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Determining the Strength Properties of Castellated Girders by Experimental and Numerical Modeling

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Abstract. Castellated girders are relatively efficient alternative to the classical beams made from rolled sections. The essence of the production process of castellated girders consists in cutting the beam for example zigzag incision and then welding the cut parts of the original beam. This will provide greater heights beam with hexagonal holes. Vertical height of the beam can be increased further by inserting short webs to form octagonal openings. Castellated girder from the original beam has greater strength and rigidity. The features can be related mainly to the weight. However, it is more prone to lateral torsional buckling, local buckling of web and rupture of weld in the web post. Other advantages of castellated girders include the possibility of plumbing, wiring and other installations through openings. The paper presents stress and strain analysis of critical points of castellated girders with circular and hexagonal holes. There were applied three modifications of standard IPE profile. For the purpose of stress and strain analysis were applied the methods and means of experimental and numerical modeling.

Introduction

Castellated beams or castellated girders are known as an effective alternative to standard profiles, especially to IPE profiles. They are made from rolled and welded sections, when the web is cutting on two symmetric sides and subsequent is welded (Fig. 1). Following such an adjustment of beam it is increasing its height with created holes in the middle of the web, which contributes to the bending stiffness while maintaining low weight. Course there is fact, that such structural update is positively reflected in the final price of the beam. Castellated beams have application in various technical works for example roof constructions, the structures for the portal cranes, bridges etc. (Fig. 2). They are application wherever, where are the emphasis on the maximum capacity with minimum weight [5,6].

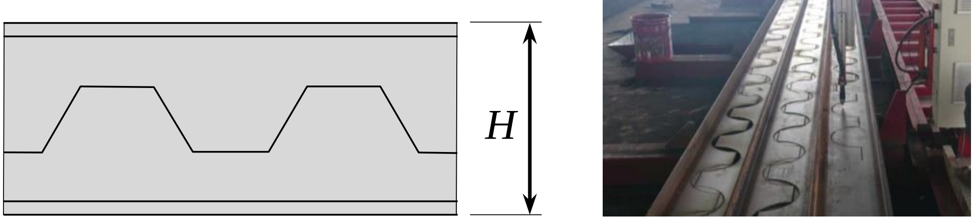

Fig. 1 Creating castellated girders using cutting and welding [1]

Fig. 2 Various applications of castellated girders [2,3,4]

Castellated girders also more effective in terms of passing service wires, pipes and ventilating ducts through opening. Castellated girders deliver increasing value of the bending section modulus W_{ox} according Fig. 3 [7] with value z according Fig. 4c.

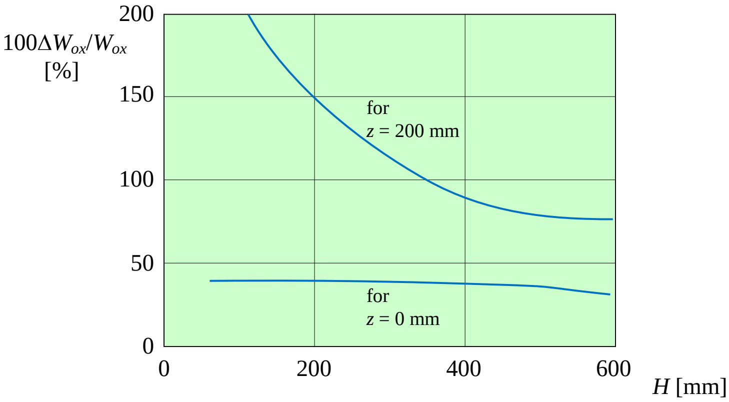

Fig. 3 Increasing value of the bending section modulus

Typology of castellated girders

Standardly produced types of castellated girders represent the following groups of shapes: Castellated symmetrical girder with a hexagonal holes (CGH) (Fig. 4a) making from IPE profile using zigzag cutting. This base type beam predominantly used as a bending stress component of steel structures. Castellated asymmetric girder with a hexagonal holes (Fig. 4b). This type of beam has application in cases, where the stress of the two flanges is different and not symmetrical. This is the case for example of composite steel structures that are not protected against lateral buckling. Castellated symmetrical girder with a hexagonal holes and with inserting element (Fig. 4c). Castellated symmetrical girder with a circular holes (CGC) (Fig. 4d). This type of beam is particularly suitable for uniform load because it has less resistance for shear loading [5]. Very special shape of castellated girder is tapered shape (Fig. 4e) and curved shape (Fig. 4f).

