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Studies on Plate Girder with Various Types of Web Plates

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Abstract:- A Plate girder is a composition of plates using rivets or welding. The arrangement of the material steel in this case is more efficient than for a rolled beam section. The design of a plate girder has maximal flexibility and is economical because of the freedom of the designer to choose components according to the requirements. Plate girders carry transverse loads economically for spans long enough to save material and costs. The main objective of the work is to understand the effect of different types of webs in the optimum design of plate girders. A comparative study is carried out between a plate girder with end and intermediate stiffeners and a plate girder with trapezoid web plate as per Indian and European Code provisions. The optimum dimensions of the plate girder are obtained by designing as per Indian Code provisions and European Code provisions. A plate girder offers limitless possibilities for the creativity of the engineer. This study may help the designer to choose components of convenient size for the necessary requirements. The economy of structures is the main goal of the modern building industry. An optimized plate girder in terms of the type of web can help a designer save material, construction weight and thus the overall cost.

Keywords:- European Code, Indian Code, optimum design trapezoid web, plate girder

I. INTRODUCTION

A plate girder is a composition from plates using riveting or welding. The arrangement of the material steel is in this case more efficient than for a rolled beam section. The design of a plate girder is maximally flexible and economical because of the freedom of the designer, to choose components according to the requirements. The engineer has the choice based on the great flexibility in fabrication. The plates can be selected with convenient size however it has to be placed at the focus on the connection between web and flange. Plate girders are a more flexural member. They can carry transverse load which cannot be carried economically from rolled beams. Rolled sections are mostly adequate, except for heavier load and longer spans. The application is efficient for industrial and residential building, up to a span of 45 m. A plate girder has the possibility to have tapered, cranked and haunched girders which makes it economical also in bridges. The depth of the structure can go up to 5 m or more. Common heights are between 1.5 and 2.5 m. A uniform or non- uniform flange along the length can make it even more economical. The economy is the most important fact in the modern building industry. The design of a plate girder offers limitless possibilities up to the creativity of the engineer and hence is more economical. The goal is to reduce weight, material and thus costs.

The components of a plate girder, shown in Figure 1, are following. The main vertical member is the web plate. The major horizontal plate is the flange plate. It is also called cover plate. The flange is connected to the web at the top and bottom and can carry cover plates. Sometimes angle plates are used which connect the web and flange at the top and bottom. Bearing stiffeners, intermediate transverse stiffeners and longitudinal stiffeners are reinforcements for the web and flange. Web and flange splices have the same purpose. They can be attached to the flange to increase the buckling resistance [13, 15].

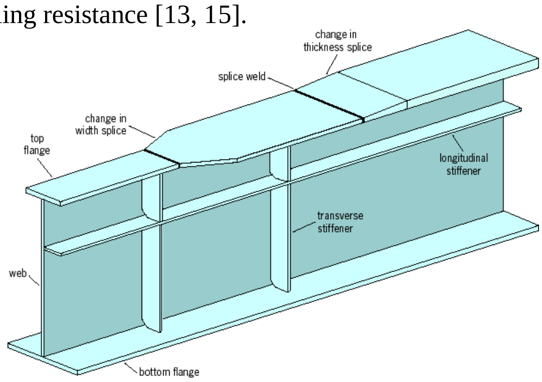

Fig. 1: Elements of a plate girder

A further possibility to improve a plate is to prepare a corrugated web. The corrugated web replaces the flat web with stiffeners. To increase the shear capacity of large steel plate girder, shaped webs may be used. The web plate is cold formed in a shape usually parallel to web depth. This corrugated plate is welded then to the flange. Two main types of corrugation are common. The trapezoid and sinusoidal shape have received the most attention. [13]

II. DESIGN REQUIREMENTS FOR PLATE GIRDER

The general dimensions of a plate girder are fixed based on the optimum behaviour of the girder. This applies to all standards. Guidelines are given for web, flange and if provided also for the stiffeners. The only limits, for the proportions, are the possibilities in manufacturing and transport. The flange of the girder is the major part which resists the moment. Most of the shear stress is carried from the web.

