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Optimum Span Length for Steel Composite Girder Expressway Bridges

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Abstract

This study presents the determination of optimum span length of steel composite girder bridges for expressways. Using a case study plate girder bridge, the cost curves for superstructure and substructure were developed for different span arrangements to find the most economical design case. The optimization is carried out for various parameters governing the girder design (web depth and balanced span arrangements). The case study bridge is designed for a span lengths ranging between 25 m and 50 m, and by varying the number of girders (3, 4 and 5 girders). The optimum spans in terms of economy are compared for two different shapes of girders (i.e. with constant depth of web and with tapered web). It is observed that tapering the girder web leads to 6%-10% reduction in weight of the girder while reducing the total cost of bridge by 8%-10% compared to the case corresponding to constant-depth web. Similarly, a significant reduction in overall cost can be achieved by reducing the number of girders in a cross-section using a similar optimization scheme. For the selected case study bridge, the three-girder case resulted in approximately 20% lower girder weight compared to four-girder case. The most economical span length is observed to be within 40m and 42m for three-girder system.

Keywords

Optimum span length, steel plate girder, tappered web, economical span, expressway bridges

1. Introduction

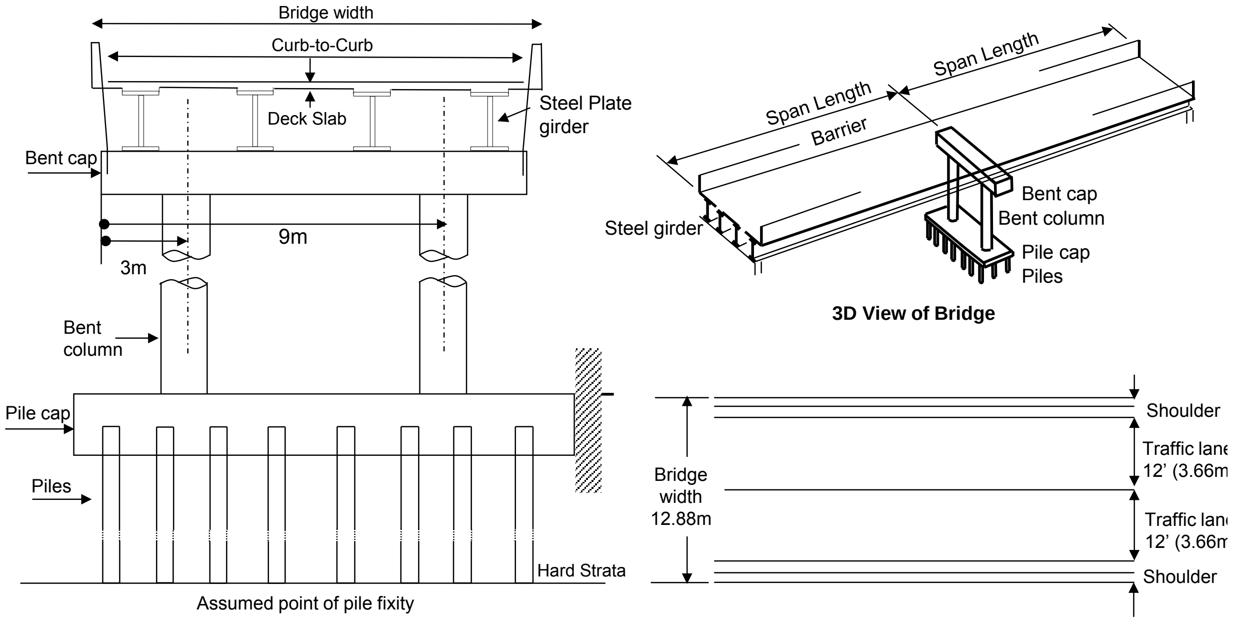
Plate girders are generally used for large spans and are constructed by riveting or welding the plates to an I-section. Since they are constructed using plates, they can be fabricated or tailor made to suit any design loads. This, in a way, offers greater freedom and convenience to the designer to choose from various sections of the plates available in the market. The optimal design of plate girders is governed by serviceability, flexural strength, shear strength and above all, the weight of the structure. The optimization of steel structures can thus be formulated as a weight minimization problem keeping in view the serviceability, flexural and shear strength aspects as suggested by the design codes. The plate girders comprise primarily of two flange plates and one web plate. The plates with different discrete thicknesses are available in the market. The designer is thus required to select the most appropriate size of the plates which will satisfy the design code provisions, while keeping the overall weight of the structure to minimum.