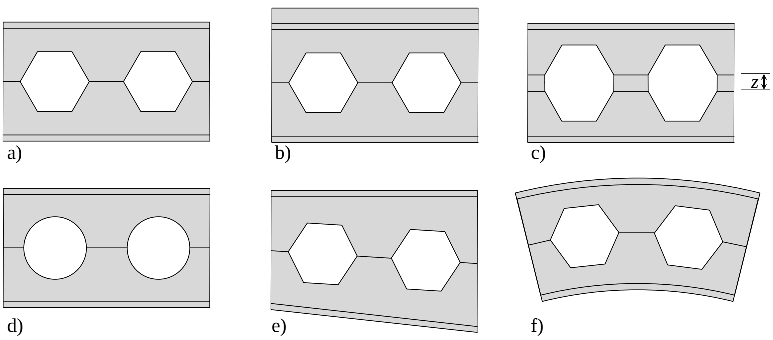

Fig. 4 Basic and special shapes of the castellated girders

The possibility of failure of castellated beams

Failure to properly design of the shape or geometry of castellated girders may be permanent damage to such proposed beams. Failure of web opening depends on opening shape, opening dimensions, the distance between opening, web post thickness. Several modes of Failure are [8]:

1. flexural failure of the section;
2. lateral torsional buckling of beam;
3. local buckling of web or flange (Fig. 5);
4. rupture of weld in the web post;
5. Vierendeel failure of perforation of section;
6. web post buckling.

Fig. 5 Collapsed castellated girder - local buckling [5,9]

Calculation and stress analysis

Calculation, strain and stress analysis of the castellated girder can be performed by analytical, experimental and numerical modeling in the comparative, complementary and verification connections.

Analytical solution

Static analytical calculation of the castellated beams can be performed in the same manner as is used in calculating Vierendeel beam. The basis for calculation of the beam (Fig. 6) is element obtained by imaginary cutting. In place of the envisaged joints are internal variables replaced with outside variables $F/2$, N_L, N_R and Q as shown on Fig. 7.

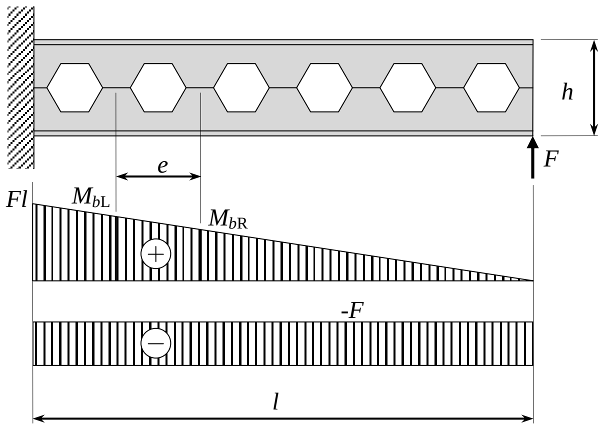

Fig. 6 Loading force F, bending moment M_b and shear force along the castellated beam