A. Indian Standard Code

The design requirements for a plate girder are stated in section 8 of the Indian Standard Code (IS 800:2007). The section states, if a laterally supported member is a beam or a plate girder, based on the d/t_w ratio, where d is the depth of the section and t_w the thickness of the web, then the critical value is 67ε. If the ratio is less than this, then the section is classified as a beam. The design methodology for beams is to follow. It is not important whether the section consists of plates or a rolled section. If the ratio of the depth and thickness is greater than 67ε then the plate girder is accepted.

The main design provisions are based on the sizing of the section. The depth is chosen in such a way that the flange is able to carry the main part of the bending moment. The other sectional requirements are according to provide an economical girder. The minimum web thickness for the serviceability includes different requirements. These are regarding the use of stiffeners. On the other hand the minimum web thickness has a limit to avoid buckling of the flange. The first criterion is critical until Fe 410. Buckling is critical for higher grades of steel. The requirements for the web and flange are sane. Due to the wide variety of stiffeners there are special provisions to control them, for example the outstand of the flange [13].

B. European Standard Code

The background of the Eurocode program is that 1975 a commission of European community decided to start a program in the field of construction. The objective was to eliminate technical barriers and the harmonization of technical specifications. The European Standard EN 1993, Eurocode 3: Design of steel structures shall give the status of a National Standard for the countries of the National Standard Organization as such Austria, Belgium, Denmark, Finland, France, Germany, Poland, United Kingdom and many other European countries. [20]

Eurocode 3 applies to the design of buildings and civil engineering work in the material steel. The base of the design is given in EN 1990- Basis of structural design. Eurocode 3 is concerned with requirements for resistance, serviceability, durability and fire resistance of steel structures. The basic requirements of EN 1990 should be deemed be satisfied where limit state design is used in conjunction with partial factor method and the load combination. [19]

In this paper is mainly used the En 1993-1-5. This European Code defines design requirements of stiffened and unstiffened plates which are subject to in- plane forces. The effects due to shear, in- plane loads and plate buckling for I- section girder are displayed. These effects shall be taken into account at the ultimate, serviceability or fatigue limit states. [20]

III. COMPARISON OF CODE PROVISIONS FOR PLATE GIRDER WITH END AND INTERMEDIATE STIFFENER

The following problem compares the main design steps of the Indian and European Code provisions, which were used in the studies. Thereby indicate the major differences.

The static system, which was chosen for the calculation, is a plate girder with a span of 36 m carrying a uniformly distributed load and two concentrated loads. Figure 2 illustrates the structure. Therefore the input values, for both calculation as per IS and EN Code, are the same.

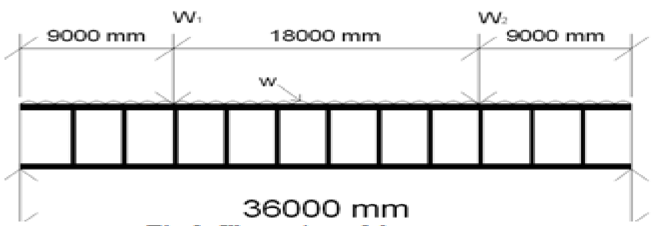

Fig.2: Illustration of the structure

The first difference is that the material and partial safety factors are different from each other. As per IS Code, the material factor for steel is 1.10. A distinction is made between two different material factors in EN Code. It is divided into resistance of cross sections to excessive yield including local buckling and resistance of members to instability assessed by member checks. The values are for the first 1.00 and for the second 1.10. A similar variation enters at the values of the partial safety factors. In the Indian Code the factor for dead and imposed load is given as 1.5. According to the European Code the values for permanent load, dead load, are 1.35 and 1.5 for variable loads as such life load. Therefore is the factor for variable loads equal to IS Code.
A major difference occurs in the provisions for load combinations. The regulations for Indian Standard Code are that the load is multiplied with the safety factor. This procedure is applied for all kinds of loads. The European Standard Code defines a formula for the load combination. The addition of four load categories is basically required. These four categories are permanent loads, leading variable load, prestressing load and other variable loads. The value for the permanent is the sum of all dead loads multiplied with the corresponding partial safety factor. The produced of the corresponding safety factor and the load arising from the prestressing action is the second term. This term is relevant if prestress action is existent in the structure. The next summand is depending on the leading variable load multiplied with the safety factor and the according factor for combination values of the variable action. All these factors are displayed in the EN 1990. The last term is existent if on the system acting more than one variable load. The sum of variable loads multiplied with safety factor as well as the factor for combination form the last summand.