One of the effective techniques to achieve cost effectiveness and reduction in self-weight is the use of tapered (varying depth) web in plate girders (Limaye & Alandkar, 2013). Historically, the plate girders were fabricated by riveting or bolting, however nowadays it is possible to have welded plate girders. With welding, it is now possible to have various forms of web to construct tapered, cranked, and hunched girders. In order to achieve design optimization, web-tapered members can be shaped to provide the maximum strength and stiffness with the minimum weight.

This study aims to determine the optimum span of steel composite girder bridge for expressways in relation with minimum weight using AASHTO LRFD 2010 standard (AASHTO, 2010). Using a case study steel composite girder bridge, an economic comparison between different design cases (span lengths, constant/tapered web etc.) is conducted. The cost curves for both superstructure and substructure are developed for a series of preliminary designs and for different span arrangements. A parametric study is conducted by varying different design parameters to identify the case with minimum weight and with least cost.

2. Description of Case Study Bridge

A case study steel composite girder bridge is selected for detailed analysis, design and cost comparison. The section, 3D view and plan of the selected bridge are shown in Figure 1. It has two lanes with a total length of 1000 m (1 km) and a total width of 12.88 m. The thickness of deck slab is 250 mm. The bent cap is supported by two bent columns with a height of 9 m. The superstructure is supported by pile foundations (as shown in Figure 1) with a pile depth of 16 m. The average daily truck traffic (ADTT $_{SL}$) of 3000 is used for the design.



Cross-section of Bridge

3D View of Bridge

Plan View of Bridge

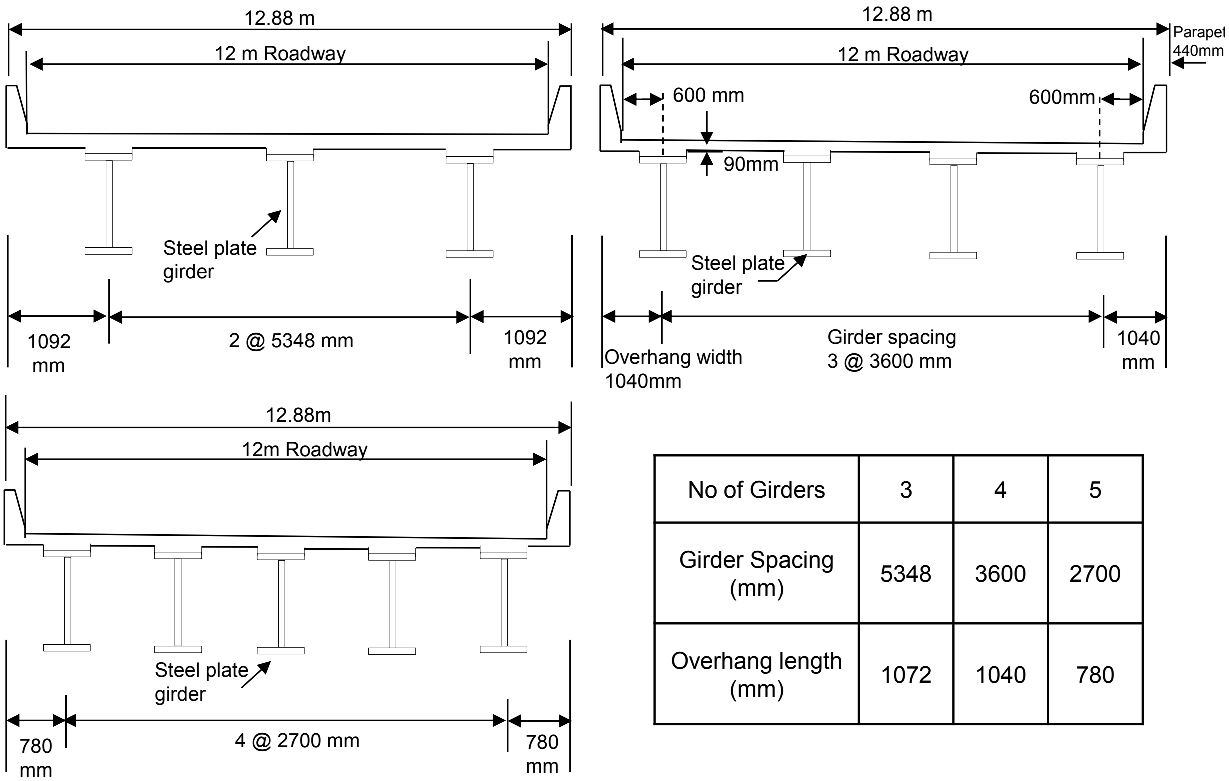
Figure 1: The section, 3D view and plan of the selected case study bridge

