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ESTIMATING DEFLECTIONS OF CASTELLATED BEAMS USING SOLIDWORKS SIMULATION

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The object of this study is a castellated beam, in which the large openings in the web have the shape of a regular hexagon. The beam is investigated for the purpose of assessing deflections. Based on a set of experimental studies, the features of the stress-strain state of castellated beams have been defined. The need to take into account the increased deflections of castellated beams due to the openings in the beam web when calculating the deflections of castellated beams at the serviceability limit state verifications has been determined. A comparative analysis of the deflections obtained as a result of the numerical experiment with the deflections of beams determined using the design code technique has been performed. It was established that for verifications of castellated beams at the serviceability limit state, the error in assessing the deflections of a single-span hinged beam loaded with a uniformly distributed transverse load in some cases reaches 20 %. Recommendations have been devised for estimating deflections of castellated beams. According to the proposed recommendations, the error in estimating castellated beam deflections does not exceed 3 % for the range of the beam span to the total height of its cross-section 8.5<L/h<25.

The results are valid only for the range of I-section profiles and only for the case of a uniformly distributed load acting on the beam when the compressed beam flange is out of bending plane restrained and the beam web is perforated with large openings in the form of regular hexagons. It is under such conditions that the results could be implemented in practice both at the stage of selecting cross-sections of the studied class of structures and when designing effective ranges of castellated beams

Keywords: castellated beam, hexagonal openings, deflections, finite element analysis, SOLIDWORKS Simulation

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1. Introduction

Modern rolled I-beams with parallel edges of the flanges, including wide-flanges ones, up to 1 m high, provide the ability to cover spans of 13…15 m in the presence of significant loads. The specific labor intensity of their manufacture in terms of basic operations is 2…2.5 times less than in trusses of similar span. However, steel consumption is 1.5 times higher than in trusses.

As a result of the search for ways to improve the efficiency of rolled I-beams, an original structural form emerged – an I-beam with large openings in the web, in which the material is concentrated closer to the flanges. In the technical literature, it received several names – an I-beam with a perforated web, an I-beam with a developed section, a build-up I-beam. Hereafter, we shall use the term "I-beams with large web openings", which is used in design codes (in particular, EN 1993-1-13:2024 "Eurocode 3 – Design of steel structures – Part 1–13: Beams with large web openings"). In case the perforation of the beam web with large openings in the form of regular hexagons such beams named "castellated beams" according to this design code.

The efficiency of the I-beam with large web openings compared to the original I-beam is explained by the fact that its height is approximately 1.4...1.5 times greater, the web thickness is 1/75...1/95 of the height. I-beam with large web openings provide 20...30 % steel savings compared to rolled I-beams and are 10...18 % cheaper. In terms of manufacturing complexity, they are 25...35 % more efficient than welded I-beams, due to the reduction of processing operations and the volume of welding [1].

Bi-steel I-beam with large web openings compared to hot-rolled solid-web I-beams made of low-carbon steel, with the same load-carrying capacity, are 34...39 % lighter and 16...20 % cheaper [2]. Structural joints in castellated beams are made using flange bolted connections [3], which largely ensures the ease of their installation. These positive qualities, combined with compactness, transportability, and the possibility of using highly automated manufacturing, make them competitive even in comparison with lattice structures [4]. In view of this, scientific research on the issue of assessing the deflections of I-beam with large web openings is considered relevant. Since I-beam with large web openings actually expand the scope of application of hot-rolled I-beams, the results of such research will be in practical demand among manufacturers of such structures.

2. Literature review and problem statement

A large body of research considers the estimation of deflections of beams with large web openings, in which the deflections were estimated analytically. One of the analytical approaches is based on the theory of compound bars [5]; the other uses the calculation scheme of the unsloped Vierendeel truss [6]. When applying analytical approaches to estimating the deflections of beams with large web openings, difficulties arise, associated with both the determination of the stiffness coefficient of the elastic layer formed by the lintels and the determination of the effective length of the T-flange. In this case, good convergence of the results of the analytical estimation of the deflections of beams with large web openings with the actual/experimental deflections of such beams is achieved only if the specified parameters are chosen correctly [5].