The calculation of the shear force and the bending moment is done with the help of these factors. The formulae for these are according to the normal standards.
The steps below are used for the sizing from web and flange of the plate girder. The description starts with the design as per IS Code and compared this with EN Code provisions. The depth of the web is an important dimension parameter for plate girders. The IS Code calculated for the economical depth *d* by the formula,

$$d = \sqrt[3]{\frac{M \times k}{f_y}} \tag{1}$$

Where M is the applied bending moment, f_y is the characteristic yield stress of steel and k is a coefficient for the economical depth assumed as $200 \times \varepsilon$. The ratio between this coefficient and the depth gives the thickness of the web, afterwards. On the other hand the dimensions of the flange are calculated with the help of the flange area A_f given by,

$$A_f = \frac{M \times \gamma_M}{f_y \times d} \tag{2}$$

The above formula shows the equation for these, where γ_M is the material factor for steel. The assumption, that the flange is a semi- compact section, is necessary to get a maximum resistance for the flange. From this we get the condition,

$$\frac{b_f}{t_f} \leq 13.6 \times \varepsilon \tag{3}$$

In this equation, b_f is the width and t_f is the thickness of the flange. The yield stress ratio is ε. The following steps are carried out to calculate the formula and then it is substituted in the below equation,

$$b_f = \frac{A_f}{t_f} \tag{4}$$

Therefore, the resulting equation is used to solve for the flange thickness. Then the calculation for the flange width with the above formula is calculated.

Variations exist in the European Code compared to IS Code. The first step is to calculate the depth of the web. The factor k in IS conforms the factor λ as per EN which represent the critical slenderness ratio. The rest of the formula (1) is equal. The next value which has to calculate is the thickness of the web. The ratio between the depth of the web and the slenderness generate the thickness. The following step of the procedure, compared to IS Code, is not much different. After finding the solution for the flange area, with the same equation as per Indian Standard, the procedure is continued. This formula based on the assumption that the flange is a cross section of class 1 or 2 as per EN Code provision. The equation for the flange thickness is deduced from the formula (2) and the flange area with maximum outstands.

$$t_f = \sqrt{\frac{A_f}{2 \times 9 \times \varepsilon}} \qquad (5)$$

The equation (4) given for the width of the flange can be used in the EN Code. What follows next is the classification of the section as per EN Code provisions. The requirements from table 5.2, in EN 1993-1-1, are to satisfy for this purpose.

The procedure continues with evidence. The provisions for the codes are varying at this point. For the Indian Code IS 800:2007 the main observations to control the shear buckling of the web. The assumption of the stiffener spacing is therefore a necessary step. If the applied shear force, at the static structure, is lesser than the shear force, corresponding to the web buckling, then the condition is satisfied. In this case, the plate girder does not need stiffeners. When the requirement is not fulfilled, then two investigations are necessary. The plate girder needs intermediate stiffeners and a check for the shear and moment capacity of the end panel.

The investigations corresponding to European Code are the following. It starts with the assumption for the stiffener spacing. The verification which follows is the resistance of the structure against shear. In contrast to the IS Code is in the EN Code the shear contribution for the flange and web a component of the evidence. The sum of both ingredients has to be greater than the shear force of resistance at the supports. The Indian Standard Code compared the buckling resistance of the web alone.

The next major step is the design of the stiffener. In this part of the design are differences noticeable. The computation starts with the end stiffener. The provisions which has to be checked for IS Code are the outstand of the stiffener, the check against buckling and the ability to act as bearing stiffener. According to the IS Code the assumption of the stiffener dimensions are the start for the calculation. The following check of the outstand is required. The limit is between 20 times the product of stiffener thickness into yield stress ratio ε and a minimum of 14 times this product. The buckling resistance as next action has to be greater than the resulting compression force at the plate girder to be safe against buckling. The end stiffener is supposed to be a bearing stiffener. The comparison between bearing capacity of the stiffener and design force of the stiffener has to show that the capacity is bigger. Also the external force is to be reduced with the bearing capacity of the web to calculate the design force.

After the calculation for the end stiffener follows the assumption that the same dimensions from the end stiffener are used for the intermediate stiffeners. The outstand and buckling resistance have to be checked. The same procedure from the end stiffener can be applied here. The design as per IS Code is completed after this step.