In this study, five different span lengths (i.e. 25 m, 30 m, 35 m, 40 m, 45 m and 50 m) of the case study bridge is considered. Similarly, the number of supporting girders is also varied to 3, 4 and 5, resulting in different design cases. For web design, the plate thicknesses of 13 mm, 14 mm, 15 mm, 16 mm, 17 mm and 18 mm are considered (AISC, 2010). For the design of web, the web depth may vary from 0.96 m to 1.90 m for Case 1 (constant web) while for Case 2 (tapered web), it can vary from 1 m to 1.8 m. The flange area is selected for each case as per the design requirement. The vertical intermediate stiffeners are also used in the design of girders. The design is carried out according to AASHTO LRFD design standard (AASHTO, 2010). No seismic and wind load effects are considered in the design.

3. Methodology and Design Procedure

The overall methodology can be described under the following steps.

a) Setting the span length (25 – 50 m with 5 m increment), number of girders (3, 4 and 5 girders) and the web type (Case 1: constant web, and Case 2: tapered web). Figure 2 shows the cross-section of bridge cases with 3, 4 and 5 girders.
b) Selecting a trial plate girder section
c) Separately analyzing and designing the superstructure of the bridge for each case. The design variables are the dimensions which determine the geometry of the optimized girders and control the overall cross-sectional area. These include,
    - Top flange width and thickness
    - Web height and thickness
    - Bottom flange width and thickness
d) Performing the cost estimation for superstructure for each case
e) Designing the substructure for each design case
f) Performing cost estimation for substructure and developing cost curves for both the superstructure and substructure for each case of span arrangement and web type
g) Identifying the optimum span for each design case. The point at which the superstructure cost curve intersects with the substructure cost curve is the optimum span of the bridge.



No of Girders	3	4	5
Girder Spacing (mm)	5348	3600	2700
Overhang length (mm)	1072	1040	780

Figure 2: The cross-section of case study bridge with 3, 4 and 5 number of supporting girders

The detailed three-dimensional finite element models were constructed for all combinations of cases and were analyzed (CSI, 2015). Figure 3 shows the FE models for both cases of web type considered in this study (i.e. constant web and tapered web). The bridge is assumed to be simply supported at the base of bent columns. The design calculations were carried out for all considered variables. Table 1 shows the range of variables considered for the design of steel girders.

Table 1: The range of variables for steel girders

Variable Elements	Geometric Constraints	Ranges (mm)	
		Case 1	Case 2
Flange Width (b_f)	$b_f \geq$ 12” $b_f \geq D/5$ (Deep section) $b_f \geq D/6$(Shallow section)	305 – 432 mm	305- 495 mm
Flange Thickness (t_f)	$¾ \leq t_f \leq 4$	19 – 70 mm	19-38 mm
Web depth (d_w)	Straight $D \geq L/30$ $D/t_w \leq 150$ for web w/o longitudinal stiffeners	962-1923 mm	1000-1800 mm
Web Thickness (t_w)	½” (minimum)	13-18 mm	13-18 mm

