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Parametric Study on Built-up Plate Girder to Eurocode 3 with Various Beam Span and Steel Grade

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ABSTRACT

This paper presents the parametric study on built-up plate girders with various steel grades and beam spans to investigate the economic aspect of built-up plate girders with truss girders. Commonly the plate girder is designed to carry heavy load over a 20 m span length and different span lengths of the girders will influence the design of plate girders and their self-weight based on the steel grades and span lengths. Therefore, this study is carried out to determine the most economical detail dimensions and the self-weight of the plate girder structure which is based on the constant uniformly distributed loading acting on the variations of span length and steel grades. Plate girders are I-shaped cross-sections with symmetrical flanges. However, the depth of the plate girder is fixed as 1/20 of the span length and allocated to the design requirements. Bending moment resistance, shear buckling resistance for the flanges and web and the torsional buckling and buckling capacity of the stiffeners are checked through Eurocode 3. To evaluate the economic aspect based on the girders' weight, parametric studies were carried out and the results obtained were compared with the truss girder. After that, comparative studies of the self-weight of the plate girders and the truss girder are carried out to study the more economical girder structure in terms of steel weight.

1. Introduction

Plate girders are typically made up of two flange plates welded to a web plate to form an I-section. The primary purpose of the flange plates is to withstand stresses caused by applied bending moments. The main objective of the web plate is to resist the shear forces that are applied. They are also deep built-up flexural members that are used to resist significant bending moments and shear forces over long spans when standard rolled, or composite beams are unable to meet the design requirements [1]. Plate girders are typically used when long spans and heavy loads [2]. In addition, they gained popularity in the late 1800s when they were used to build railroad bridges. In the case of the railway bridge, the plate girder carries the wooden sleepers over which the steel rails are

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fastened. It also will brace the lateral load due to the top flange and the bottom flange, besides cross bracings to resist the lateral load due to wind [3]. Plate girder bridges are used for spans less than 30 meters while box girder bridges are used for continuous spans up to 250 meters. Besides, river crossings and curved interchange ramps are common uses for plate girder bridges with a typical span length of between 150 and 300 feet [4]. Meanwhile, the benefits of using plate girders are numerous, for example, plate girders are expedient transportation, prompt assembly, the ability to withstand higher carrying capacity, higher stability, and longer fatigue life as well they can designed for variation of spans and loading capacities [5]. To make plate girders as light and cost-effective as possible, the web depth must be increased to minimize the required flange area while keeping the web thickness as thin as possible. As a result, the web would be a thin plate. Next, because the web buckling under shear forces is smaller than its capacity, the girder may fail. To prevent web buckling, apply vertical and horizontal stiffeners [1]. Apart from that, except for the maximum stability over the dimensions, designing a plate girder is essentially the same as designing a normal beam: proportioning a component with a section modulus adequate to resist bending, a web capable of resisting shear in the typical method and sufficient stiffness [5]. A plate girder is economical in the construction of a structure on which a repeatedly heavy load is needed to carry for a larger span over 20 m, especially for the road bridge because the depth-to-weight ratio of the girder is relatively high. Different spans of girders will influence the design of plate girders. It can be designed more efficiently by increasing the distance between flanges while keeping the web thickness as thin as possible, but it will be susceptible to shear buckling [6]. To address this problem, the depth-to-thickness ratio of the web can be made small enough and stiffeners are needed. Therefore, research is required to be carried out to obtain the appropriate size of plate girder with various spans and steel grades to achieve an efficient and economical plate girder design. It is also interesting to investigate the steel weight of the plate girders as the beam span and steel grade increase. Optimization is needed in structural design to maximize the efficiency of structural steel yet able to reduce construction costs.

The specific objectives to be achieved for this research study are to develop a design spreadsheet for a built-up plate girder in accordance with BS EN 1993-1-5 [7]; conduct a parametric study on a built-up plate girder with various steel grades and beam spans and study the economic aspect of built-up plate girder with truss girder. Only an I-shaped plate girder will be introduced and considered throughout this study. All the design works will refer to the design code of BS EN 1993-1-1 [8]. In this context, the cross-section classification and geometry properties of the plate girder structure are determined to refer to BS EN 1993-1-1 [8] while the design of the plate girder is in accordance with BS EN 1993-1-5 [7]. However, for this research study, the loading is fixed at 15 kN/m on a span length from 20 m to 50 m with an interval of 5 m as well as with different steel grades of S275, S355 and S450 applied on each span. After that, the design works on the plate girder of each case proceeded to determine the dimensions of the plate girder. Checking for shear and bending resistance of every plate girder is also carried out to ensure a safe and suitable girder structure [9]. At the end of the result, the self-weight of the designed plate girder is calculated and compared with the truss girder of the same condition to determine the most economical structure.