Another approach to estimating the deflections of beams with large web openings is to perform a numerical experiment using the finite element method [7]. In [8], the behavior of steel I-beams with rectangular openings in the web was studied. The authors investigated the effect of the radius of curvature at the corners of the rectangular openings, the effect of the ratio of the sides of the rectangular openings, and the effect of the location of stiffeners around the openings on the load-carrying capacity of such beams.

In [9], the deflections of cellular beams were studied using the finite element method. The authors showed that the main reason for the additional deflection of such beams is the deformation of the beam web post between the openings and the relative displacement between the upper and lower T-sections of the beam. The increase in the deflection of cellular beams compared to the deflections of beams with a solid web is more significant for short span beams.

The authors of work [10] reported experimental studies on beams with perforated web, which were carried out on full-scale samples of beams with sinusoidal openings in the web. Analysis of the experimental results revealed two possible types of failure of such structures – due to the formation of four plastic hinges in the corners of the opening or due to the loss of local stability of the web in the vicinity of the sinusoidal part of the opening.

It should be noted that in [8–10] the authors did not compare the obtained experimental values of the deflections of beams with large web openings with the deflection values calculated according to the design code recommendations. Therefore, the issue of assessing the degree of accuracy of the design code recommendations for assessing the deflections of such beams compared to experimental data remained unresolved.

Increasing the load-carrying capacity of a castellated beam requires developing the beam cross-section as much as possible in height by forming openings in the beam web of the maximum possible size [11]. However, too large openings in the web of the beam lead to premature exhaustion of its load-carrying capacity taken into account normal stresses verification at the design points at the top and bottom of the opening. At the same time, normal stresses arise in the extreme fibers of the beam cross-section, which are significantly less than the yield strength of the steel. In view of this, it is considered relevant to state and solve the problems of optimizing the dimensions of the cross-section of beams with large web openings [12].

The task to find the optimal cross-sectional dimensions of beams with large web openings can be represented as a nonlinear programming problem. The methodology for stating and solving problems of parametric optimization of steel structures is reported, for example, in [13], and is based on the use of gradient methods [14]. However, due to the discreteness of the profile assortment, the variation of the variable cross-sectional dimensions of beams with large web openings occurs with a violation of continuity, which complicates the use of gradient methods for solving such problems [15]. The approach of stating the problem of optimizing the cross-sectional dimensions of beams with large web openings as a multi-criteria optimization problem with the use of various compromise search methods [16] is also promising. Given the peculiarities of the stress-strain state of castellated beams, in work [17] the problem of optimizing the dimensions of the cross-section and openings in the web of castellated beams in the presence of continuous and discrete design variables was stated and solved. As a result of the optimization calculation, castellated beams with optimal cross-sectional dimensions were obtained depending on the steel class, beam span, and the magnitude of the uniformly distributed load acting on the beam. However, it should be noted that in this case, as part of the mathematical model, the assessment of the deflections of a castellated beam was performed using an approximate methodology proposed by the design codes.

Our review of the literature demonstrates that the proposed methodologies for calculating deflections caused by transverse bending for I-beams with large web openings differ greatly and do not have a single concept. In addition, there is no comparative analysis of them, and the issue of assessing the degree of their accuracy compared to experimental data remains unresolved. At the same time, experimental data on the assessment of beam deflections can be obtained by performing a numerical experiment using the finite element method.

3. The aim and objectives of the study

The purpose of our study is to identify the features of the stress-strain state of castellated beams. This will allow for an accurate assessment of the deflections of castellated beams for verifications at the serviceability limit states.

To achieve the goal, the following tasks were set:

– to perform a numerical experiment to study the stress-strain state of castellated beams in a wide range of geometric parameters;

– to determine additional deflections of castellated beams due to the openings in the web;

– to compile recommendations for assessing deflections in castellated beams for verifications of the serviceability limit states.

4. The study materials and methods

The object of our study is castellated beams (Fig. 1), which are investigated to determine the deflections of such beams to assess their load-carrying capacity according to the serviceability limit states.