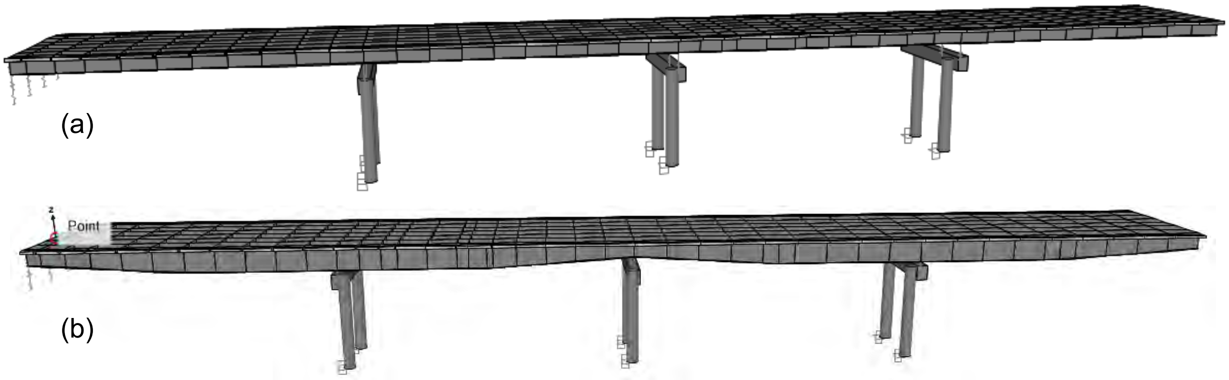


Figure 3: The 3D finite element models of the girder section with (a) uniform web, and (b) tapered web

After the design, the cost analysis was performed for each case by considering the unit cost of materials. The cost estimation was performed for each span and separately for both superstructure and substructure. The following three components of cost were included in the analysis in this study.

a) Basic cost of the material involved in construction/fabrication of the structure
b) Placement/ launching at the designated location of the structure
c) Finishing cost of the structure

4. Results and Discussion

Tables 2 and 3 show the design results in terms of final cross-sections of girders for all spans for Case 1 and 2, respectively. It can be seen that as the span length increases from 25 m to 50 m, the corresponding depths of girders increase from 962 mm to 1923 mm. The depth of a girder is often limited in industries due to headroom constraints and house service requirements. In this study, the girder depth is increased for six different span lengths and for different number of girders in order to evaluate the effect of changing web depths. The results reveal that the total weight of the girders is increasing constantly and gradually for a web depth ranged from 962 mm to 1923 mm. The result is predictable since it is reasonable to expect an increase in the depth of the plate girder, which would consequently increase the volume of the steel used and therefore a rise in the total steel weight.

Table 2: Cross-section of girders for different spans – Case 1

Plate Dimension Table											
			Variables (mm)								
No of girders	Span Length (m)	Width (mm)	Flange width (mm)	Top Flange Thickness (mm)			Bot Flange Thickness (mm)			Web height (mm)	Web thickness (mm)
				G1	G2	G3	G1	G2	G3		
3	25	12.88	305	19	38		22	41		962	13
	30	12.88	305	19	38		22	41		1300	14
	35	12.88	330	19	34	51	22	37	54	1500	15
	40	12.88	356	22	38	51	25	41	54	1539	16
	45	12.88	406	22	44	64	25	47	67	1731	17
	50	12.88	432	25	48	64	28	51	70	1923	18
4	25	12.88	305	19	38		22	41		926	13
	30	12.88	305	19	38		22	41		1118	14
	35	12.88	318	19	34	51	22	37	54	1296	15
	40	12.88	356	22	38	51	25	41	54	1482	16
	45	12.88	393	22	44	64	25	47	67	1667	17
	50	12.88	419	25	48	64	28	51	70	1852	18
5	25	12.88	305	19	38		22	41		893	13
	30	12.88	305	19	38		22	41		1072	14
	35	12.88	308	19	34	51	22	37	54	1250	15
	40	12.88	356	22	38	51	25	41	54	1429	16
	45	12.88	381	22	44	64	25	47	67	1607	17
	50	12.88	407	25	48	64	28	51	70	1786	18

The design of web design can also have a significant impact on the overall cost of a plate girder. From the standpoint of material costs, it is usually desirable to make girder webs as thin as design considerations will permit. However, this may not always result in the least cost solution since fabricating and installing stiffeners and shop operations may also affect the overall cost due to labor-intensive nature of work. Furthermore, as the web depth increases, it becomes more vulnerable to shear buckling. Consequently, it is necessary to increase the web thickness to satisfy the web buckling requirements. It can be seen that by increasing the span length, the depth of the web also increases in order to satisfy the upper limit constraint of the span-to-depth ratio. Moreover, the increase in the dimensions of both depth and width also requires a proportional increase in the thickness, resulting in an overall increase in the weight of the structure.