2. Design of Plate Girder

2.1 Types of Plate Girders

Plate girders are fabricated and designed to provide a high strength-to-weight ratio and it is an I-shaped section built-up sections that consist of two flanges and one web plate [10]. Besides, the statement in Clause 4.4 of BS 5950-1 [11] suggests that when the universal beam is inadequate and the bending moment and shear force resistance of the beam capacity to carry large loads over long spans are exceeded, plate girders are recommended [1]. In addition, the plate girders are sometimes also used in building as transfer beams and are usually used in the construction of small to medium-span bridges. Therefore, in the civil engineering construction field, there are a lot of types of plate girders designed and constructed for different purposes. Additionally, there are also different types of connections of plate girders such as riveted or bolted and welded plate girders. the optimum use of material, fabricated section plate girders are more emphasized as it is constructed to support heavier loads over longer spans which will result in the consequence of bending moments exceeding the moment resistance of available rolled sections [7]. Besides, there are six types of a plate girder, for example, welded plate girder, plate girder with cover plate, built-up girder with "T" section, welded box girder, riveted or bolted plate girder and rolled I-section plate girder [10]. However, by the 1950s, welded plate girders became more popular than bolted or riveted plate girders and they are usually prefabricated, and their length is decided depending on the approach of transportation utilized [5]. However, for this research paper, a hot-rolled I-section plate girder will be studied and designed.

2.2 Components of Plate Girder

The main components of a plate girder consist of a web, flanges, and stiffeners. Additionally, the web plate is the vertical plate in the plate girder and its thickness is usually between 8 mm and 15 mm which is known as t_w while its depth, h_w depends on the site condition. Besides, the main function of a web plate is to resist shear applied to the plate girder [4]. Furthermore, it is stated in BS 5950-1 [11] that the recommended span-to-depth ratio for plate girders is used for different applications for the building. In BS 5950-1 [11], it tabulates that if the constant depth beams are used in simply supported composite and non-composite girders with concrete decking, its span-to-depth ratio is between 12 and 20, while for the second condition if the constant depth beams are used in continuous composite and non-composite girders, its ratio is in between 15 and 15, then for the third condition, if there are simply-supported crane girders, its span-to-depth ratio is between 10 and 15 [1]. The flange components are the horizontal elements in a plate girder structure which consist of two where one of them located at the top while another is placed at the bottom and they are separated by a web plate. The function of the top flange is to resist the bending moment in compression while the bottom flange is to resist the tensile force [4]. In the determination of the thickness of the flange, t_f, the thickness is about 1/12 to 1/8 of its span length and it is limited to 100 mm, while the flange width, b_f should not exceed 1 m [5]. Apart from that, according to BS EN 1993-1-1 [8], the thickness of the flange, t_f is normally between 40 mm and 63 mm for every steel grade, but for different steel grades, its yield strength will be different. Apart from the determination of dimensions of web plate and flanges of plate girders, classification of cross-section also known as maximum depth to thickness ratio (c/t) must be carried out to ensure that the plate girder is under the limitation in which the structure exceeds the Class 3 section [7]. Apart from the web plate and flanges, stiffeners are also provided in the plate girders, and it is usually located at the web plate. There are two types of stiffeners which are longitudinal and transverse web stiffeners [12]. According to BS 5950-1 [11], it states that stiffeners are usually in compression to prevent local buckling [1]. Other than that, transverse stiffeners are provided perpendicular to the flange to ensure the satisfactory performance of the web plate of plate girders, and it is classified into two types which are intermediate transverse stiffeners and bearing stiffeners. For bearing stiffener also known as a load-bearing stiffener, this stiffener is used to prevent local failure of the web under concentrated loads applied on the flange and it also acts as a rigid end post which is required to resist anchorage force [4]. Moreover, BS EN 1993-1-5 [7] suggests that a bearing stiffener is required to provide at the end support of the plate girder which the web is susceptible to web buckling and it can also be placed at any location of the concentrated loads if the resistance of the unstiffened web is exceeded. For intermediate transverse stiffeners, these stiffeners are provided to enhance the resistance to shear near the supports [4]. Th the same time, intermediate transverse stiffeners are required to increase elastic shear buckling resistance and ultimate shear buckling resistance of the slender web. Intermediate transverse stiffeners are spaced where the web plate aspect ratio is between 1.0 and 2.0 while sometimes these stiffeners are placed at the end supports to create a rigid end post. By determining the minimum second moment of area, it can control the lateral deflection of the web plate and the effective cross-section stiffener is also needed to be designed to withstand compressive axial force, P_{Ed} and these compressive axial forces are acting on the mid-plane of the web plate [7]. Besides, longitudinal stiffeners are needed with the addition of transverse stiffeners if the web thickness does not satisfy the limitations for the minimum thickness of the web. These stiffeners are located 2/5 of the compression flange from the neutral axis and consist of two types of longitudinal stiffeners which are continuous or discontinuous [13]. However, longitudinal stiffeners are rarely provided in plate girder use in building structures [14].

