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TEHNO-EKONOMSKA ANALIZA SAĆASTIH I PUNIH "I" ČELIČNIH GREDNIH NOSAČA U POGLEDU NOSIVOSTI I FUNKCIONALNOSTI

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Rezime:

Prednosti saćastih u odnosu na pune I gredne nosače mogu biti značajne. Oni mogu imati i do 50% veću visinu poprečnog presjeka u odnosu na "izvorne" nosače od koga su oni nastali a samim tim i veću nosivost na moment savijanja. Cilj rada je pokazati ekonomsku opravdanost saćastih nosača u odnosu na pune u pogledu nosivosti i funkcionalnosti. Varirani su rasponi i opterećenja na statičkom sistemu proste grede te je se za uredjeni par (raspon, opterećenje) dodijeljen jedan puni i jedan saćasti nosač čija nosivost i funkcionalnost (ugibi) zadovoljavaju a potom se porede njihove cijene. Saćasti nosač je ekonomičniji u pogledu ukupne težine čelika ali on zahtjeva dodatne troškove izrade. U radu su prikazani specifičnosti proračuna saćastih nosača, budući da oni trenutno nisu "obrađeni" u aktuelnim evropskim standardima (Eurocode 3).

Ključne riječi: saćasti nosači, proračun saćastih nosača, tehno-ekonmska analiza

TECHNO-ECONOMIC ANALYSIS OF CASTELLATED AND SOLID "I"- PROFILED STEEL BEAMS IN TERMS OF LOAD CAPACITY AND SERVICEABILITY

Abstract:

Advantages of castellated beams compared to solid steel beams can be significant. They can have up to 50% increase of cross section height compared to its original beam from which they were made of, i.e. greater bending capacity. Aim of this paper is to show the economic justification of castellated beams compared to solid beams in terms of load capacity and serviceability. The spans and loads on simple beam are varied and for a regulated pair (span, load), one solid and one castellated beam are determined, whose load capacity and serviceability are satisfied, and then their price was compared. Castellated beams are more economical in terms of total weight, but their production demands additional costs. Also in this paper, particularities of castellated beams design will be presented, since current European regulations (Eurocode 3) do not cover mentioned design methods.

Keywords: castellated beams, design of castellated beams, techno-economic analysis

1. INTRODUCTION

Increase in load-bearing capacity of solid I-profiled beams can be achieved in several ways. One of the ways is welding additional steel plates on flanges of I profile (Figure 1. a) and so increasing part of area of cross section that is mainly intended for bending resistance (Flanges). Consequence of adding additional material is, logically, additional weight, which is, in economical way, downside of this type of load-bearing optimization. Other way of increasing bending resistance is increasing height of cross section by cutting web in two equal parts, placing plate in-between and then weld them together, like shown on Figure 1. b. Moment of inertia then has higher value but additional weight cause more cost.

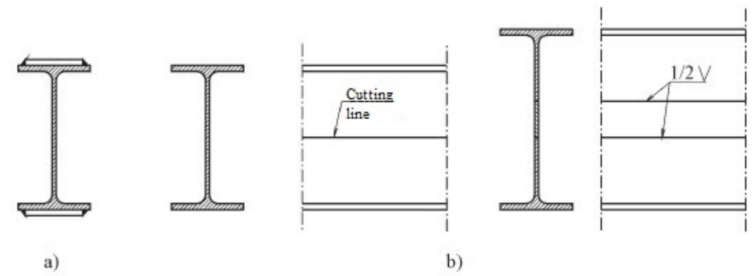

Figure 1. Types of increasing load-bearing capacity: a) By adding plates on flanges; b) By web cutting and putting plate inbetween

Most popular way of increasing load-bearing capacity of solid beams without additional weight is way of producing castellated beams (name of castellated beams comes from specific look of cut parts that looks like top of castle). Web is cut in specific zig-zag line then those parts are displaced and welded at specific places so that final height can be increased up to 50% like shown of Figure 2.. That way, additional cost will be only caused by cutting and welding and significant increase in moment of inertia will be achieved.