Also in European Standard Code is the beginning the calculation for the end stiffener. The first step is the check of the resistance for shear force at the distance 0.5 times the depth from the edge of the end panel. This shear force has to be greater than the axial force for which the stiffener has to be designed for. The base of this evidence is the same as for the buckling resistance evidence in the Indian Standard Code. Unlike in the IS Code follows the calculation for the intermediate stiffeners next in the EN Code.

According to the Eurocode is the coming calculation the dimensioning of the stiffener. The assumption that end and intermediate stiffeners have the same size is also made here. The stiffeners have to act as rigid support for the web panels. To ensure that the effective section of stiffener have a minimum moment of inertia for two different cases which are displayed in the EN 1993-1-5 clause 9.3.3 (3). With the help of a assumed stiffener thickness and the second moment of area is the calculation of the stiffener width possible.

Another evidence for the stiffener is required for the design of plate girder. The out- of- plane buckling resistance of the transverse stiffener under transverse loads are dependent from different regulations which are displayed in EN 1993-1-5. The main comparison between the design buckling resistance according to the chosen dimension and the shear force at the support has to show that the design buckling resistance is greater. For both end and intermediate stiffeners has the shear force to be less.

In the European Code is the last step a check of the torsional buckling of the stiffener. The equation (6) has to be satisfied for this.

$$\frac{I_T}{I_p} \geq 5.3 \times \frac{f_y}{E} \qquad (6)$$

The detailed equations for all the calculations are documented in the respective codes and not within the scope of this paper.

IV. COMPARISON OF CODE PROVISION FOR PLATE GIRDER WITH TRAPEZOID WEB PLATE

To increase the shear capacity of large plate girder may be used shaped web plates. Many types of corrugation are possible, trapezoid and sinusoidal corrugations. In India are not commonly used these kinds of webs for example for highway bridges or industrial buildings. In European countries or Japan is this more the case. The following paragraph represent a comparison between Indian and European Code provisions for the commonly type of corrugation, the trapezoid web.

Plate girder with trapezoid web is a precast element. The study of the corrugated web should be as much realistically as possible. Due to this are the dimensions for the trapezoid web according to the production materials of the company Corrugated Plate Industry BV (Netherland) [16]. The possible standard dimensions are given in the Table 1. These values were used for the calculation for both Indian and European Code.

Table 1: Font Sizes for Papers

company: Corrugated Plate Industry BV			
depth of web	thickness of web	width of flange	thickness of flange
[mm]			
500	3	200	10
625	4	220	12
750	5	240	15
1000	6	260	20
1250	8	280	25
1500	10	300	30
2000		400	35
2500			40
3000			
3500			
4000			

The following Figure 3 shows the geometry of a trapezoid web with the corresponding notations.

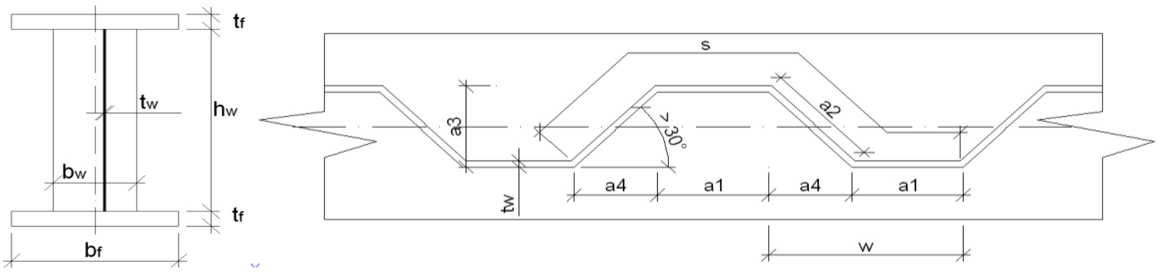

Fig.3: (l) transverse and (r) longitudinal cross section of plate girder with trapezoid web

A. **Indian Standard Code**

The procedure for the design of plate girder with transverse stiffener is described in the paragraph III. The calculations which are given there are the basic for the following considerations. Until the dimensions for the web and flange are calculated the steps are equal to the design of plate girder with stiffeners.