2.3 Bending Resistance of Plate Girder

The plate girder must be designed to ensure that its structure can resist bending and avoid the phenomenon of vertical buckling of the compressed flange into the web to be occurred [15,16]. For the first condition which is known as a low shear condition where the V_{Ed} is less than 50 % of $V_{pl,Rd}$, shear buckling will not occur, hence the structure will only need to be designed to withstand bending moment capacity by using the normal method stated in BS EN 1993-1-1 [8] depending on the classification of the cross-section based on the flange strength either using plastic section modulus, W_{pl} or elastic section modulus, W_{el}. Then, for the second condition (high shear condition), it is where the V_{Ed} is more than 50 % of $V_{pl,Rd}$, the "flange only" method is introduced but according to BS EN1993-1-5 [7], the "effective width method" is utilized [17]. In this condition, the web plate is designed to carry only shear but no moment, while the flanges will take all the bending moment resistance, $M_{f,Rd}$ if the flanges are not classified as Class 4 section. Next, for the third condition where the V_{Ed} is more than 50 % of $V_{pl,Rd}$ and maximum apply bending moment, M_{Ed} is less than bending moment resistance, M_{Rd}. The plate girder structure will experience shear and bending action and thus bending moment resistance is equal to $M_{f,Rd}$ plus the web designed for moment and shear (moment in web) [1,8].

2.4 Shear Resistance of Plate Girder

In discussing the shear resistance of plate girder, the shear strength applied on plate girder is a function of web slenderness ratio and aspect ratio which web depth, h_w over the thickness of the web, t_w. But, if the web of the plate girder is under high shear conditions, the plane will incline with respect to the longitudinal axis of the plate girder structure, hence, the principal stress will be in diagonal tension or compression [5]. Beyond that, when the web is susceptible to shear buckling, it will occur in three successively stages where stage 1 of pure shear, stage 2 of post-buckling and stage 3 which is the collapse mechanism. While for $V_{bf,\ Rd}$, the flange contribution to shear buckling resistance is affected by the flange width, b_f and it should not be taken greater than $15\varepsilon t_f$ and bending moment resistance of flange $M_{f,Rd}$ depends on the effective cross-section if the flange is under Class 4 slender section as well as the width of the tension band, c. However, the verification of shear resistance must be checked to ensure that it is always less than 1.0 [14].

2.5 Panels with Openings

In accordance with Clause 4.4.5.5 BS 5950-1 [11], web panels with openings are usually provided in the plate girders constructed for the building for service ducts. the length and width of the openings must be less than or equal to 10 % of the smaller web panel dimensions [1]. Other than that, there is a limitation for the determination of the dimension of the openings which referred to design rules stated in BS EN 1993-1-5 [7] by using effective width when the diameter of the openings is greater than 5% of the minimum dimension of the web panel [14,18].

