Toma, S. "Statistics of Steel Weight of Highway Bridges."
Bridge Engineering Handbook.
Ed. Wai-Fah Chen and Lian Duan
Boca Raton: CRC Press, 2000

54

Statistics of Steel Weight of Highway Bridges

Shouji Toma
Hokkai-Gakuen University, Japan

54.1 Introduction

In this chapter, a database of steel highway bridges is formed to assess designs by analyzing them statistically. No two bridges are exact replicas of each other because of the infinite variety of site conditions. Each bridge meets specific soil, traffic, economic, and aesthetics conditions. The structural form, the support conditions, the length, width, and girder spacing, pedestrian lanes, and the materials, all depend on a unique combination of design criteria. Even if the stipulated criteria are identical, the final bridges are not, as they naturally reflect the individual intentions of different designers. Therefore, steel weight is a major interest to engineers.

Steel weight of highway bridges is one of the most important of the many factors that influence bridge construction projects. The weight gives a good indication of structural, economic, and safety features of the bridge. Generally, the weight is expressed by as a force per square unit of road surface area (tonf/m² or kN/m²). Stochastic distribution of the weight includes many influential factors to designs that cause scatter. The analysis of this scatter may suggest the characteristics of the bridges. As a general rule, simple bridges are lighter than more complex ones, bridges with high safety margins are heavier, and composite construction results in a lighter bridge overall. A designer thereby gets insight into the characteristics of a bridge. As bridge design also requires the estimate of steel weight in advance, the data collected here are useful.

In Japan, many steel bridges have been constructed in the past few decades. The weight of steel used in these bridges has been collected into a single database. The bridges are all Japanese, but engineers from other countries use similar structural and economic considerations and can usefully employ these in their designs. In this chapter, Japanese design criteria are presented first. The live loads and material properties are described in special detail to clarify differences that other countries may note. Then, the computer database is explained and used to make comparisons between plate and box girders, truss and frame bridges, simply supported and continuously supported bridges, reinforced concrete slab deck and steel deck, and more.

54.2 Design Criteria

54.2.1 Live Loads

The strength required for a bridge to sustain largely depends on the live load, and the live load generally differs from country to country. Since the weight information used here follows Japanese specifications, those will be the ones explained. The last version of the bridge design specification was published in 1996 [1], and is based on a truck weight of 25 tonf (245 kN). However, the bridges studied here were designed using an old version of the code [2], and thus used a truck load of 20 tonf (196 kN).

The 20 t live load (TL-20) takes the two forms shown in Figure 54.1a. The T-load is used to design local components such as the slab or the floor system and the L-load is used for global ones such as the main girders. The T-load is the concentrated wheel loads and the L-load is further subdivided. A partially distributed load (caused by the truck) and a load distributed along the length of the bridge (corresponding to the average traffic load) comprises the L-load. Most of the bridges were designed for TL-20, but on routes, such as those near harbor ports, heavy truck loads are expected and these were designed for TT-43 (Figure 54.1b). In this database the difference is not considered.

When a bridge has side lanes for pedestrian traffic, and the live load (the crowd load) is small compared to vehicular traffic loads, usually less steel is required. However, the difference of the weight for pedestrian and vehicular lanes is not considered in this database. The surface area of the sidewalk is considered equally as heavy as the area in the vehicle lanes.

54.2.2 Materials

The strength of steel varies widely. A mild steel may have a yield strength of about 235 N/mm² and is commonly used in bridge design but higher strengths of 340 or 450 N/mm² are also used, often in large bridges. Various strength of steel are considered in this study. Clearly, when higher-strength steels are used, the weight of steel required goes down. However, the difference in strength level of steel is not distinguished in the database. Aa a selection of strength level is made considering rationality of design, it will generally result in similar decisions for many bridges. In other words, similar bridge designs specify similar material strengths. The effect of strength is thus included implicitly in the database.