The estimated cross-section of a castellated beam represents two T-shaped beams (upper and lower flanges of the beam), the joint operation of which is ensured by the existing web posts between the openings [18]. The T-shaped beams of the upper and lower flange of the beam, located within the opening, work both under the action of the bending moment in the beam due to the action of the transverse loading, and under the action of the shear forces, which cause additional bending of the flanges. In this case, the limit state of the T-shaped beam is characterized by a significant development of plastic deformations that penetrate almost its entire cross-section in the corners of the openings [19]. The beam web post behaves mainly in shear, and its load-carrying capacity is determined by local stability. In the limit state, the cross-sectional elements (web/flange) of the compressed T-beam flange may also compromise local stability [20].

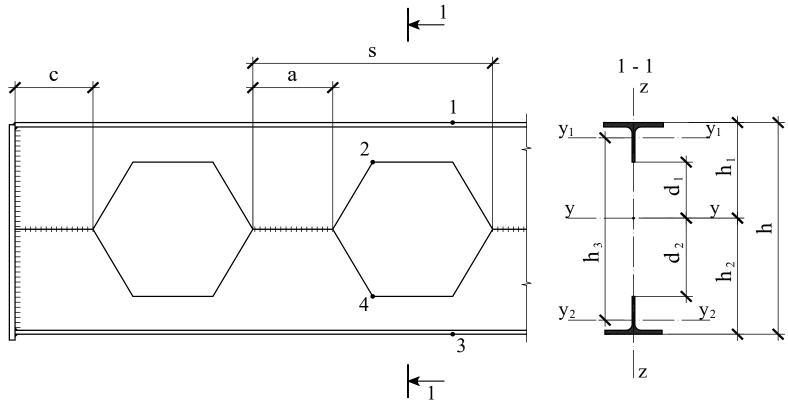

Fig. 1. Diagram of a castellated beam section

There are several approaches to the load-carrying verifications of castellated beams; from simple engineering models of calculation in the elastic domain without taking into account stress concentrators near the openings to complex models of elastic calculation based on the finite element method [21, 22]. There have also been attempts to estimate the load-carrying capacity of castellated beams according to the criterion of limit equilibrium or the criterion of limited plastic deformations [5].

In our work, the numerical finite element method is used to estimate the stress-strain state of a castellated beam. A set of experimental numerical studies on the calculation of deflections of castellated beams was performed using the SolidWorks Simulation 2023 software (Dassault Systèmes S.A., France) (academic license).

The assessment of deflections of bending structural members for compliance with the building codes requirements is performed for design loads at the serviceability limit state that are significantly less than the design loads at the ultimate limit state. In view of this, the main hypothesis of the study was that the assessment of beam deflections occurs under the condition that the beam material operates in the zone of elastic deformations of steel. The steel of the beams was modeled as a perfectly elastic material with elastic modulus E=2.06×10^5 MPa. In this case, the physical and mechanical properties of the beam material were assumed to be the same in all directions. Imperfections or residual stresses in the beam were not taken into account.

5. Results of studying the deflections of castellated beams using SolidWorks Simulation

5. 1. Numerical studies of the stress-strain state of castellated beams

Fig. 2 shows the finite element modeling of a castellated beam in the SolidWorks Simulation 2023 program using solid finite elements taking into account the figured conjugation of the flanges with the beam web. The beam was modeled as hinge-supported and loaded with a transverse load uniformly distributed along the plane of the upper flange of the beam. Horizontal/transverse shear links/supports were applied along the upper flange of the beam, which restrained the compressed beam flange in out of bending plane.

The beam deflections were estimated after performing the static linear analysis step using the finite element method (FEM) with linear operation of the beam material (Tables 1–3). In this case, the dimensions of the cross-section of the beams, which are determined by the number of the rolled profile and the dimensions of the hexagonal opening in the beam web, were taken based on the results of solving the optimization problem of such beams, reported in [17].