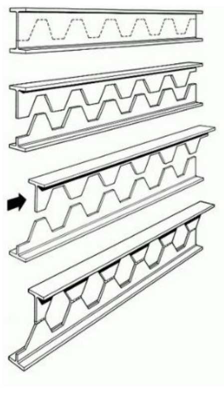

Figure 2. Zig-zag cutting, displacement and welding of solid beams - Castellated beam

Idea of paper is to compare costs of one solid I profiled beam and one castellated beam that both have same load-bearing capacity at ultimate limit state and both fulfill serviceability requests. Castellated beams, compared to their correspond solid-profiled-beam pair, with same load-bearing characteristics, have less weight because they were made of solid profile with smaller height, but similar capabilities because of similar value of moment of inertia. Generally, costs in steel constructions are calculated relative to steel weight, so castellated beams will surely cost less, but additional cost are required due to procedure of cutting and welding. This paper shows in which range of production costs castellated beams will be cost-effective version of load carry-optimized solid beams.

Unrelated to previously mentioned possible cost-effectiveness of castellated beams, they have numerous advantages, such as possibility of setting installation ducts through the web, increase in floor height, increase in illumination of space and unique aesthetic appeal.

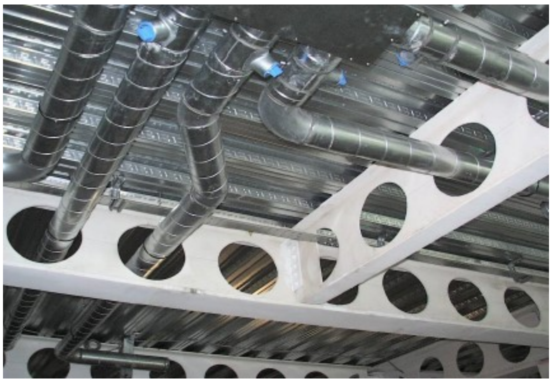

Figure 3. Advantage of web openings

2. LOAD-BEARING MECHANISM AND DESIGN OF CASTELLATED BEAM

Presence of web openings have significant influence on castellated beams so they behave different in comparison to ordinary solid I profiled beams. Because of those openings, application of classic procedures for designing and determining internal forces for linear beams should be questioned. Not only typical types of failures are present but some new types of failure are possible, that are especially characteristic for castellated beams.

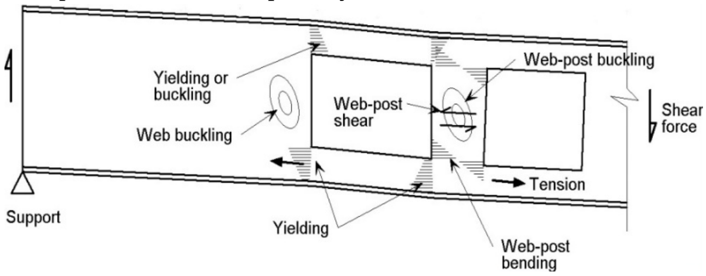

Figure 4. Type of failures

When bending and shear resistance of castellated beams are considered separately, calculation methods are same as for solid beams, therefore, statics should be determined on simple beam, and couple of design checks on characterical cross-sections (cross section on place with opening and without opening) with extreme values should be made

(Figure 5. a) and b)). Bending resistance are typically determined by area of flanges, so that, presence of web opening doesn't have much influence on it and generally all area of web can be neglected. Shear resistance are, mostly, determined by area of web, so web opening presence does have significant influence. It is interesting fact that, although web opening reduce shear resistance of the web, generally when static system of simple beam is consider, "usage" of shear resistance of solid I profiled steel beams does not exceed 30%, hence, that reducement of the area of web represent optimization of cross section in terms of shear resistance.

Ordinal number of calculation	Corresponding I solid profile	Bending resistance efficiency of cross section	Shear resistance efficiency of cross section
1	IPE 200	86%	19%
2	IPE 270	78%	24%
3	IPE 300	90%	31%
4	IPE 360	74%	15%
5	IPE 450	89%	21%
6	IPE 550	82%	22%
7	IPE 500	78%	13%
8	IPE 600	97%	19%
9	HEB 550	92%	24%
10	HEB 500	63%	12%
11	HEB 650	83%	17%
12	HEB 650	65%	11%
13	HEB 900	75%	14%

Table 1. Efficiency of load capacity of I solid profile cross-sections due to applied load

Cross section of castellated beam on place with web opening is generally divided into two "T" sections (upper and lower) and all the resistance are consider as isolated T section. Design bending moment (M_{Ed}) is decomposed on two equal normal forces ($N_{M,Ed}$) with oposit direction so that one of each acts on each T section and then it is compared with normal force resistance of T section ($N_{T,Rd}$). The half of design shear force (V_{Ed}) is assigned to each T section and so it compared to shear resistance of each T part ($V_{T,Rd}$).