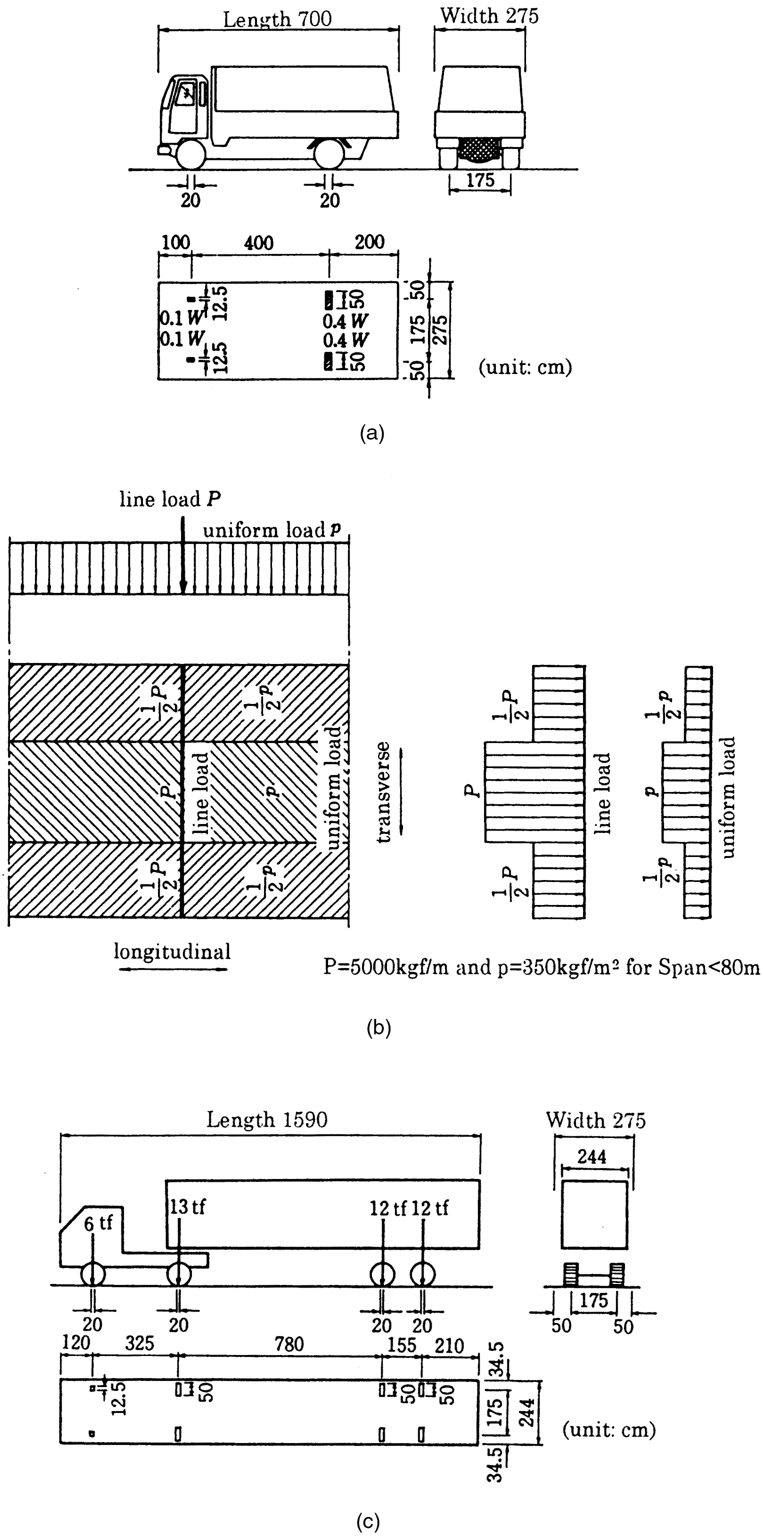


FIGURE 54.1 Live load (TL-20). (a) T-Load (W = 20 tf); (b) L-Load; (c) TT-43 (W = 43 tf).

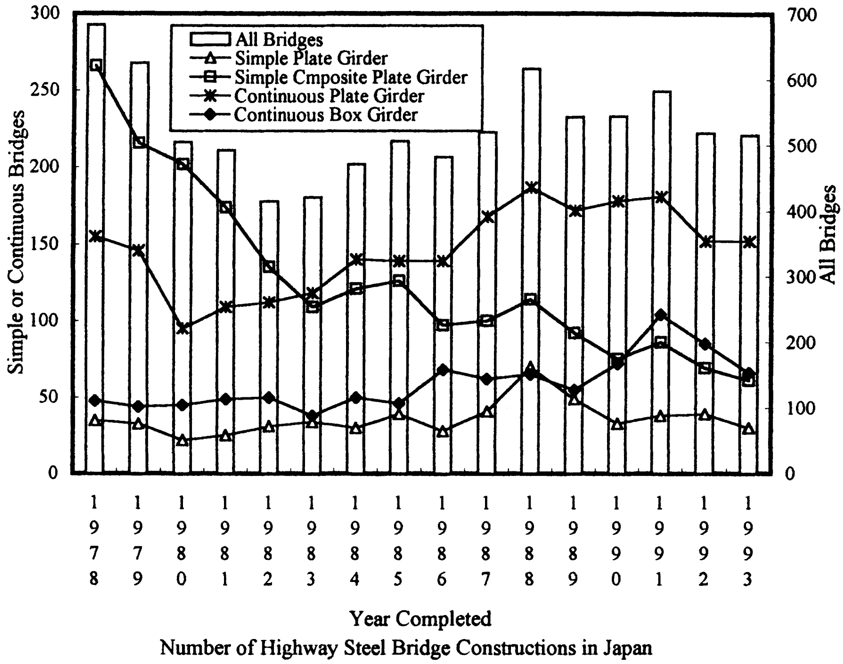


FIGURE 54.2 Number of highway steel bridge constructions in Japan.

54.3 Database of Steel Weights

The Japan Association of Steel Bridge Construction (JASBC) publishes an annual report on steel bridge construction [3]. Information about the weight of steel was taken from these reports over a period of 15 years (from 1978 to 1993). The database was collected using a personal computer [4]. The weight was expressed in terms of intensity per unit road surface area (tonf/m^2). Table 54.1 shows the quantity of data available for each year relating to various types of bridges. When enough data exist to perform a reliable statistical analysis, new data are used. When the year's sample is small, all the data are included.

The data in Table 54.1 are plotted in Figure 54.2, which also shows the number of steel bridges constructed in Japan. From Figure 54.2, it can be seen that about 500 steel bridges are constructed each year. The tendency of the structural types can also be seen: simply supported composite plate girders are gradually replaced by continuous girders. This can be explained as expansion joints damage the pavement and cause vehicles to make noise as they pass over the joints.

54.4 Statistics of Steel Weights

Weight distributions for various types of bridges are shown in Figures 54.3 through 54.13. The weights are plotted against the span length which shows applicable length for the type of bridge. In the figures the mean values are shown by a line and a parabola curve; the equations are given in Table 54.2.

54.4.1 Simply Supported Noncomposite Plate Girder Bridges

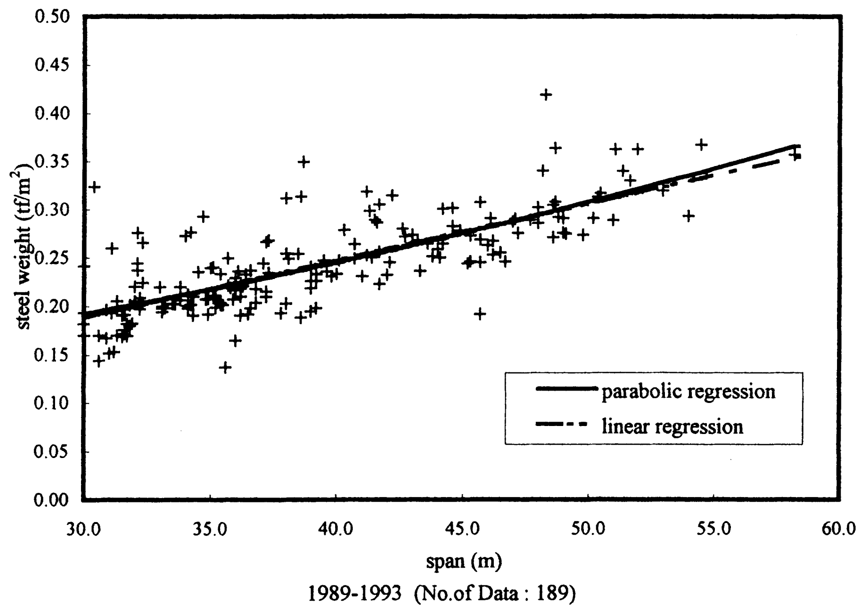
In Figure 54.3 the distributions for simply supported plate girder bridges with reinforced concrete (RC) slab and steel decks are shown. The steel weight varies considerably, from which one can investigate the peculiarity of the bridge.