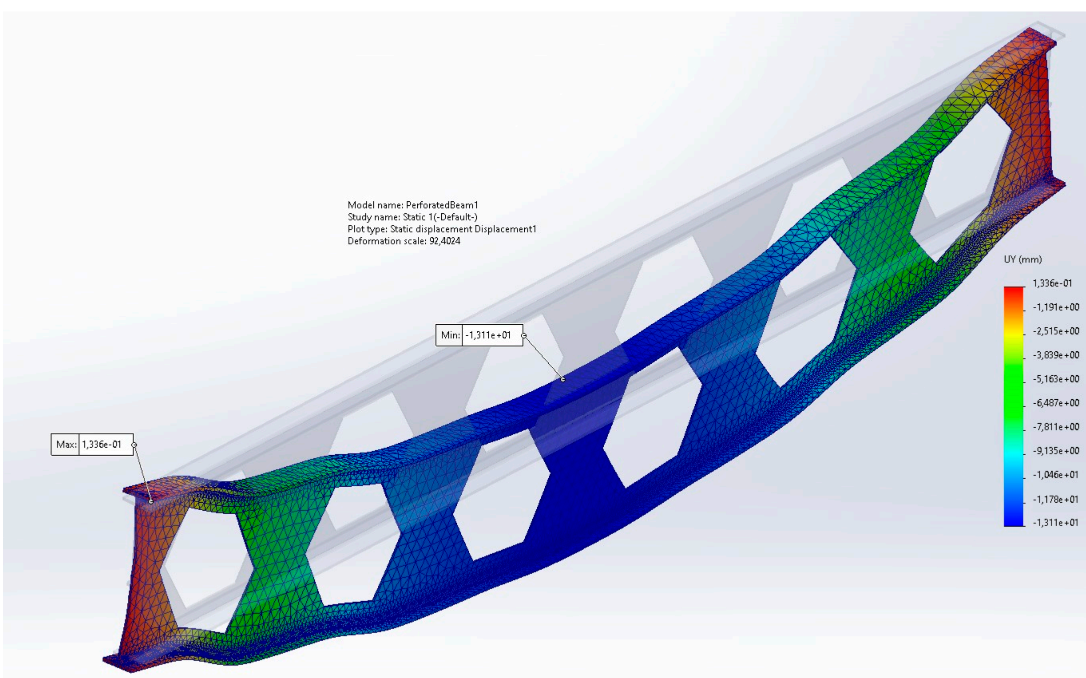

Fig. 2. Vertical deflections of a castellated beam (linear material work)

Table 1

Deflections of castellated beams with a span of 12 m

L/h	Load q_{sls}, kN/m	Profile number for beam flanges	Cross-sectional dimensions, mm		Deflection, mm		
			Opening width a	Total beam height h	Based on FEM	Calculated by (1)	Discrepancy, %
12.18	58.82	70B2	333	985	29.03	25.83	–11.01
10.80	77.21	80B1	369	1111	28.48	24.99	–12.25
9.57	95.59	90B1	417	1254	23.89	20.22	–15.35
8.59	150.74	100B2	461	1397	23.61	18.88	–20.04
8.61	172.79	100B3	447	1393	24.09	19.38	–19.53
8.63	176.47	100B3	443	1390	24.62	19.88	–19.24
8.54	183.82	100B4	453	1405	23.18	18.42	–20.54
8.55	187.5	100B4	450	1403	23.57	18.85	–20.04
8.58	191.18	100B4	446	1399	24.05	19.30	–19.75

Table 2

Deflections of castellated beams with a span of 15 m

L/h	Load q_{sls}, kN/m	Profile number for beam flanges	Cross-sectional dimensions, mm		Deflection, mm		
			Opening width a	Total beam height h	Based on FEM	Calculated by (1)	Discrepancy, %
18.80	18.38	55B1	290	798	52.59	49.70	–5.49
17.34	25.74	60B1	314	865	51.8	49.07	–5.27
17.44	29.41	60B2	304	860	54.63	51.35	–6.01
15.06	36.76	70B1	352	996	47.89	44.55	–6.97
15.02	40.44	70B2	349	999	46.27	42.69	–7.74
13.12	47.79	80B1	406	1143	39.98	36.34	–9.10
11.51	55.15	90B1	473	1303	30.65	27.02	–11.84
11.61	58.82	90B1	461	1292	32.74	29.16	–10.94
11.71	62.5	90B1	448	1281	35.37	31.39	–11.24
11.80	66.18	90B1	437	1271	37.54	33.62	–10.44