In the code are no specifications given for the calculation for a trapezoid web. The procedure and equations are taken from Subramanian (2008) [13]. The check of the moment capacity of the plate girder is the first difference. The assumption is made that only the flange resists the moment. After this step follows the calculation of the bending strength $M_{d.}$

$$M_d = \frac{z_e \times f_{yf}}{\gamma_{m0}} \tag{7}$$

Where z_e is the elastic section modulus, f_{yf} the characteristic yield stress of the flange material and γ_{m0} the material factor. This value compared with the resulting moment has to be greater. If this case is given then is the flange of the section capable to carry the moment.

The second evidence is to check the capability of the web to carry the shear force. Corrugated webs fail because of local and global buckling. Local buckling is critical for one single panel which is called fold. The global buckling is critical for more than one fold. In the IS Code are two evidence for the shear force necessary. One is norminal shear strength based on local buckling against the shear force at support. The strength has to be greater to get a safe structure. To calculate the norminal shear strength is the procedure from IS 800 clause 8.4

to follow. The difference is given for the calculation of the elastic shear buckling stress of the web. The equation for this value is displayed below as per Subramanian (2008) [13].

$$\tau_{cr.l.el} = k_L \times \left[\frac{\pi^2 \times E}{12 \times (1-\mu^2) \times \left(\frac{w}{t_w}\right)^2} \right] \quad (8)$$

The buckling coefficient k_L has to be calculated. The values for the modulus of elasticity E and Poisson ratio μ are constant and given in the code. The dimension t_w is the thickness of the web. The maximum of the longitudinal fold width and the inclined fold has to be chosen for w. The procedure can be continued normally after this as per IS Code provisions.

The second action is the evidence to check if the norminal shear strength based on global buckling is greater than the resulting shear force. The trapezoid web has an influence on elastic shear buckling stress of the web. The elastic shear buckling stress is given by

$$\tau_{cr.g.el} = k_G \times \left[\frac{{t_w}^{0.5} \times E \times b^{1.5}}{12 \times h^2} \right] \times F(\alpha, \beta) \quad (9)$$

Where k_g is the global buckling coefficient that depends on boundary conditions. The non- dimensional coefficient $F(\alpha,\beta)$ is a value which has to be calculated. After the calculation of stress follows the standard procedure as per IS Code.

The last step which is required for the Indian Standard Code provisions is the check for the necessity of bearing stiffener. This single evidence is given in the code IS 800 clause 8.7.4 and can be conducted as usual. The trapezoid web has no influence at this calculation.

B. **European Standard Code**

In the paragraph III is the design procedure of the European Code compared with IS Code. The following part explains the required steps for the design of a plate girder with trapezoid web plate and compares it with the provisions of Indian Standard Code. The main formulas for this are displayed in the Annex D of Eurocode 3 part 1-5.

The basic system does not differ between both codes. The design is until the sizing of the plate girder equal to a plate web. As per ultimate limit state is the first evidence the moment of resistance which is also carried out in the IS Code procedure. In the EN Code is the main step the calculation for the moment of resistance due to bending. The minimum out of the tension flange, compression flange and compression flange with reduction factor must be found. After the minimum is found out the moment of resistance has to be greater than the moment which results out of the applied uniformly distributed and concentrated loads. This is equal to the other code.

The next step which is similar to the IS Code is the calculation of the shear resistance. This had to exceed the resulting shear force on the plate girder. The relevant equation is

$$V_{Rd} = \chi_c \times \frac{f_{yw}}{\gamma_{M1} \times \sqrt{3}} \times h_w \times t_w \quad (10)$$

Where h_w is the depth of the web, f_{yw} the characteristic yield stress of the web material and γ_{M1} is the partial factor for resistance of members. The reduction factor for buckling is the relevant factor in this formula. Two variations are investigated. The lesser value is required. It is divided into factor for global and local buckling. The equations to find them are given in EN 1993-1-5, Annex D clause D.2.2.

The last provision as per EN Code for plate girder with trapezoid web is the requirement for end stiffener. The Annex refers the section 9 of the EN 1993-1-5. This paragraph is equal to the calculations for the plate web. The evidence is the comparison between design axial force in the stiffener and the resulting shear force at the system.

V. RESULTS AND DISCUSSION

Studies all over the world have indicated that the fatigue strength of girder with corrugated web can be 50 % higher compared to flat webs with stiffeners. The weight could be reduced by 30 to 60 % and have the same capacity. This type of plate girder can archive larger spans with less weight and improve the aesthetic of the structure.