It is rare that "global" moment or shear force will cause failure of castellated beams. Very specific failure mechanism, especially for castellated beams, that is more often, is "Vierendeel" mechanism which occurs when there's certain interaction of bending moment and shear force. It is shown that shear force cause additional "secondary" bending moment that can, in extreme case, cause occurrence of four plastic hinges at the corner of openings. This means that T sections are not only loaded on normal and shear force but additional bending moment so T section has interaction of normal and shear force and bending moment. (Figure 5. c))

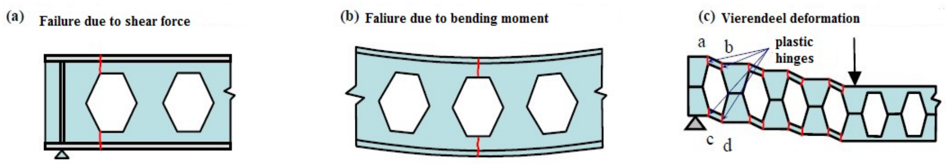

Figure 5.

For beams that are not axially compressed, only global mode of buckling is lateral-torsional buckling. If the beam isn't laterally braced, failure of lateral-buckling will be dominant over other failure mode. Newer experiments [1] shows that there is no difference in behaviour of solid and castellated beams in terms of lateral-torsional buckling. All the calculation for solid beams can be used for castellated beams using reduced cross section (at web opening).

One the other most common type of failure of castellated beams is web post buckling, which is actually type of local buckling mode. Generally, this kind of failure is caused by normal stress distribution in parts of web between openings where one diagonal is compressed, like shown on Figure 6. There is no actual theoretically based formula that describes and calculate this phenomenon but all the solution for securing the beam from faliure is by empirial formulas. Popular theoretical model is strut model (Figure 6.) but more practical one is connecting the bending moment in 3-3 intersection on Figure 7. with web-post buckling using empirial coefficients. Also, design checks on horizontal shear force in intersection 4-4 should be made, where beam is welded.

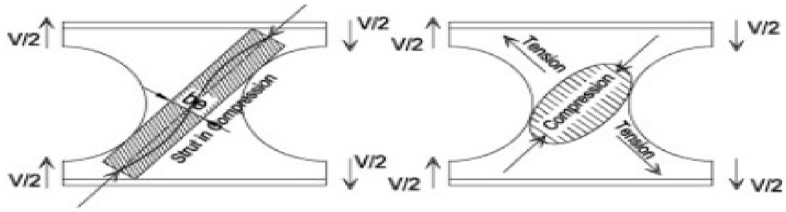

Figure 6. Strut model and actual stress distribution in web between openings

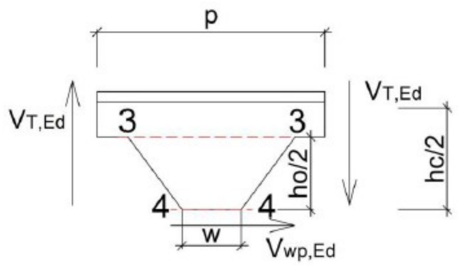

Figure 7. Characteristic intersections of web-post

All types of failures suggest that the best choice of static system for calculating internal forces is not simple beam but Vierendeel truss with rigid nodes (Figure 8.). In the past, engineers used simplifications, due to static indeterminacy, in terms of adding joints in middle of "struts" where bending moment has zero value in "real" rigid Vierendeel truss. Nowadays, problem with static indeterminate systems is overcame with usage of various software for static analysis and there is no real need for such simplification.

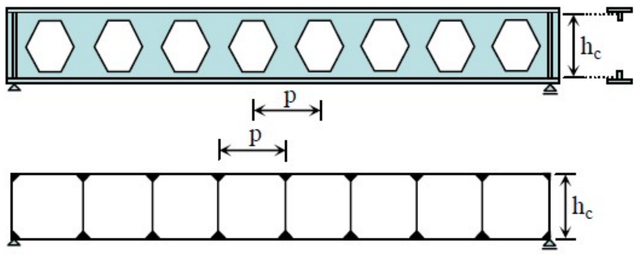

Figure 8. Vierendeel truss

Mistake in selection of static system is often made when castellated beam is considered as a simple beam with characteristic of reduced cross section (on a web opening place). With such consideration many types of important failures are neglected and level of uncertainty is extremely high. Also, the deflection calculation is most accurate when Vierendeel truss is chosen as model. Many softwares use the principal of virtual forces and it is more practical and accurate enough than using finite element method especially in every day engineering practice. Also, it is very important to mention that using static system of simple beam, with reduced cross section charactetics, in deflection calculation gives 10-70% [2] smaller values of deflection which shows that model isn't appropriate.