Table 3

Deflections of castellated beams with a span of 18 m

L/h	Load q_{sls}, kN/m	Profile number for beam flanges	Cross-sectional dimensions, mm		Deflection, mm		
			Opening width a	Total beam height h	Based on FEM	Calculated by (1)	Discrepancy, %
25.10	7.35	50B1	260	717	65.66	64.76	–1.37
20.50	18.38	60B2	325	878	68.35	65.40	–4.31
17.49	29.41	70B2	383	1029	65.1	61.93	–4.87
15.44	33.09	80B1	433	1166	54.33	51.09	–5.96
15.40	36.76	80B1	437	1169	59.88	56.26	–6.04
15.37	40.44	80B2	431	1171	57.62	53.78	–6.66
13.67	40.44	90B1	490	1317	44.77	40.79	–8.90
13.81	44.12	90B1	474	1303	48.87	45.12	–7.68
13.72	47.79	90B1	484	1312	52.58	48.22	–8.30
13.75	55.15	90B2	472	1309	53.8	49.32	–8.33
12.5	62.5	100B1	520	1440	48.3	43.65	–9.63
12.58	66.18	100B1	509	1431	51.18	46.65	–8.85
12.41	69.85	100B2	523	1451	47.23	42.17	–10.70
12.48	73.53	100B2	513	1442	49.81	44.78	–10.11
12.40	77.21	100B3	515	1452	46.53	41.42	–10.97
12.47	80.88	100B3	506	1444	48.82	43.74	–10.40
12.54	84.56	100B3	495	1435	51.99	46.21	–11.13
12.40	88.24	100B4	507	1452	47.96	42.86	–10.64
12.47	91.91	100B4	497	1443	51.01	45.06	–11.66

Tables 1–3 show the results of our numerical studies, in particular for beams with a span of 12 m, 15 m, and 18 m; the values of deflections obtained as a result of the implementation of a numerical experiment using the finite element method are given. It should be noted that the lateral-torsional buckling phenomenon in the elastic stage of the beam material did not arise due to the transverse shear links/supports present in the model, arranged along the upper (compressed) flange of the beam [23].

5. 2. Determining additional deflection of the beam due to large openings in the web

Deflections of steel beams under the action of design loads corresponded to the serviceability limit states q_{SLS} are usually estimated using the well-known analytical formula:

$$f_{\max} = \frac{5}{384} \frac{q_{SLS} L^4}{EI_{x,\Sigma,net}}, \tag{1}$$

where $f_{\max}$ is the maximum deflection of the beam in the mid-span section; L is the beam span; $I_{x,\Sigma,net}$ is the moment of inertia of the net beam section (minus the opening in the web); E is the elastic modulus of steel, E=2.06·10^8 kN/m^2. In this case, for beams with large openings in the web, the deflections can be estimated using the moment of inertia $I_{x,\Sigma,net}$.

A comparative analysis of the beam deflections calculated analytically using the moment of inertia of the net beam section $I_{x,\Sigma,net}$ with the beam deflections obtained as a result of the implementation of a numerical experiment was performed. Tables 1–3 give a comparison (calculated discrepancy) of the beam deflections obtained as a result of the implementation of a numerical experiment with the beam deflections calculated analytically using the calculated net beam section (minus the opening) in the absence of shear deformations.

The comparative analysis performed allowed us to determine additional (due to the large openings in the beam web) deflections of beams subjected to bending and shear deformations. In the case of calculating the deflection of castellated beams based on the net moment of inertia of the beam section $I_{x,\Sigma,net}$ (minus the opening in the web), the error in estimating the deflections of the beams was 20.5 % (Table 1) for beams with a span of 12 m, 11.8 % for beams with a span of 15 m (Table 2), and 11.7 % for beams with a span of 18 m (Table 3). Our comparative analysis demonstrated the need to take into account the increased deflections of castellated beams due to the large openings in the beam web when calculating the deflections of castellated beams in serviceability limit state verifications.