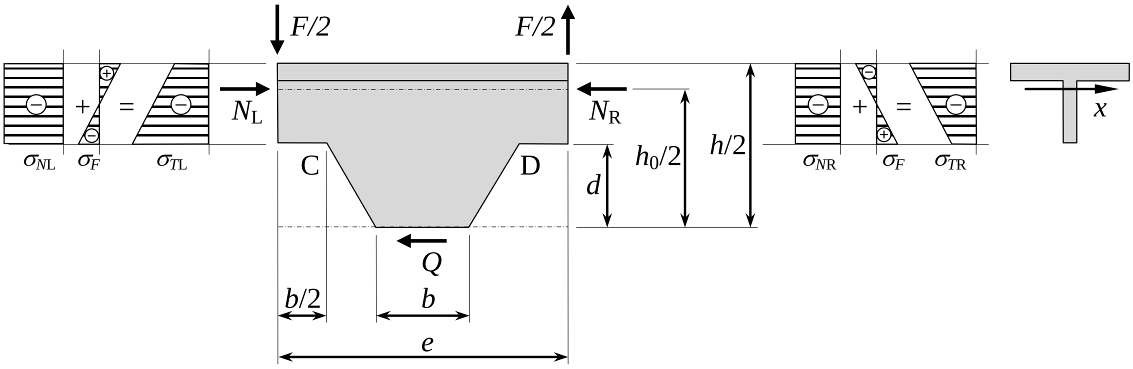

Fig. 7 Preparing of the castellated beam CGH to analytical solution

The forces N_L, N_R and Q are expressed:

$$N_L = \frac{M_{bL}}{h_0},\ N_R = \frac{M_{bR}}{h_0},\ Q = \frac{F \cdot e}{h_0}. \tag{1}$$

Total sum of normal stress in the point C is:

$$\sigma_{TC\max} = \sigma_N + \sigma_{F\max} = \frac{M_{bL}}{h_0 A} + \frac{Fb}{4W_{ox}}, \tag{2}$$

where A is the area and W_{ox} is the bending section modulus of the cross section of the upper belt [7].

Experimental solution

During the experiment was used measuring system as shown in the Fig. 8. The main parts of the measuring chain were: the active and compensation resistance 120-ohm strain gauges (single and 90-degree rosette) (Ekolab, Micro Measurements Group Vishay and Baldwin Lima Hamilton) in quarter and half-bridge circuits, the digital strain indicator Model P-3500 (Micro Measurements Group Vishay), the switch & balance unit SB-10 (Micro Measurements Group Vishay) and respective loading units and elements. The models P-3500 and SB-10 are portable, battery-powered high precision instruments for use with resistive strain gages and transducers, primarily intended for the experimental stress analysis (ESA).

Fig. 8 Experimental model of the IPE 100, CGC, CGH and respective experimental chain and loading unit

The position of the electric resistance strain gauges on the IPE 100 shows Fig. 9, on the CGC shows Fig. 10 and on the CGH shows Fig. 11.