The optimum span arrangement can be determined by comparing the cost curves for superstructure, substructure and total structure for each span length considered in this study. It is obvious that the total weight of the steel girder increases proportionally with the span length. Similarly, with increase in the number of girder systems, the total required weight also increases, resulting in an increased total cost of superstructure. Figure 4 shows the overall cost comparison (per meter of both superstructure and substructure) for different span lengths of both cases (i.e. constant web and tapered web). The intersection point between the cost curves of superstructure and substructure is the optimal span length. It can be seen that by increasing the number of girders, the intersection point is shifted towards the higher span length. Table 4 shows the optimum span lengths for three-girder, four-girder and five-girder systems. The optimum span was found to be around 40 m with 3 girders at 5.34 m spacing. In 4-girder case, the optimum span lies between 40 m and 45 m with 3.6 m spacing. In 5-girder case, the optimum span was found to be within a range of 45 m to 50 m with a spacing of 2.7 m.

Table 3: Cross-section of girders for different spans – Case 2

Number of Girders	Web Height (mm)	Span Length (m)	Thickness of web (mm)	Flange Width (mm)	Flange Thickness (mm)
3	1 m at crown 1.8 m at support	25	13	305	19
		30	14	305	19
		35	15	330	22
		40	16	394	28
		45	17	438	32
		50	18	495	38
4	1 m at crown 1.8 m at support	25	13	305	19
		30	14	305	19
		35	15	330	22
		40	16	394	28
		45	17	438	32
		50	18	495	38
5	1 m at crown 1.6 m at support	25	13	305	19
		30	14	305	19
		35	15	330	22
		40	16	394	28
		45	17	438	32
		50	18	495	38

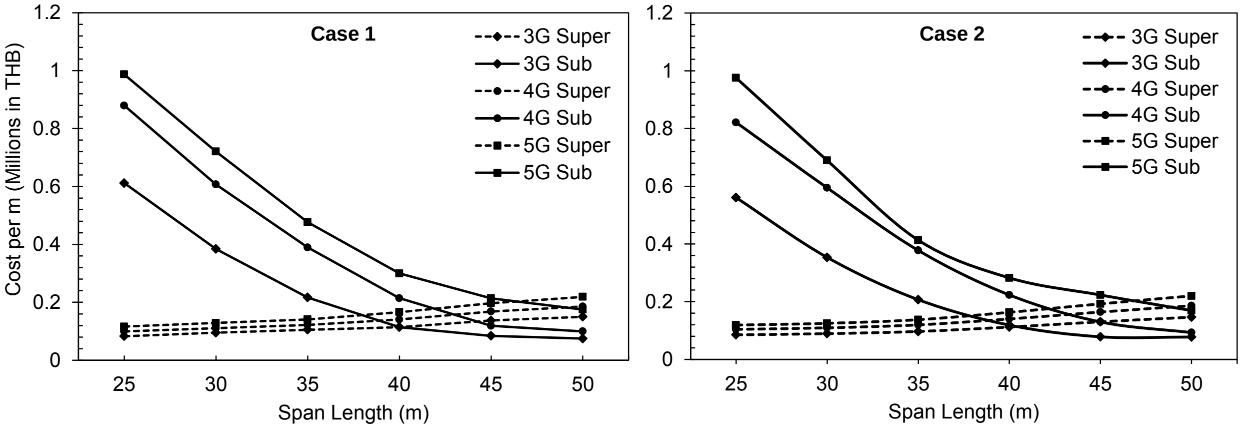


Figure 4: The overall cost comparison (for both superstructure and substructure) of both cases (i.e. constant web and tapered web)

Table 4: Optimum span lengths for three-girder, four-girder and five-girder systems

Girder Case	Optimal Span Length (m)
3G	40 – 42 m
4G	40 - 45 m
5G	45 – 50 m

Figure 5 shows the comparison (in terms of total weight and total cost) for three-girder, four-girder and five-girder systems at different span lengths. The result shows that Case 2 would result in a minimum of 6 % and a maximum of 10 % reduction in weight of plate girder compared to Case 1. It is also observed that an increase in the span length for each girder system will increase the total weight of steel girders by approximately 12 – 20% for Case 1. However, for case 2, this increase is approximately 6 – 19%. In terms of overall cost comparison shown in Figure 5, Case 2 is observed to be an economical solution. The total cost of bridge for Case 2 is around 8% - 10 % less than the total cost for Case 1.