In the paragraph are compared various results between the two codes and the different construction types. The following Table 2 summarizes important results. The comparison can be carried out in several directions. At first consideration can be done between corrugated and plain web plate. The differences between the codes are comparable. This opportunity exists also according to the web type.

Table 2: Results of calculation

parameters		Indian Standard Code		European Code	
		plate web with stiffener	trapezoid web	plate web with stiffener	trapezoid web
Grade of steel	[N/mm²]	250,00	250,00	275,00	275,00
price	[Rs/t]	108,10	108,10	108,10	108,10
resistance moment	[kNm]	12.272,73	22.909,00	22.022,00	22.540,61
resistance shear force	[kN]	2.001,48	6.495,00	3.566,38	4.884,38
depth of web	[mm]	2.400,00	2.500,00	2.820,00	3.000,00
volume per meter	[m³]	0,11	0,05	0,07	0,04
volume for full span	[m³]	3,02	1,83	2,17	1,47
weight per meter	[t]	0,83	0,40	0,58	0,32
weight for full span	[t]	23,73	14,38	17,03	11,51
cost per meter	[Rs]	89,50	43,19	63,20	34,57
cost for full span	[Rs]	2.565,02	1.554,90	1.840,91	1.244,68

The first parameter to compare is the moment of resistance. For this component are the maximum and minimum displayed for the IS Code. The greatest resistance is given for the trapezoid web. Compared to this is the value for the flat web almost 50 % smaller. In the European Code are the results almost similar. The difference amounts around 2 % only. But for both codes has the corrugated web more resistance strength.
Similarity to the moment shows the resistance against shear. The value for the IS Code shows the extremes. The plate girder with stiffeners has the smallest resistance. However the trapezoid web exceeds with circa 70 %. The corrugated plate girder has the greatest shear resistance. In the European Code is recognizable that between plain and trapezoid web 30 % rise is there. Compare to IS Code is the flat web of EN Code almost the half of the shaped web. The webs with corrugation show 25 % difference to each other.

A comparison for the main dimension, the depth, is displayed in Table 2. The variations between the results are small. The depth has a range from 2.40 m until 3.00 m. The IS Code displays smaller values for both types of webs. Unlike to all results the trapezoid web gives greater dimensions than the web with stiffeners. Ti is shown for both codes. The corrugated web according to the calculation of Eurocode 3 produces the highest depth. Plate girders are steel structures which can be compared according to their weight for one meter or for the full span. The results compared to each other are almost equal. It is shown that a 36 m long plate girder can have a weight between 12 until 24 tons. The greatest value is displayed for the plate web of IS Code. The trapezoid web on the other hand has a circa 50 % lower weight. Also the calculation as per European Code provision creates lower values for the shaped web.

Lastly is displayed a comparison between the material cost for this four structure types. The cheapest plate girder can be produced for the trapezoid variations with EN Code. A small value is also given for the shaped web as per IS Code. The cost is determined by the effective of the price in Indian Rupee per ton from October 2012.

VI. CONCLUSION

The results can divide in three groups. The first group builds the resistances. The moment and shear show the same distribution of the results. Extremes are given for the IS Code. The main fact which is shown is that the trapezoid webs are able to carry more forces then the plate webs with stiffeners. A relation to the capacity and the weight is given. The greater capacity not cases a greater weight. Another fact for the EN Code is that the differences between plain and trapezoid web are less. Hence the flat web with stiffener has almost the same effectivity as a corrugated web.

The results for the depth shows a different behavior compared to the other results. The distribution is not similar. The lowest value is displayed for the plain web as per IS Code. The weight is not depending only on the depth. When the depth is less the other dimensions chances according to this and creates still greater volume. The results show that the depths of the plate girder for EN Code are not economical. The limit is 2.50 m. The safety factors make it difficult to be still economical for the calculation as per EN Code.

The trapezoid web gives better results for almost all parameter. This is the main reason for the production of corrugated webs. The reduction in weight and cost can compare with a greater effort in manufacturing. The trapezoid web can show a more effective behavior compared to its boundary conditions. The main reason for a better economy is that weight and cost are depending from each other. The weight increases because of a greater needed capacity then also increases the cost. The cost of the plate girder and the resistance has to require a ratio which makes it economical. In the modern building industry is the economy of a structure the main goal.

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