TABLE 54.1 Number of Input Data

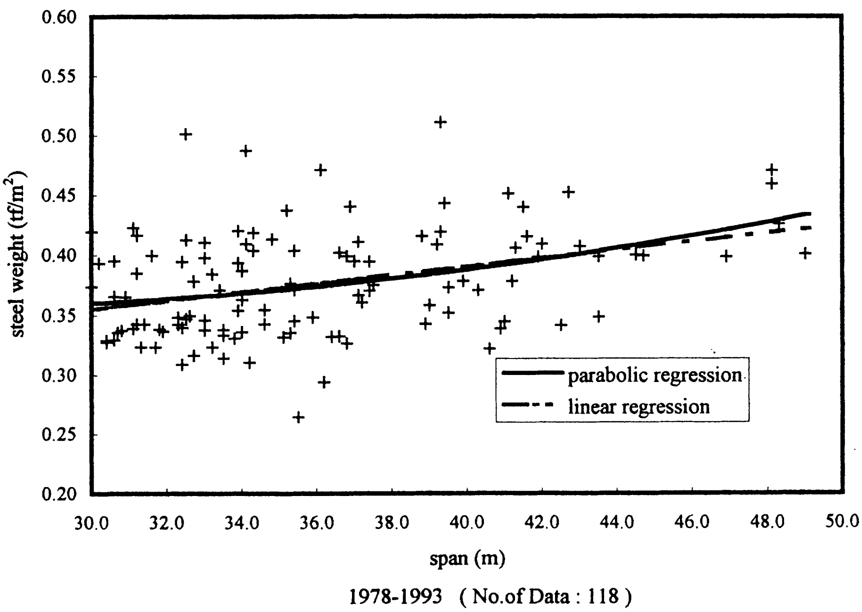
Type of Bridge	Year Completed																Total
	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	
Simple plate girder	35	33	22	25	31	34	30	39	28	41	70	49	33	38	39	30	577
Simple plate girder (steel deck)	6	2	5	4	6	9	6	8	9	11	12	9	14	5	4	8	118
Simple composite plate girder	266	216	202	174	135	109	121	126	97	100	114	92	75	86	69	61	2043
Simple box girder	30	29	34	24	24	12	29	33	24	36	41	36	35	40	32	44	503
Simple box girder (steel deck)	15	12	6	6	4	7	6	10	16	5	16	14	14	21	20	28	200
Simple composite box girder	42	36	18	23	9	13	10	13	12	17	21	18	11	8	6	10	267
Continuous plate girder	155	146	95	109	112	118	140	139	139	168	187	172	178	180	147	150	2335
Continuous plate girder (steel deck)	0	4	4	0	0	5	6	6	6	1	4	5	6	5	0	2	54
Continuous box girder	48	44	45	49	50	38	50	46	68	62	65	55	72	104	85	66	947
Continuous box girder (steel deck)	9	18	19	16	11	16	19	24	23	17	25	20	23	27	28	42	337
Simple truss	16	26	15	7	11	16	11	14	9	15	15	10	17	8	10	11	211
Continuous truss	10	13	9	10	0	6	12	8	6	12	7	6	12	5	6	2	124
Langer	19	12	8	12	7	10	7	12	4	5	3	7	5	4	8	11	134
Trussed Langer	2	9	4	5	2	2	0	3	2	1	5	2	4	1	4	1	47
Lohse	11	12	12	10	9	11	11	8	19	7	8	11	13	17	17	7	183
Nielsen Lohse	2	0	0	0	1	4	4	2	4	3	4	5	5	7	5	7	53
Rigid frame (Rahmen)	16	12	5	15	3	9	8	10	10	12	17	15	10	8	14	18	182
Rigid frame (π type)	3	6	4	6	4	4	4	5	2	5	6	6	7	6	8	7	83
Arch bridge	—	—	—	—	—	—	—	—	—	—	—	2	4	3	4	2	15
Cable-stayed bridge (steel deck)	0	0	2	2	0	2	1	5	4	5	2	4	5	5	5	6	48
Total	685	630	509	497	419	425	475	511	482	523	622	538	543	578	511	513	8461

TABLE 54.2 Coefficients of Regression Equations

Type of Bridge	a ($\times 10^{-2}$)	b	Standard Deviation (1)	α ($\times 10^{-4}$)	β ($\times 10^{-2}$)	γ	Standard Deviation (2)	Year	No. of Data	Correlation Coefficient	Fig. No.
Simple plate girder	0.5866	0.0124	0.0325	0.4621	0.2075	0.0881	0.0324	1989–1993	189	0.758	54.3a
Simple plate girder (steel deck)	0.3504	0.2499	0.0420	0.1228	–0.5853	0.4252	0.0419	1978–1993	118	0.353	54.3b
Simple composite plate girder	0.6084	–0.0306	0.0249	0.3824	0.2985	0.0307	0.0249	1989–1993	383	0.830	54.4
Simple box girder	0.5917	0.0778	0.0410	0.4350	0.1488	0.1866	0.0409	1989–1993	187	0.803	54.5a
Simple box girder (steel deck)	0.3019	0.2738	0.0709	0.0616	0.2303	0.2930	0.0709	1978–1993	200	0.556	54.5b
Simple composite box girder	0.4765	0.1007	0.0412	0.3329	0.1290	0.1887	0.0411	1981–1993	171	0.714	54.6
Continuous plate girder	0.3729	0.0533	0.0331	–0.3092	0.6425	–0.0035	0.0330	1991–1993	477	0.653	54.7a
Continuous plate girder (steel deck)	0.2329	0.2464	0.0484	–0.2413	0.4482	0.2022	0.0481	1978–1993	54	0.508	54.7b
Continuous box girder	0.3029	0.1510	0.0499	0.0099	0.2906	0.1546	0.0499	1989–1993	382	0.665	54.8a
Continuous box girder (steel deck)	0.1516	0.3110	0.0634	0.0213	0.1080	0.3307	0.0633	1978–1993	337	0.593	54.8b
Simple truss	0.2993	0.1421	0.0504	0.3711	–0.2355	0.3284	0.0493	1978–1993	211	0.592	54.9a
Continuous truss	0.2221	0.1633	0.0602	0.0959	0.4830	0.0257	0.0567	1978–1993	124	0.799	54.9b
Langer	0.2907	0.1433	0.0632	–0.0135	0.3140	0.1338	0.0632	1978–1993	134	0.675	54.10a
Trussed Langer	0.2696	0.1700	0.0609	0.1693	–0.1173	0.3794	0.0592	1978–1993	47	0,741	54.10b
Lohse	0.2372	0.1956	0.0942	0.0110	0.2128	0.2076	0.0941	1978–1993	183	0.676	54.11a
Nielsen Lohse	0.2372	0.1956	0.1019	0.0110	0.2128	0.2076	0.1018	1978–1993	53	0.735	54.11b
Rigid frame (Rahmen)	0.4326	0.0542	0.0737	0.4399	–0.1004	0.2024	0.0711	1978–1993	182	0.659	54.14a
Rigid frame (π type)	0.4982	0.0050	0.0555	0.2477	0.1528	0.1160	0.0544	1978–1993	83	0.813	54.14b
Cable-stayed bridge (steel deck)	0.2102	0.2944	0.2056	0.0407	–0.0014	0.4736	0.1937	1978–1993	48	0.784	54.15
Equations (tf/m^2)	$aL + b$ … (1)			$\alpha L^2 + \beta L + \gamma$ … (2)					L = span (m)		