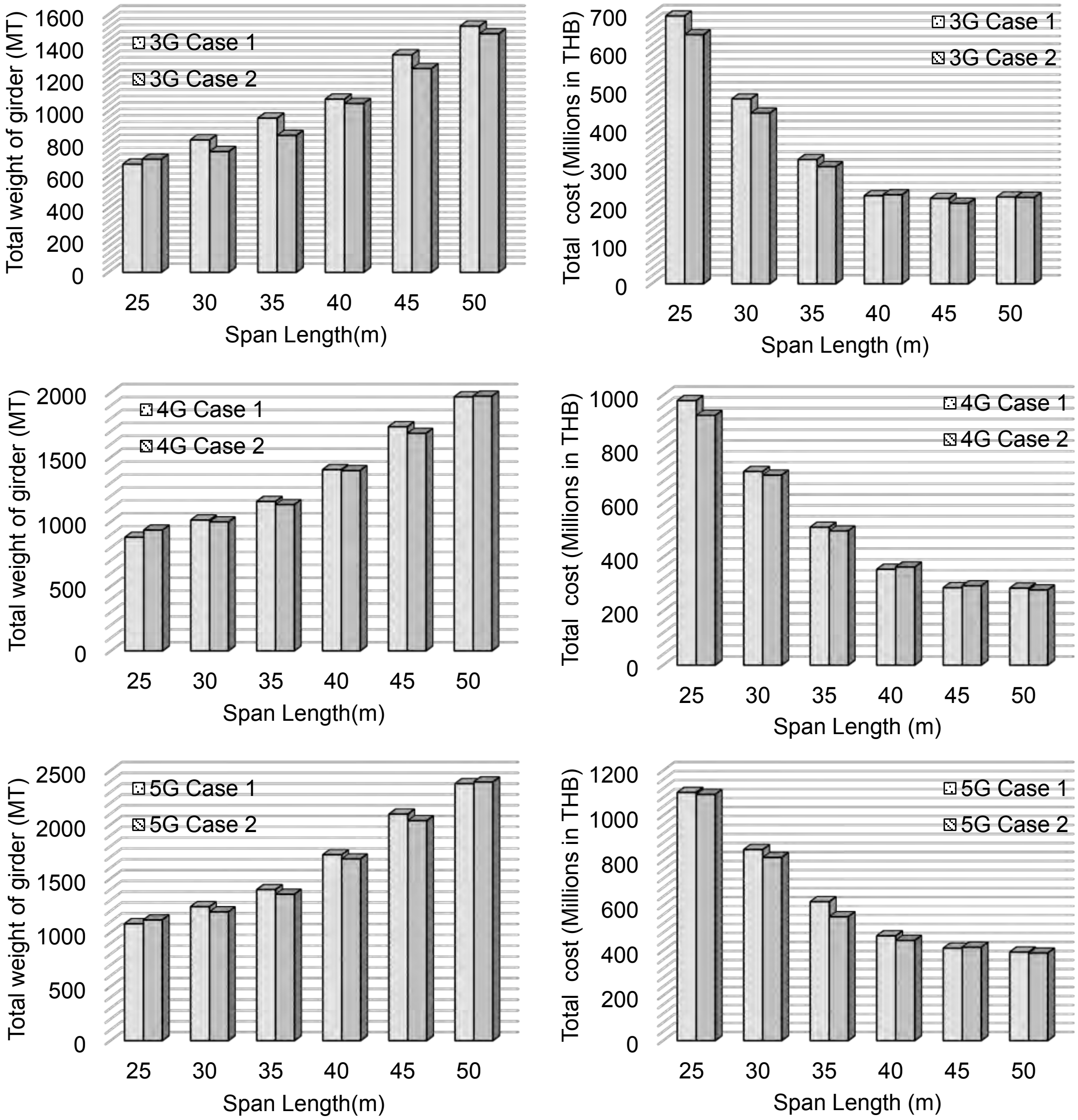


Figure 5: The comparison (in terms of total weight and total cost) for three-girder, four-girder and five-girder systems at different span lengths

5. Conclusions

In this study, several parameters affecting the cost of steel girder bridges are investigated including the variation of web depths, the thickness and width of flanges, the thickness of web and the effect of changing the span lengths. The results show that the use of tapered web leads to 6%-10% reduction in weight of the girder. The overall cost of case study bridge with tapered webs is observed to be 8% - 10% less than that with constant web. The 3-girder bridge case resulted in approximately 20% lower cross-sectional area compared to the 4-girder case which is again approximately 18% lower compared to 5-girder case. The optimal span range lies between 39 m and 41 m of 3-girder system for Case 1, while it ranges from 40 m to 42 m for Case 2.

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