5. 3. Compiling recommendations for assessing deflections of castellated beams for serviceability limit state verifications

In the design code for steel castellated beams DBN V.2.6-198:2014 "Steel structures. Design standards", the deflections of such beams under the action of design loads at the serviceability limit states are regulated to be assessed taking into account the coefficient μ=0.95, which is applied to the moment of inertia of the beam section net $I_{x,\Sigma,net}$. This is how these design code take into account the increase in deflections of castellated beams. Thus, for the case of a single-span hinged-supported castellated beam, which is loaded with a uniformly distributed transverse load q_{SLS}, the maximum deflection of the beam in the cross-section in the middle of its span is proposed to be calculated as:

$$f_{\max} = \frac{5}{384} \frac{q_{SLS} L^4}{\mu EI_{x,\Sigma,net}}. \tag{2}$$

In the design code EN 1993-1-13:2024 "Eurocode 3 – Design of steel structures – Part 1–13: Beams with large web openings" [24] the maximum deflection of a single-span hinged-supported castellated beam, which is loaded with a uniformly distributed transverse load q_{SLS}, is proposed to be estimated as:

$$f_{\max} = \frac{5}{384} \frac{q_{SLS} L^4}{EI_x} \left(1 + 10 n_0 \frac{3a^3\sqrt{3}}{hL^2}\right), \tag{3}$$

where n_0 is the number of openings in the beam web along its span; I_x is the moment of inertia of the beam cross-section, calculated for a beam with a solid web (in the absence of openings in the web).

Tables 4–6 and Fig. 3 show a comparative analysis of the beam deflections obtained as a result of the implementation of a numerical experiment with the deflections determined according to the design code recommendations. Such an analysis allowed us to identify the limits of applying the simplified methodology for estimating the deflections of castellated beams, which is described in DBN V.2.6-198:2014 "Steel structures. Design standards" and EN 1993-1-13:2024 "Eurocode 3 – Design of steel structures – Part 1–13: Beams with large web openings".

The numerical studies have shown that in the case of a verification of a castellated beam at the serviceability limit states in accordance with DBN V.2.6-198:2014 "Steel structures. Design standards", the error in estimating the deflections of a single-span hinged beam loaded with a uniformly distributed transverse load reaches 20 %. At the same time, for beams with a ratio of the beam span to the total height of the beam cross-section L/h<12, this error exceeds 5 %, at L/h<10 – it exceeds 10 %, and for short beams at L/h<9 the error reaches 20 %.

Table 4

Deflections of castellated beams with a span of 12 m

L/h	Load q_{sls}, kN/m	Profile number for beam flanges	Deflection, mm				
			Based on FEM	Based on DBN V.2.6-198:2014	Discrepancy, %	Based on EN 1993-1-13:2024	Discrepancy, %
12.18	58.82	70B2	29.03	27.194	–6.75	27.85	–4.24
10.80	77.21	80B1	28.48	26.308	–8.26	27.139	–4.94
9.57	95.59	90B1	23.89	21.29	–12.23	22.348	–6.90
8.59	150.74	100B2	23.61	19.872	–18.81	21.256	–11.07
8.61	172.79	100B3	24.09	20.405	–18.06	21.697	–11.03
8.63	176.47	100B3	24.62	20.93	–17.63	22.623	–8.83
8.54	183.82	100B4	23.18	19.389	–19.55	20.711	–11.92
8.55	187.5	100B4	23.57	19.839	–18.81	21.151	–11.44
8.58	191.18	100B4	24.05	20.316	–18.38	21.603	–11.33

Table 5

Deflections of castellated beams with a span of 15 m

L/h	Load q_{sls}, kN/m	Profile number for beam flanges	Deflection, mm				
			Based on FEM	Based on DBN V.2.6-198:2014	Discrepancy, %	Based on EN 1993-1-13:2024	Discrepancy, %
18.80	18.38	55B1	52.59	52.32	–0.52	51.478	–2.16
17.34	25.74	60B1	51.8	51.651	–0.29	51.018	–1.53
17.44	29.41	60B2	54.63	54.048	–1.08	53.743	–1.65
15.06	36.76	70B1	47.89	46.897	–2.12	46.95	–2.00
15.02	40.44	70B2	46.27	44.937	–2.97	45.231	–2.30
13.12	47.79	80B1	39.98	38.253	–4.52	38.74	–3.20
11.51	55.15	90B1	30.65	28.444	–7.76	29.116	–5.27
11.61	58.82	90B1	32.74	30.692	–6.67	31.265	–4.72
11.71	62.5	90B1	35.37	33.045	–7.04	33.957	–4.16
11.80	66.18	90B1	37.54	35.39	–6.08	36.188	–3.74