(a)



(b)

FIGURE 54.3 Simple noncomposite plate girders. (a) RC slab deck; (b) steel deck.

54.4.2 Simply Supported Composite Plate Girder Bridges

The distribution for a simply supported composite plate girder bridge is shown in Figure 54.4. Since many bridges of this type were constructed every year, only 4 years of data are used (1989 to 1993).

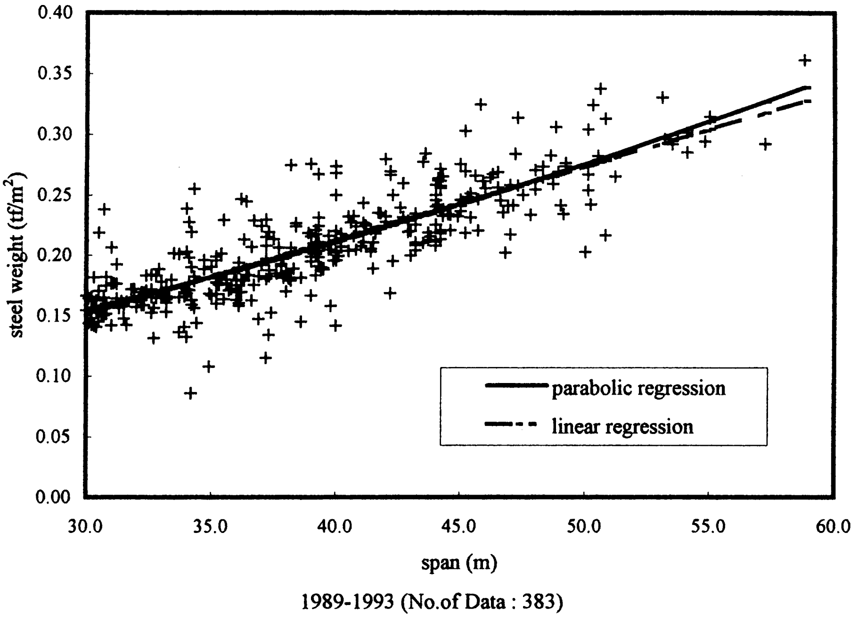


FIGURE 54.4 Simple composite plate girders.

54.4.3 Simply Supported Box-Girder Bridges

The distribution for a simply supported box-girder bridge (noncomposite) for RC slab and steel decks is plotted in Figure 54.5. Steel deck bridges show more variation than RC deck bridges. A simply supported composite box-girder bridge is plotted in Figure 54.6.

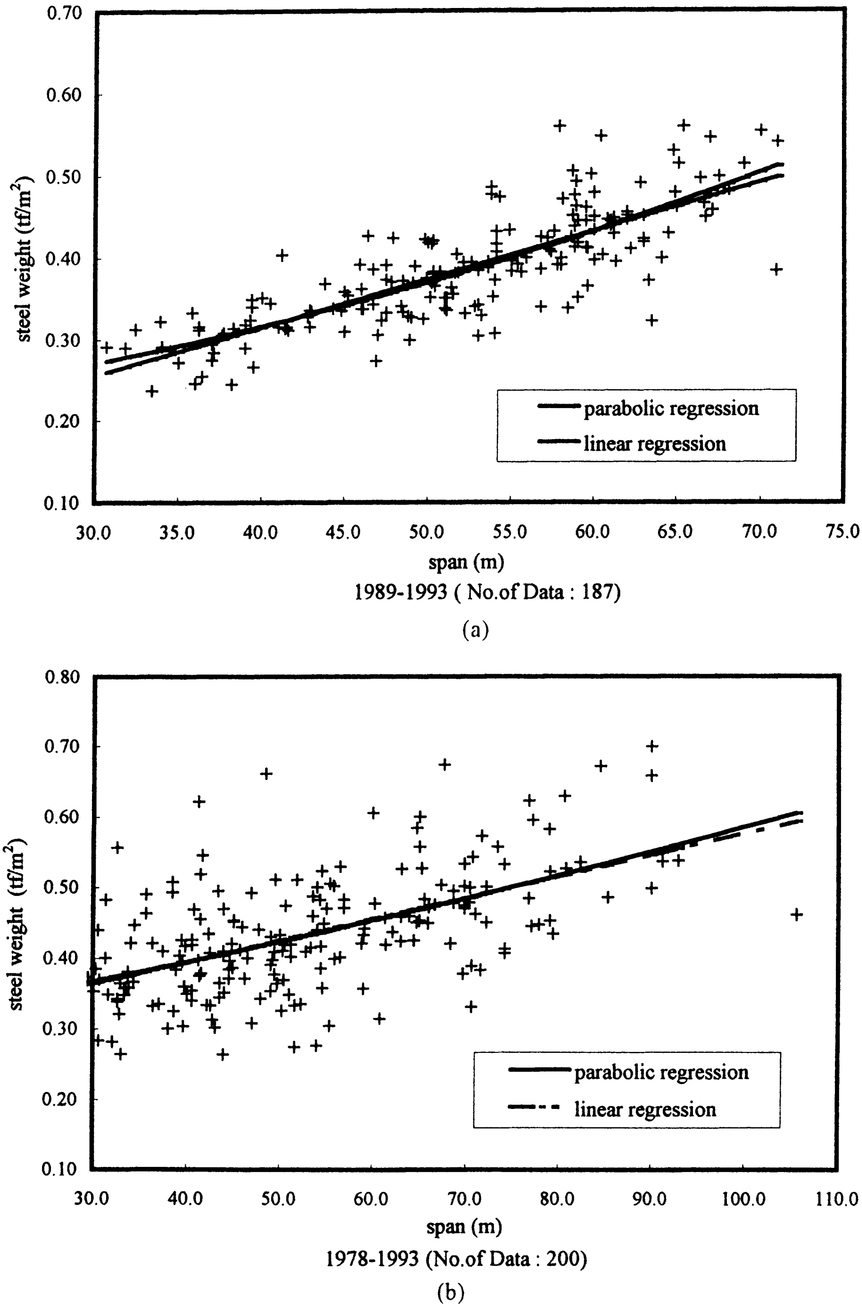


FIGURE 54.5 Simple noncomposite box girders. (a) RC slab deck; (b) steel deck.

