCLUSION

In this paper the behavior of I sections with batten plates under St. Venant and warping torsion is investigated. Closed form expressions for torsion constant I_T and I_w are derived. It is shown that the analysis of a two-cell closed cross section (I section and batten plates) can be simplified to a one-cell closed cross section comprised of I section flanges and batten plates. Analytically, the web doesn't contribute neither to the torsion constant I_T nor to the warping constant I_w.

The same problem was investigated using FEM software ANSYS and IDEA StatiCa. Obtained values for I_T and I_w are somewhat different from analytically calculated ones.

The discrepancy between the values for I_T calculated using Equation (20) and the ones obtained from ANSYS are small, ranging from 2.4% to 6.8%. This difference in the results is caused by neglecting the fillet between the web and the flange in the analytical solution. Nevertheless, Equation (20) can be used as a safe and precise enough estimate of the torsion constant for I sections with batten plates in practice.

The discrepancy between the calculated values of I_w and the ones obtained from ANSYS is significantly larger than that for I_T and thus can't be ignored. Thickness warping and fillet between the web and flanges are two main reasons for these observed large discrepancies. These effects are especially pronounced for the cases that have small values of parameter β. If parameter β is less than 0.4 the relative difference between the calculated values for I_w and the ones obtained by ANSYS is larger than 16% and the Equation (24) cannot be considered valid anymore.

The values for I_T and I_w obtained using IDEA StatiCa software are very close to those obtained using ANSYS. This proves that although IDEA StatiCA is a less sophisticated software than ANSYS it could be used for determining the torsion properties of the sections with high accuracy.

Bearing everything said in mind, the torsion constant I_T and warping constant I_w for IPE sections with batten plates given in Table 1 and obtained by ANSYS can be considered as exact values. Therefore, they can be recommended to be used in practice.

Further research needs to be carried out in order to quantify the individual contributions of filet between the web and the flange, common web and thickness warping to the warping constant I_w. On the basis of that analysis, those contributions could be taken into account by modifying the derived analytical expression.

REFERENCES

[1] 1. Weimar C., Händler P., Lange J.: Wölbsteifen und ihr Potenzial zur Versteifung biegedrillknickgefährdeter I-Träger – eine Fallstudie, Stahlbau, Vol 90, Issue 8, 2021

[2] Prado N. et al: Experimental assessment of I-shaped steel beams with longitudinal stiffeners under lateral torsional-buckling, DYNA, vol. 85, no. 207, pp. 278-287, 2018

[3] Subotić P., Lučić D.: Batten plates effectiveness on flexural and lateral – torsional buckling of steel I members, Nordic Steel Construction Conference 2024 (NSCC 2024) Luleå, Sweden. doi 10.5281/zenodo.12529522

[4] Lubarda V.: On the torsion constant of multicell profiles and its maximization with respect to spar position, Thin-Walled Structures, Vol 47, pp.798-806, 2009

[5] Kollbrunner C., Hajdin N.: Dünnwandinge Stäbe, Springer, pp. 1-296, 1972

[6] Gjelsvik A.: The theory of thin walled bars, John Wiley and Sons, pp. 1-248, 1981

[7] Kraus M., Kindmann R.: St. Venants Torsion Constant of Hot Rolled Steel Profiles and Position of the Shear Centre, Nordic steel conference, 2009