3. Parametric and Comparative Study of Plate Girder

This study consisted of three key activities; development of a Microsoft Excel Spreadsheet, parametric study with variations spans and steel grades and comparative study of self-weight. There are three main contents in the development of Microsoft Excel Spreadsheet, which are the determination of geometry, determination of load and design of plate girder. For the geometry determination, assumed that the application of the plate girder used as constant depth beams used in simply supported composite and non-composite girders with concrete decking, hence, for this research study, the span-to-depth is fixed at 20 [1]. The spacing between the transverse stiffener, a is obtained by web plate aspect ratio, a/h_w with the ratio of 1.5 throughout this study. Then, the shear force diagram is drawn manually to determine the maximum shear force as well as the force and spacing of every stiffener along the span. However, the web thickness, t_w is calculated by the ratio of the flange to web thickness equal to 4 and always make sure that the web is classified as Class 4 where the ratio of web depth, h_w to web thickness, t_w must be larger than 124ε. Next, the thickness of the flange is then determined from the flange area while the width of the flange is also obtained from 0.3 h_w. After that, the classification of the cross-sections will be done and the cross-section must exceed Class 3 according to BS EN 1993-1-1 [8]. For web, the width-to-thickness ratio (c_w / t_w) must be larger than 124ε, while for flange, the maximum width-to-thickness ratio (c_f / t_f) must be limited to between Class 1 to 3. The next step is although the web thickness determined fulfilled the limitations of the classification of the cross-section, it also needed to be checked to avoid serviceability problems and prevent the flanges from buckling into the web according to Clause 8(1) BS EN 1993-1-5 [7].

For this study, the loading applied is uniformly distributed throughout the plate girder and it is fixed at 15 kN/m including the dead and live load calculated from EN 1991-1-1 [19]. Meanwhile, a similar uniform distributed load will also be applied on the truss girder with the same steel grade and span length for the comparison of the self-weight between them. Additionally, since the web is susceptible to shear buckling and the cross-section is classified as Class 4, the bending moment is resisted by the flanges alone which are known as $M_{f,Rd}$. In this context, there are five components in obtaining the flange moment resistance, $M_{f,Rd}$ which is the yield strength of the flange, f_{yf}, the width of the flange, b_f, flange thickness, t_f, web depth, h_w and partial factor γ_{M0} value of 1.0. The following step is checking for shear buckling resistance of the plate girder structure. Since the loading applied on the plate girder structure is uniformly distributed, therefore the maximum shear force, V_{Ed} the critical zone is at the beam end. In accordance with Clause 5.2 (1) of BS EN 1993-1-5 [7], the shear buckling resistance, $V_{b,Rd}$ is calculated from the summation of the contribution of the web, $V_{bw,Rd}$ and the flange contribution, $V_{bf,Rd}$ from Clause 5.2 (1) and 5.4 (1) BS EN 1993-1-5 [7]. Since the shear is only carried by the web, hence the shear resistance only considered the contribution of the web, $V_{bw,Rd}$. After that, for the stiffener design, the addition of $15\varepsilon t_w$ must be added as an effective web width. the stiffeners also need to be checked for their buckling resistance, $N_{b,Rd}$ according to Clause

6.3.1.1 (3) of BS EN 1993-1-1 [8]. Intermediate transverse stiffeners should have sufficient buckling resistance to withstand the compressive axial force which arises from the tension field action, P_{Ed} as stated in BS EN 1993-1-5 [7].

3.1 Parametric Study with Variations Spans and Steel Grades

For this study, the hot-rolled I-shaped steel structure will be introduced to use for the plate girder design because the hot-rolled steel section comprises high yield and undamaged coating as well as I-shape steel highly efficient to resist flexure and compression. Therefore, the spanning of the plate girder is designed between 20 m to 50 m with increments of 5 m. Such as spanning 20 m, 25 m, 30 m, 35 m, 40 m, 45 m and 50 m. Each of the span lengths is loaded with the same uniform loading of 15 kN/m. In addition, three different steel grades of S275, S355 and S450 will also be applied to each condition to observe which steel grade will contribute to the more economical girder structure in terms of their self-weight. A sample of the modelling of the plate girder structure is drawn. The side view of the I-shaped plate girder structure for every span length, L (mm) of the plate girder structure is modelled with the uniform load distribution, w (kN/m) which is 15 kN/m will also be shown. Additionally, the transverse stiffener spacing, a (mm) will also be established in the plate girder model structure. Then, the model is assembled with the labelling of dimensions of span length and stiffener spacing as shown in Figure 1. Based on the design parameters tabulated above, there will be 21 plate girder structures are needed to be designed.