Table 6

Deflections of castellated beams with a span of 18 m

L/h	Load q_{sls}, kN/m	Profile number for beam flanges	Deflection, mm				
			Based on FEM	Based on DBN V.2.6-198:2014	Discrepancy, %	Based on EN 1993-1-13:2024	Discrepancy, %
25.10	7.35	50B1	65.66	68.17	3.68	65.039	–0.95
20.50	18.38	60B2	68.35	68.84	0.72	67.187	–1.73
17.49	29.41	70B2	65.1	65.19	0.14	64.13	–1.51
15.43	33.09	80B1	54.33	53.78	–1.01	52.91	–2.69
15.40	36.76	80B1	59.88	59.23	–1.10	58.319	–2.68
15.37	40.44	80B2	57.62	56.61	–1.78	56.185	–2.55
13.67	40.44	90B1	44.77	42.94	–4.10	43.00	–4.11
13.81	44.12	90B1	48.87	47.49	–2.82	47.35	–3.21
13.72	47.79	90B1	52.58	50.75	–3.60	50.745	–3.62
13.75	55.15	90B2	53.8	51.92	–3.63	52.151	–3.16
12.5	62.5	100B1	48.3	45.946	–5.12	46.544	–3.77
12.58	66.18	100B1	51.18	49.104	–4.23	49.566	–3.26
12.41	69.85	100B2	47.23	44.394	–6.39	45.305	–4.25
12.48	73.53	100B2	49.81	47.133	–5.68	47.929	–3.92
12.40	77.21	100B3	46.53	43.605	–6.71	44.581	–4.37
12.47	80.88	100B3	48.82	46.045	–6.03	46.918	–4.05
12.54	84.56	100B3	51.99	48.637	–6.90	49.945	–4.09
12.40	88.24	100B4	47.96	45.113	–6.31	46.045	–4.16
12.47	91.91	100B4	51.01	47.434	–7.54	48.807	–4.51

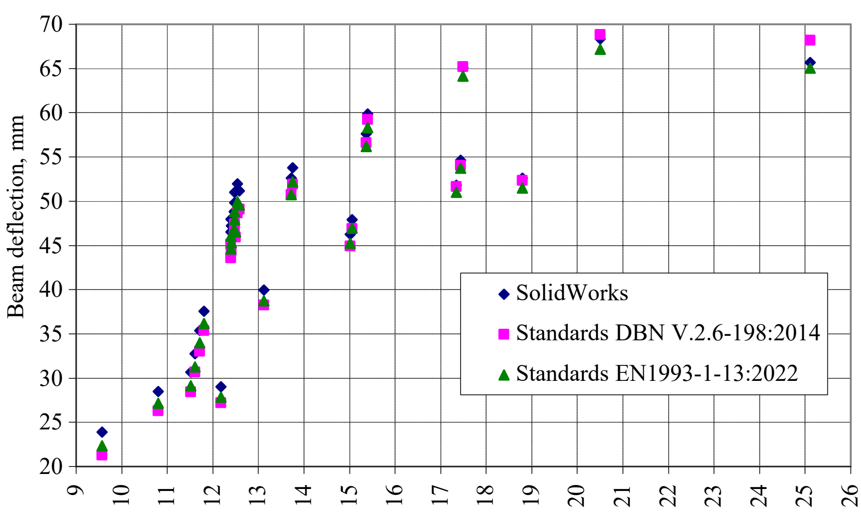

Fig. 3. Plot of beam deflection as a function of the ratio of beam span to total cross-sectional height of the beam

For a more accurate assessment of the deflections of castellated beams when performing verifications at the serviceability limit states in accordance with DBN V.2.6-198:2014 "Steel structures. Design standards" it is proposed to calculate the coefficient μ depending on the ratio of the beam span to the total height of the beam cross-section L/h as:

$$\mu = 0.00009\left(\frac{L}{h}\right)^3 - 0.0051\left(\frac{L}{h}\right)^2 + +0.1032\left(\frac{L}{h}\right) + 0.2407. \quad (4)$$

In this case, the error in estimating beam deflections will not exceed 3 % for a wide range of beam span to total beam cross-sectional height ratios $8.5 < L/h < 25$.