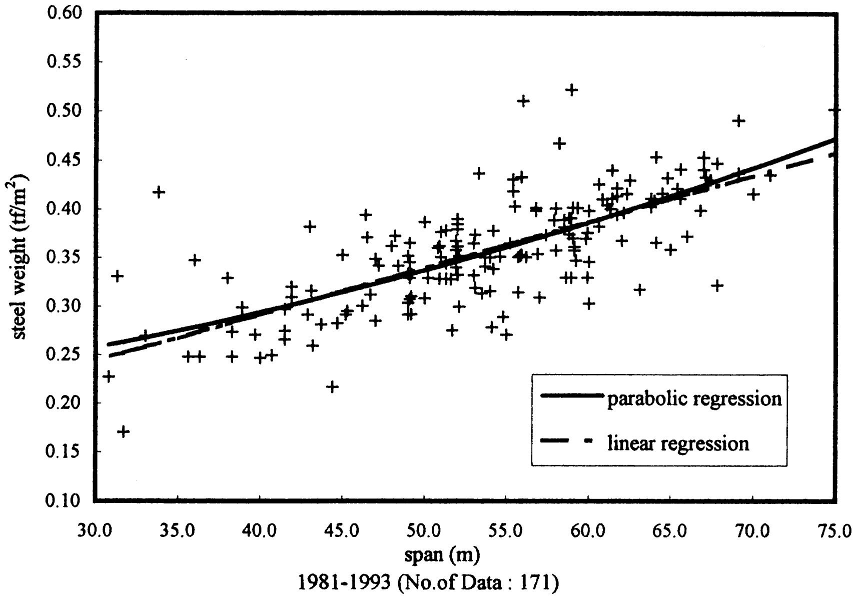
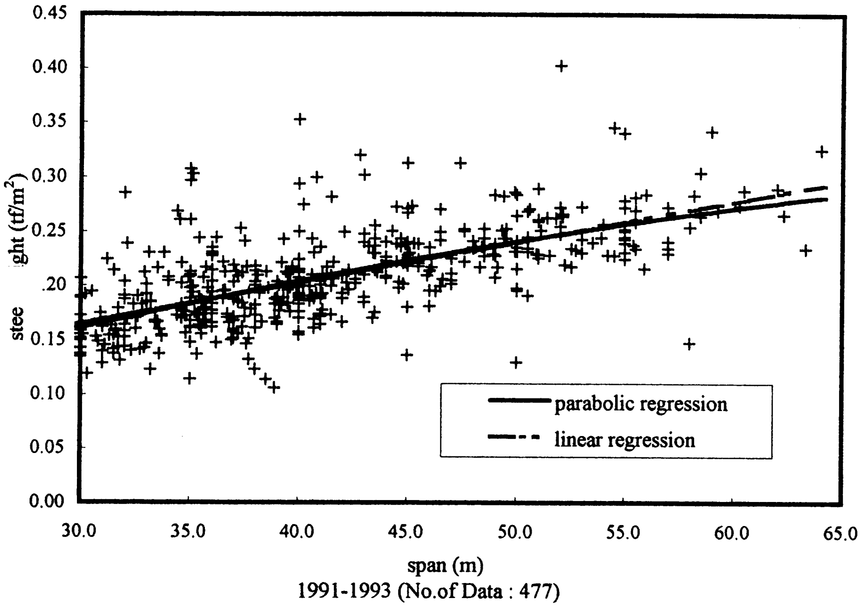


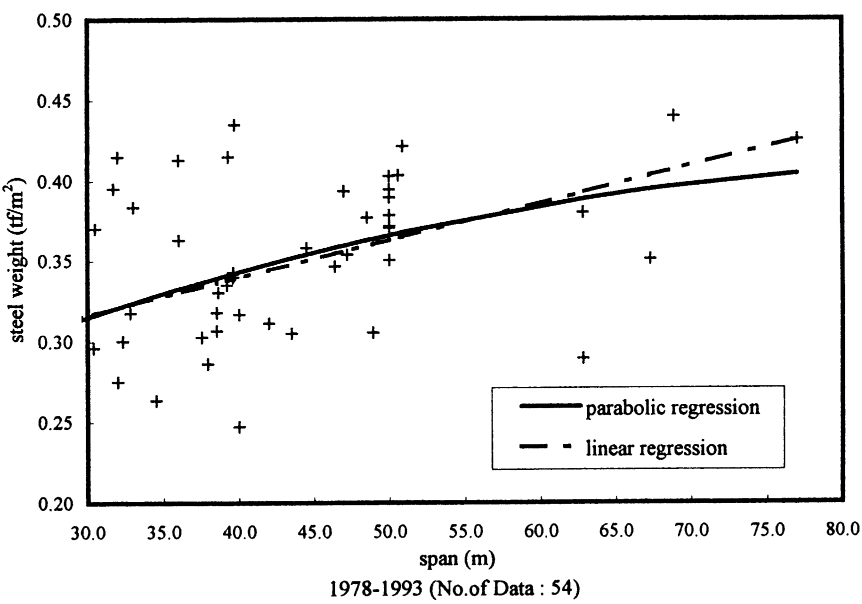
FIGURE 54.6 Simple composite box girders.

54.4.4 Continuously Supported Plate Girder Bridges

Recently, continuous bridges are gaining popularity as defects caused by expansion joints are avoided. Steel weights for continuous bridges with RC slab deck (noncomposite) constructed in the 3 years 1991 to 1993 and with steel deck constructed in the 15 years 1978 to 1993 are plotted in Figure 54.7. The steel deck has only few data and shows wide scatter.