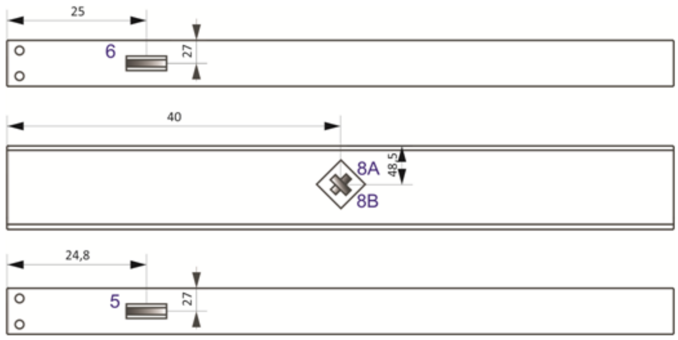

Fig. 9 Position of the resistance strain gauges on the IPE 100

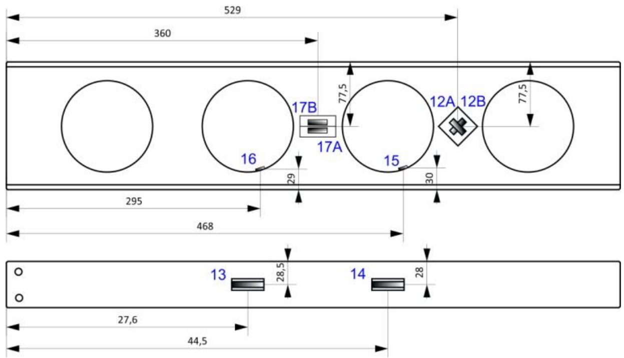

Fig. 10 Position of the resistance strain gauges on the CGC

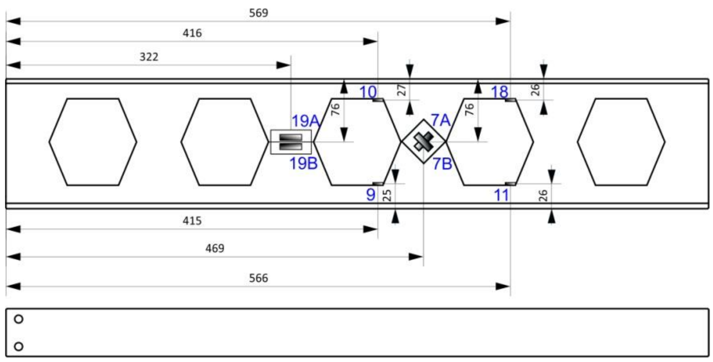

Fig. 11 Position of the resistance strain gauges on the CGH

The experimental solution has included also ultrasonic check the integrity of the weld as shown on Fig. 12.

Fig. 12 Ultrasonic check the integrity of the weld

The analysis of the concentration of stress can be also advantageously used by optical methods, especially by the method reflection or transmission photoelasticimetry (Fig. 13) [5].

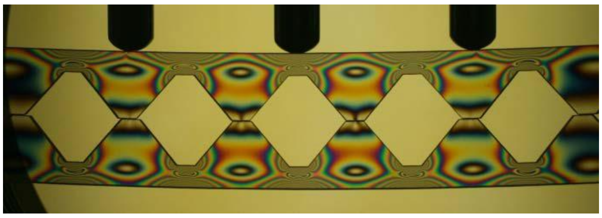

Fig. 13 Field of isochromatics in the CGH [5]

Numerical solution

Numerical solution for stress analysis by finite element method (FEM) was realized using SolidWorks software and Abaqus software. There were applied laws of model similarity in order to use the physical models for experimental modeling. The field of shear stresses τ_{zy} in the IPE 100, in the CGC and in the CGH shows Fig. 14, Fig. 15 and Fig. 16. The field of normal stresses σ_z in the IPE 100, in the CGC and in the CGH shows Fig. 17, Fig. 18 and Fig. 19.