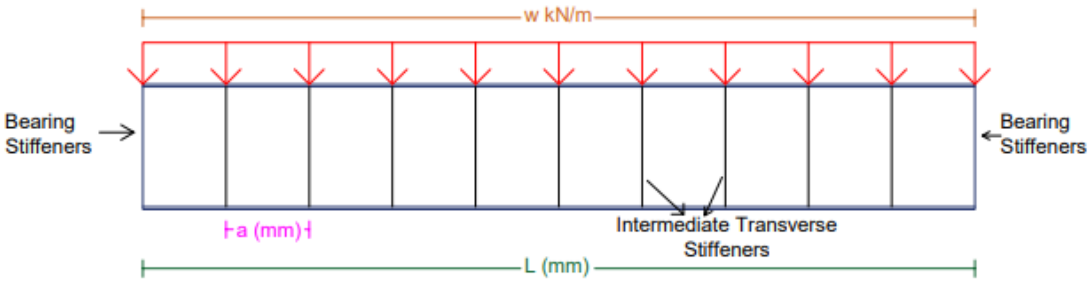

Fig. 1. Sample modelling of the side view of the plate girder

3.2 Comparative Study of Self-weight

Once all the designs of the plate girders are determined and satisfied all the design criteria [7][8], then the self-weight for all the cases is computed. Self-weight of the plate girder is based on the density of steel which is 7850 kg/m^3 as stated in EN 1993-1-1 [8]. After that, the self-weight of the plate girder is then compared with the truss girder of the same condition. The results of the comparison are then tabulated and discussed. Based on the self-weight of the plate and truss girder, the analysis of the economic aspect which only considered the self-weight can be done.

4. Results

The results of the development of the Microsoft Excel Spreadsheet in determining the final detail dimensions and the self-weight of the plate girder are tabulated and discussed later. In addition, one of the examples of the calculations where how the spreadsheet worked to get the final plate girder and stiffener sizing for each condition is shown below. Besides, the results of the self-weight of the truss girder are also obtained and organized and then the discussion on the comparative study of the self-weight between the plate girder and truss girder is presented later.

4.1 Comparison Between Different Steel Grades and Span Lengths

From the tabulated results of the dimensions of the flange, web, bearing and intermediate transverse stiffeners, it can be observed that when the steel grade is higher, the strength of the steel is stronger and the resistance of the plate girder will increase significantly, therefore, the smaller dimensions of the plate girder are required to support the girder from failure for the same span length. However, when the span length increases, the dimensions of the plate girder will increase because when the span length is longer, the girder structure will be slenderer and more prone to failure, hence, larger dimensions of the flange and web are needed to assist the structure to support the bending and shear reaction applied to it. From the analysis, it can be determined that the sizing of intermediate stiffeners is 2 or 3 times smaller than the bearing stiffeners and when the span length and the steel grade rise, the dimensions of the bearing and intermediate stiffeners will also increase. This is because when the higher steel grade is utilized, the dimensions of the girder are relatively smaller than the smaller steel grade, hence, a larger size of the stiffeners is required to assist the whole girder structure from buckling failure and vice versa. Besides, when the span length increases, the dimensions of the stiffeners will also get larger so that the longer girder is more stable with the presence of the larger sizing stiffeners. After determining the dimensions of the plate girder and the stiffeners as well as the spacing of the stiffeners, the area of the girder and stiffener are then calculated and tabulated as shown in Table 1. From the results, it can be observed that the stronger the steel strength of the plate girder, the lighter the total self-weight of the structure and the longer the span length, the heavier the total self-weight of the girder structure. However, the range of the total self-weight of the plate girder is 1.60 tonnes and 38.08 tonnes. Lastly, from the overall calculated self-weight, the plate girder of 20 m span length with steel grade S450 is the lightest girder and the plate girder of 50 m span length with steel grade S275 is the heaviest girder.