(a)

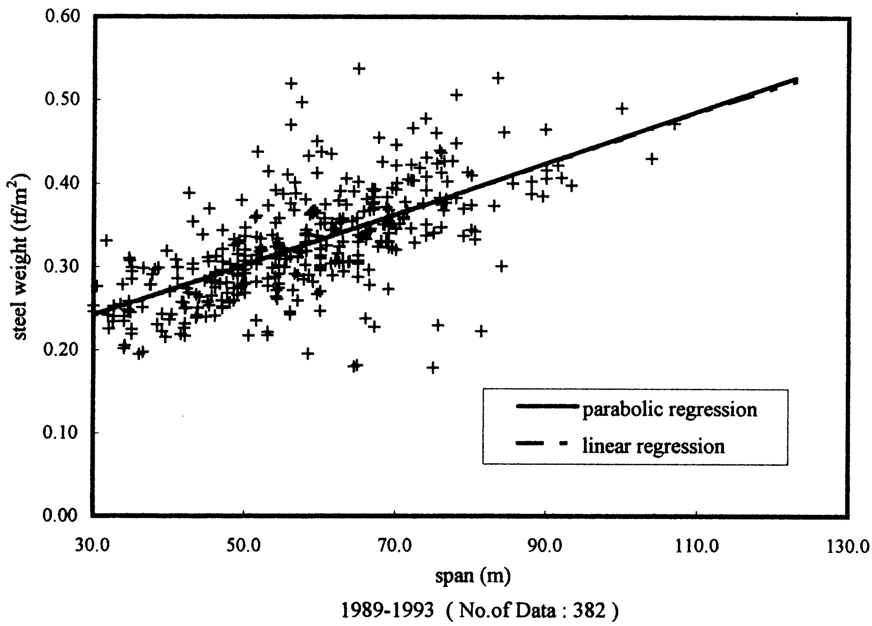


(b)

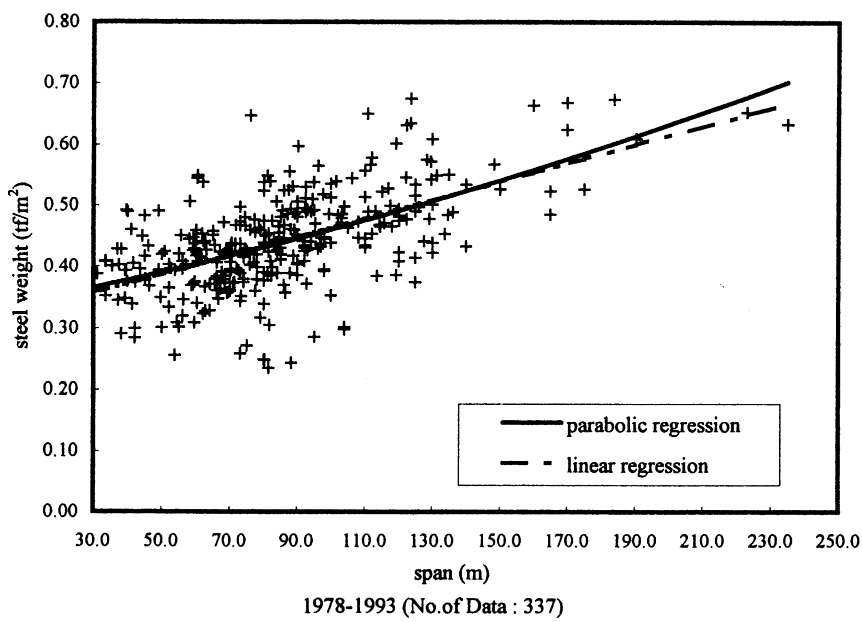
FIGURE 54.7 Continuous plate girders. (a) RC slab deck; (b) steel deck.

54.4.5 Continuously Supported Box-Girder Bridges

Figure 54.8 shows the distribution for a continuous box-girder bridge with RC slab deck and steel deck. This type has a relatively wide scatter. It can be seen that the applicable span length of steel deck bridges (Figure 54.8b) is much longer than RC slab deck bridges (Figure 54.8a).



(a)

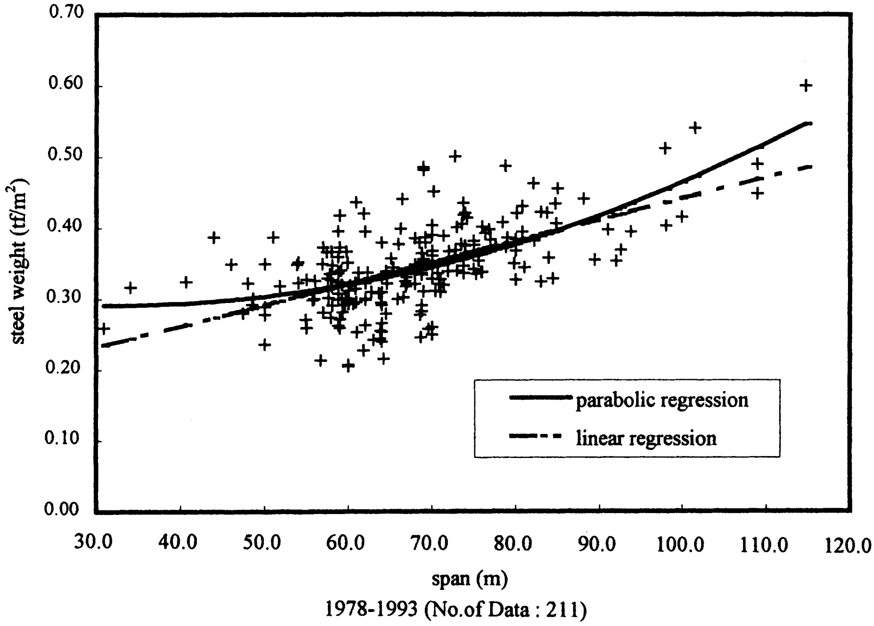


(b)