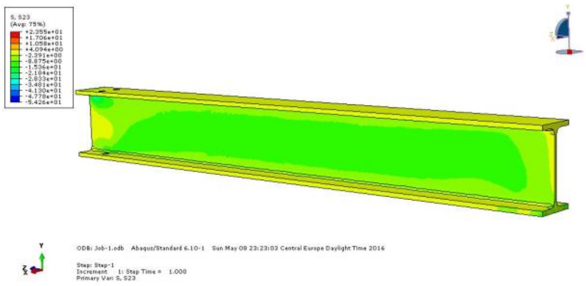

Fig. 14 Field of shear stresses τ_{zy} in the IPE 100

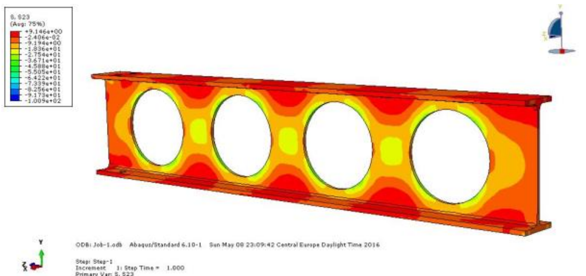

Fig. 15 Field of shear stresses τ_{zy} in the CGC

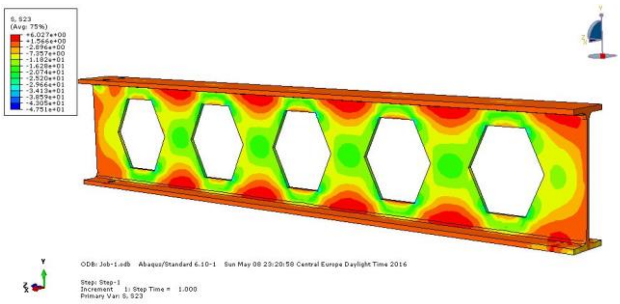

Fig. 16 Field of shear stresses τ_{zy} in the CGH

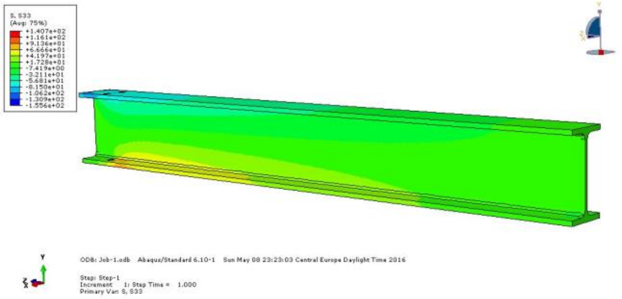

Fig. 17 Field of normal stresses σ_z in the IPE 100

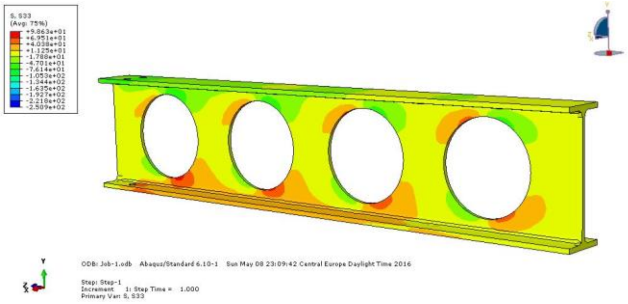

Fig. 18 Field of normal stresses σ_z in the CGC

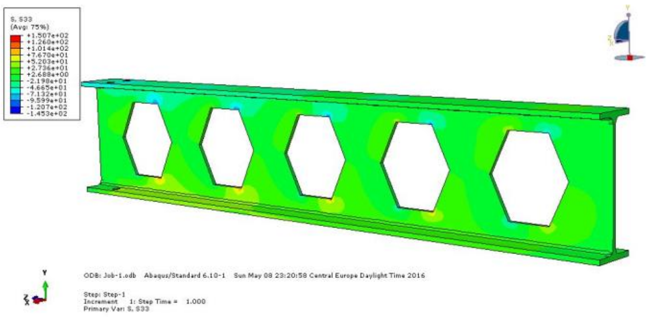

Fig. 19 Field of normal stresses σ_z in the CGH

Measured and calculated values of stresses

The data obtained by experimental and numerical analysis in selected critical points of the IPE, CGC and CGH are shown in Tab. 1 – Tab. 3 for input parameters: $F = 3\,500$ N, $l_{IPE} = 720$ mm, $l_{CGC} = 650$ mm, $l_{CGH} = 720$ mm.

Tab. 1 Measured and calculated values of stresses in the IPE

Position on the IPE	Stress (kind)	Value [MPa] Experimental analysis (strain gauges)	Value [MPa] Numerical analysis (FEM)
5	σ_z	55,70	52,00
6	σ_z	55,50	51,70
8	τ_{zy}	15,10	10,80

Tab. 2 Measured and calculated values of stresses in the CGC

Position on the CGC	Stress (kind)	Value [MPa] Experimental analysis (strain gauges)	Value [MPa] Numerical analysis (FEM)
12	τ_{zy}	28,90	23,69
13	σ_z	23,50	24,58
14	σ_z	14,50	14,16
15	σ_z	78,10	76,47
16	σ_z	89,10	84,37
17	τ_{zy}	28,40	23,80

Tab. 3 Measured and calculated values of stresses in the CGH

Position on the CGH	Stress (kind)	Value [MPa] Experimental analysis (strain gauges)	Value [MPa] Numerical analysis (FEM)
7	τ_{zy}	38,90	19,77
9	σ_z	74,50	67,20
10	σ_z	70,20	75,19
11	σ_z	73,60	72,24
18	σ_z	86,60	88,35
19	τ_{zy}	29,80	19,19

Conclusions

Based on a wide range of analytical, numerical and experimental strain and stress analyzes performed on castellated girders with circular and hexagonal holes and on beams without holes were obtained relevant data. These data serve to assess critical characteristics and behavior of standard beams and castellated girders.

Acknowledgement

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