Table 1
Total self-weight of the plate girders and the weight increment ratio with respect to a span length of 20 m

Span length (m)	Steel grade	Girder area (m^2)	Girder weight (kg)	Stiffener area (m^2)	Stiffener weight (kg)	Total self-weight (kg)
20	S275	0.015	2339	0.009	68	2408
	S355	0.012	1821	0.013	100	1922
	S450	0.009	1460	0.018	141	1601
25	S275	0.025	4882	0.018	175	5057
	S355	0.019	3778	0.021	206	3984
	S450	0.015	2993	0.028	273	3266
30	S275	0.037	8796	0.025	295	9090
	S355	0.029	6818	0.029	338	7155
	S450	0.023	5405	0.041	481	5886
35	S275	0.048	13222	0.033	460	13682
	S355	0.037	10289	0.042	576	10866
	S450	0.030	8126	0.056	775	8901
40	S275	0.060	18903	0.047	744	19647
	S355	0.046	14570	0.058	904	15474
	S450	0.036	11430	0.075	1174	12604
45	S275	0.073	25831	0.058	1031	26863
	S355	0.057	20029	0.075	1329	21358
	S450	0.045	15737	0.095	1683	17420
50	S275	0.094	36699	0.071	1385	38084
	S355	0.073	28554	0.090	1756	30311
	S450	0.058	22569	0.118	2320	24889

4.2 Comparative Study of The Self-weight Between Plate Girder and Truss Girder

In this context, the plate girders and truss girders are designed based on the optimum size that satisfies both ULS and SLS using the trial-and-error method and then their weight is calculated. However, Table 2 displays the self-weight of the plate and truss girder and the ratio. The loading applied on the plate girder and truss girder is fixed at a uniformly distributed loading of 15 kN/m, the span length is also the same which utilizes span lengths of 20 m, 25 m, 30 m, 35 m, 40 m, 45 m and 50 m as well as three different steel grades of S275, S355 and S450. However, the results of the self-weight of the truss girder are obtained from another thesis [20]. From the comparative results, it can be declared that the self-weight of the plate girder is heavier than the truss girder and the range of the self-weight of the plate girder is between 1601 kg and 38084 kg while the range of the self-weight of the truss girder is only between 1168 kg and 9209 kg which is relatively heavier than a truss girder. When comparing the self-weight of the plate girder to the truss girder, the ratio of the plate girder self-weight to the truss girder self-weight is greater than 1.0. This means that the plate girder is heavier than the truss girder. Then, if the self-weight is larger, it means that the structure is not economical as the construction cost will increase as the construction cost is influenced by the self-weight of the girder structure.

Table 2
Table shows the comparison of the self-weight of plate girder and truss girder with their ratio

Span Length (m)	Steel Grade	SELF-WEIGHT {tonne)		
		Plate Girder	Truss Girder	Ratio between plate to truss girder
20 m	S275	2.408	1.247	1.93
	S355	1.922	1.168	1.65
	S450	1.601	1.168	1.37
25 m	S275	5.057	2.092	2.42
	S355	3.984	1.986	2.01
	S450	3.266	1.986	1.64
30 m	S275	9.090	3.075	2.96
	S355	7.155	2.823	2.53
	S450	5.886	2.823	2.09
35 m	S275	13.682	4.167	3.28
	S355	10.866	3.946	2.75
	S450	8.901	3.946	2.26
40 m	S275	19.647	5.168	3.80
	S355	15.474	5.115	3.03
	S450	12.604	5.055	2.49
45 m	S275	26.863	6.953	3.86
	S355	21.358	6.574	3.25
	S450	17.420	6.574	2.65
50 m	S275	38.084	9.209	4.14
	S355	30.311	8.455	3.59
	S450	24.889	8.330	2.99

5. Conclusions

This study concludes that the truss girder is more economical compared to the plate girder based on the steel weight. The findings conforming to the objectives of this study can be summarized below:

i. A parametric study of the built-up plate girder with the variations of the beam spans and the steel grades is carried out. A relationship between the beam spans and the steel grades with the self-weight of the plate girder is established. The increases of the beam spans require larger sizing and heavier plate girder while the increases of the steel grades, the smaller sizing and lighter plate girder are needed to support the structure. However, the self-weight of the plate girder falls between 2 to 38 tonnes.

ii. In the economic aspect of the plate girder compared to the truss girder which considers their self-weight only, the plate girder is relatively heavier than the truss girder where the ratio of the weight of the plate to truss girder is always greater than 1.0. However, the plate girder and truss girder have their priority during the selection of the structure when different economic aspects are considered.

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