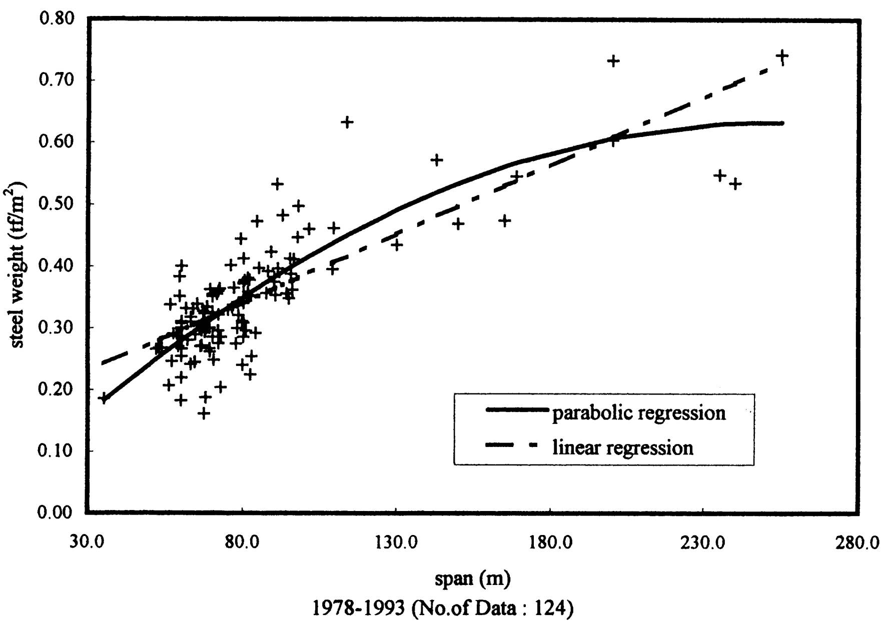
FIGURE 54.8 Continuous box girders. (a) RC slab deck; (b) steel deck.

54.4.6 Truss Bridges

Figure 54.9 is for simply and continuously supported truss bridges. The data cluster at moderate span length making prediction for the weight of truss bridges for short or long spans not accurate.



(a)

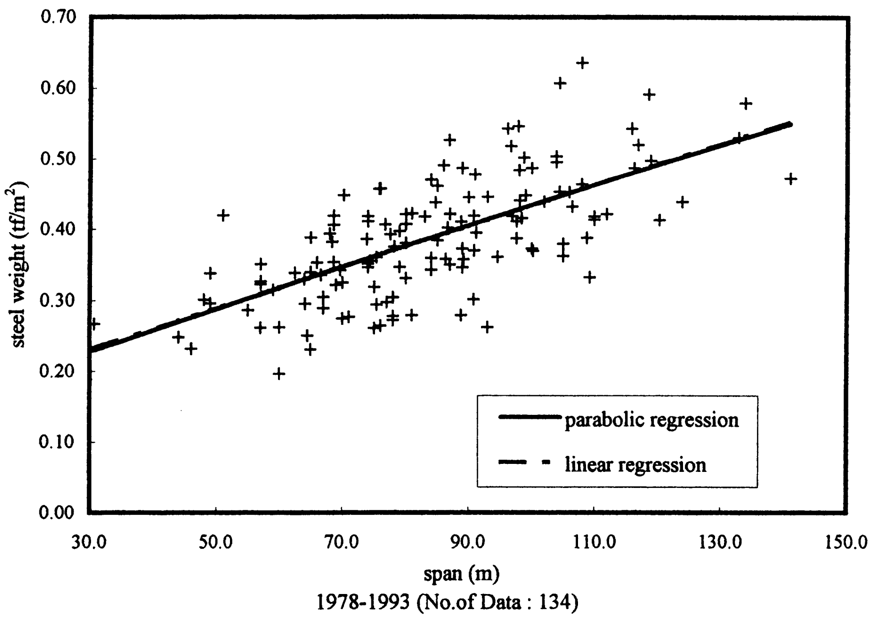


(b)

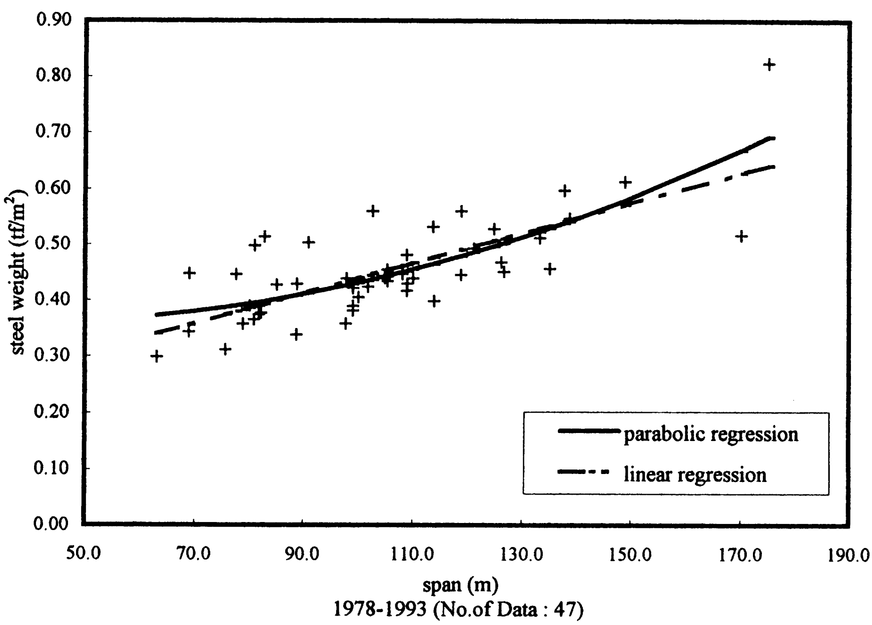
FIGURE 54.9 Truss bridges. (a) Simple truss; (b) continuous truss.

54.4.7 Arch Bridges

Figures 54.10 and 54.11 are the distributions for two arch types; Langer bridges and Lohse bridges. It is assumed in the structural analysis that the arch rib of Lohse bridge carries bending moment, shear force, and axial compression while Langer bridge only carries axial compression. In the Langer bridge, the main girders are stiffened by the arch rib through the vertical members. The trussed Langer uses the diagonal members for the same purpose.