6. Discussion of results based on evaluating the deflections of castellated beams

Our results of the performed numerical experiments are explained primarily by the type of the considered cross-section of the structural members and the features of its stress-strain state. The reliability of the results regarding the magnitude of the maximum deflection of castellated beams (Tables 1–6) is confirmed by the rigor and correctness of the mathematical model for the problem of determining the stress-strain state of the studied class of structures. In addition, the reliability of the findings is evidenced by the stability of the obtained numerical solutions in relation to the initial data.

We report numerical results regarding the magnitude of the maximum deflection of castellated beams (Tables 1–6) obtained for the range of normal I-beam profiles and only for the case of the action of a distributed transverse load on the beam when the compressed flange of the beam is out of bending plane restrained and the perforation of the beam web with openings in the form of regular hexagons. It is under such conditions that the results could be implemented in practice both at the stage of selecting cross-sections of the studied class of structures and when designing effective assortments of castellated beams.

Comparison of the obtained results of numerical studies on the deflections of castellated beams with the known and described in the literature results of similar numerical studies is not considered possible. After all, the latter were obtained for other design conditions (other design schemes, other types of openings or sizes of openings in the web and a different assortment of rolled profiles). However, the difference of this work compared to similar known studies (such as, for example, [25]) is in deriving a polynomial dependence for the reduction coefficient, which corrects the bending stiffness of a castellated beam when assessing its deflections. This reduction coefficient depends on the ratio of the beam span to the total height of its cross-section. The specified dependence is of practical value and could be used in engineering design practice for a more accurate assessment of the deflections of castellated beams at the stage of serviceability limit state verification.

Our study has certain limitations. Indeed, the proposed polynomial dependence for the reduction coefficient intended for adjusting the bending stiffness of a castellated beam when assessing its deflections has certain application limits. In particular, it is valid only for the range of normal I-beam profiles and only for the case of a distributed transverse load acting on the beam when the compressed beam flange is out of bending plane restrained and the beam web is perforated with large openings in the form of regular hexagons with optimal dimensions.

The shortcomings of the reported study include the lack of numerical studies on the assessment of deflections of beams with a web without perforation. Such studies would allow us to further devise recommendations on the assessment of deflections of castellated beams depending on the deflection of beams with a solid web without, which, without a doubt, would have practical value.

Further research to build on this paper may involve performing a set of experimental studies on the assessment of deflections of beams with large web openings for other design conditions – other assortments of rolled I-beam profiles, other shapes of openings in the beam web, and other beam loading schemes. This could allow us to further devise practical recommendations on the assessment of deflections of beams with large web openings for a wide range of the studied class of structures.

7. Conclusion

1. The deflections of castellated beams with spans of 12 m, 15 m, and 18 m under the action of a transverse uniformly distributed load have been calculated. The beams were modeled using solid finite elements taking into account the figured conjugation of the flanges with the beam web and in the absence of imperfections and residual stresses. The beam deflections were estimated after performing the static linear analysis step using the finite element method when the beam material operates within the elastic deformations of the steel. For castellated beams with the ratio of the beam span to the height of its cross section $8.5<L/h<25$, experimental values of deflections of 23.18…64.76 mm were obtained under loads corresponding to the serviceability limit states.

2. We have performed comparative analysis of beam deflections calculated analytically using the net beam section moment of inertia (excluding openings) in the absence of shear deformation with beam deflections obtained as a result of a numerical experiment. This analysis demonstrated the need to take into account the increased deflections of castellated beams (by 20.5 % for beams with a span of 12 m, by 11.8 % for beams with a span of 15 m, and by 11.7 % for beams with a span of 18 m) due to the openings present in the beam web when calculating the deflections of castellated beams in verifications at the serviceability limit states.

3. Recommendations have been compiled for assessing the increased deflections of castellated beams due to the openings present in the web. These recommendations are based on the use of a polynomial relationship for the reduction factor that adjusts the bending stiffness of a castellated beam when estimating its deflections. This reduction factor depends on the ratio of beam span to the total height of its cross-section. When applying the proposed reduction factor, the error in estimating beam deflections will not exceed 3 % for a wide range of the ratio of beam span to the total height of the beam cross-section $8.5<L/h<25$.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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