All the detailed calculation, formulas and geometry recommendation based on principles of Eurocode 3 is given in [3] and are used for purpose of analysis of this paper.

3. CURRENT STANDARDS, DESIGN GUIDEBOOKS AND SOFTWARE FOR DESIGN OF CASTELLATED BEAMS

Taking in consideration various types of failures and complex behavior of castellated beams under the load, it is understandable that is extremely hard to simplify design for engineering practice. Practice demands simple models, which describes, as close as possible, realistic behavior of beam, like classic linear models. Although, castellated beam, on first, look like linear models with constant cross section height, but they can't be modeled as one, because of specifics described in previous chapter. This fact also makes problem to software intended for static analysis and design of steel construction, because they don't take in consideration all the specifics of castellated beams and consider them as a beam with reduced cross section, so the results aren't reliable.

Current and actual standard in Europe (in Bosnia and Herzegovina, Eurocode is still in procces of adoption) for steel constructions is Eurocode 3. It mainly covers design of almost all the steel elements that are used in construction industry but that is not the case with castellated beams, currently. Actually, Eurocode society published 1992. an Annex N in prestandard of Eurocode 3 [4] especially intended for designing and geometry recommendation of the castellated beam but withdraw it with offical version of Eurocode 3 [6] published in 2005. so that design of castellated beam isn't cover by Eurocode until today (January, 2018.). In 2016. European committee for standardization has initiated procedure of creating new part of Eurocode 3 that would be intented for castellated beam design („EN 1993-1-13: Rules for beams with large web openings“) but for now, it is in early stage.

Although design method is not "covered" with actual standards and regulations, it doesn't mean that castellated beams cannot be designed using the principles of Eurocode. For this very reason, design guidebooks that describes design procedures based on Eurocode 3 are popular. One of the most popular guidebook is one published by The Steel Construction Institute (SCI) named "Design of composite beams with large web openings" (populary called "P355") and it is free to download. Even though it's about composite beam it is stated that all the calculation are adjustable to non-composite beams just with neglecting the influence of concrete slab in formulas. Other popular guidebook is published by ArcelorMittal named "ACB-Cellular Beams" which are popular mostly because of ther diagrams for fast choosing appropriate beam for specific load and span. Since the ArcelorMittal is one the worlds biggest producers and sellers of steel elements, this guide book is just valid for their elements, but it can be used for rough estimation of profile size.

Most of the commercial softwares for static analysis and designing of construction elements does not give possibility to calculate and do design check of castellated beams with all of their specifics mentioned in previous chapter. It is clear that software for finite element method give best accuracy but that modeling is time-consumption and inefficent for everday practice. Because of that reason, worlds manufacturers and sellers of castellated beams and other steel elements produced their own software which is specially made for castellated beam design. These software ("ACB+" by ArcelorMittal, "Cellbeam" by Westok and "FBEAM" by Fabsec) offer the most complete design of castellated beam, taking into consideration all possible type of failures. The only flaw of this softwares is that the shape of opening is restricted to circular shape.

4. CALCULATION SET UP AND RESULTS ANALYSIS (TECHNO-ECONOMIC ANALYSIS)

It is obvious that load-bearing capacity of castellated beam is greater than its original beam from which it were made of, and such knowledge, that for certain span and certain load castellated beam has more load-bearing capacity form its original solid I profile which also satisfy mentioned requests, is not of practical benefit. Therefore, it is more convenient to choose castellated beam made from "smaller" profile that meets requirements for mentioned load and span and then compare it to previously mentioned solid beam. Castellated beam has less weight and consequently are more economic in terms of total steel weight but they demand additional cost production. Presence of web openings contribute to better space utilization and that is one of the major advantages which is why engineers decide for their usage. In this paper, economic justification of castellated beams compared to solid I profiled steel beams, in terms of load capacity and serviceability, is analyzed.
Next cases are considered:

- Static system: Simple beam (with lateral bracing)
- Spans: 5 m, 10 m, 15 m, 20 m and 25 m (Allowable deflection: L/200)
- Steel profiles: IPE and HEB
- Steel quality: S235
- Loads:
    - Dead: 5 $\frac{kN}{m}$, 10 $\frac{kN}{m}$ and 15 $\frac{kN}{m}$
    - Live: 5 $\frac{kN}{m}$, 10 $\frac{kN}{m}$ and 15 $\frac{kN}{m}$

	Dead load g [kN/m]	Live load q [kN/m]	Total load for ULS (1.35g+1.5q) [kN/m]	Total load for SLS (1.00g+1.00q) [kN/m]
I Load Case	5	5	14.25	10
II Load Case	10	10	28.5	20
III Load Case	15	15	42.75	30

Table 2. Load cases

Regulated pair of spans and load cases are given below. Each of pair has its own ordinal number.

Ordinal number of calculation	Span [m]	Load case
1	5	I
2	5	II
3	5	III
4	10	I
5	10	II
6	10	III
7	15	I
8	15	II
9	15	III
10	20	I
11	20	II
12	25	I
13	25	II

Table 3. Regulated pairs of span and load cases

Ordinal number of calculation	Span [m]	Load case	Corresponding solid I profile beam	Corresponding castellated beam	Weight of solid profile [kg]	Weight of castellated beam [kg]	Material savings [kg]
1	5	I	IPE 200	IPE 180 (244)	112.00	94.00	18.00
2	5	II	IPE 270	IPE 240 (340)	180.50	153.50	27.00
3	5	III	IPE 300	IPE 270 (379)	211.00	180.50	30.50
4	10	I	IPE 360	IPE 300 (438)	571.00	422.00	149.00
5	10	II	IPE 450	IPE 400 (593)	776.00	663.00	113.00
6	10	III	IPE 550	IPE 500 (768)	1060.00	907.00	153.00
7	15	I	IPE 500	IPE 450 (670)	1360.50	1164.00	196.50
8	15	II	IPE 600	IPE 550 (845)	1830.00	1590.00	240.00
9	15	III	HEB 550	HEB 450 (652)	2985.00	2565.00	420.00
10	20	I	HEB 500	HEB 400 (575)	3740.00	3100.00	640.00
11	20	II	HEB 650	HEB 550 (804)	4500.00	3980.00	520.00
12	25	I	HEB 650	HEB 500 (728)	5625.00	4675.00	950.00
13	25	II	HEB 900	HEB 700(1038)	7275.00	6025.00	1250.00

Table 4. Comparison of solid and castellated beams

Ordinal number of calculation	Weight of solid profile [kg]	Weight of castellated beam [kg]	Material savings [kg]	Percentage [%]
1	112.00	94.00	18.00	16.07
2	180.50	153.50	27.00	14.96
3	211.00	180.50	30.50	14.45
4	571.00	422.00	149.00	26.09
5	776.00	663.00	113.00	14.56
6	1060.00	907.00	153.00	14.43
7	1360.50	1164.00	196.50	14.44
8	1830.00	1590.00	240.00	13.11
9	2985.00	2565.00	420.00	14.07
10	3740.00	3100.00	640.00	17.11
11	4500.00	3980.00	520.00	11.56
12	5625.00	4675.00	950.00	16.89
13	7275.00	6025.00	1250.00	17.18

Table 5. Material savings in percentages

When castellated beams are used instead of solid profiles for same span and load material savings, are, in average, around 15%. Therefore, economic justification, in terms of load capacity and serviceability, will exist only if cost of production of castellated beams (cutting and welding) are in range of costs of material savings. Price of steel elements are billing by weight. Price of production costs are also (because it's more practical) bill by weight of material from which is castellated beam made from. So, as long as production cost (unit price) is less than 15% of unit price of steel, castellated beam will be more economic in terms of load capacity and serviceability.

5. CONCLUSION

Economic justification, in terms of load capacity and serviceability, of castellated beam is only dependent of costs of their production (cost of cutting and welding). If the unit price of production (billed by unit weight of original material) is below 15% of general unit price of steel, castellated beams will be more economic than solid beams that fulfill same load requests.

Such low production cost is very hard to achieve, so economic justification of castellated beam, surely, should be questioned. It is maybe possible for large manufacturers of steel elements to achieve those price but it is sure that is not possible for regular workshops.

Castellated beams have numerous advantages which don't relate to their economic side, such as possibility of ducting the installation through web openings, increase in floor height, aesthetic appeal and many others and so should be used for these advantages.

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