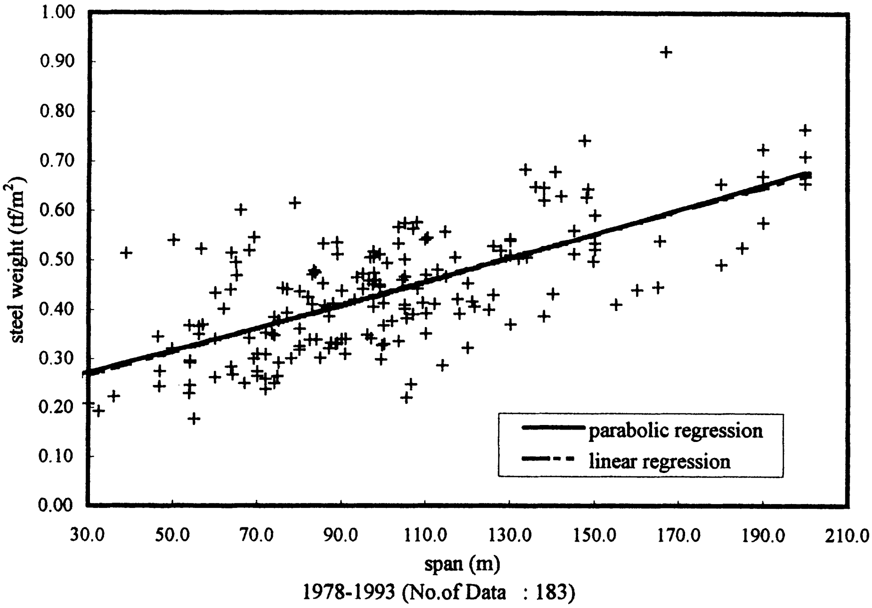


(a)

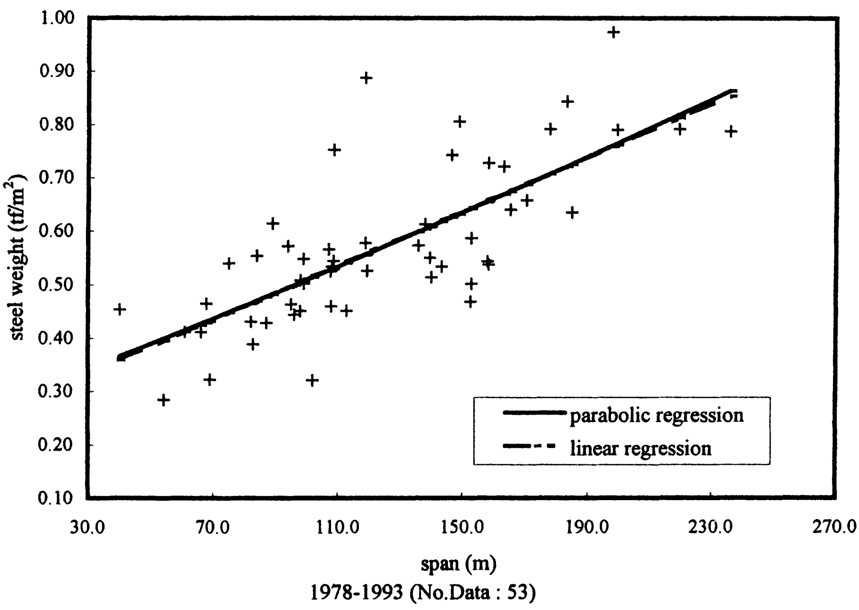


(b)

FIGURE 54.10 Langer bridges. (a) Langer; (b) trussed langer.



(a)



(b)

FIGURE 54.11 Lohse bridges. (a) Lohse; (b) Nielsen Lohse.

The Lohse also has vertical members between the arch and main girders, but the Nielsen Lohse has only thin rods which resist only tension and form a net. The types of arch bridges are illustrated in Figure 54.12.

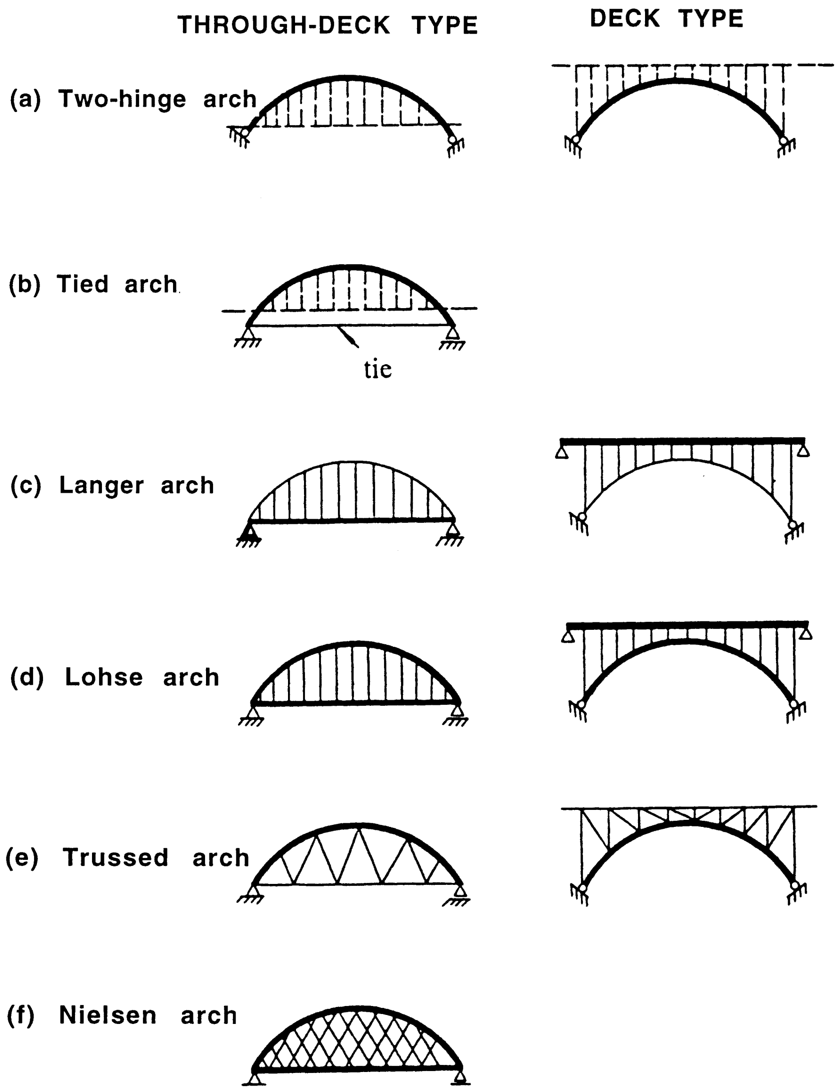


FIGURE 54.12 Types of arch bridges. (a) Two hinge; (b) tied; (c) Langer; (d) Lohse; (e) trussed; (f) Nielson.

54.4.8 Rahmen Bridges (Rigid Frames)

The Rahmen bridge is a frame structure in which all members carry bending moment and axial and shear forces. There are many variations of structural form for this type of construction as shown in Figure 54.13. Figure 54.14 shows the weight distribution for typical π-Rahmen and other types.

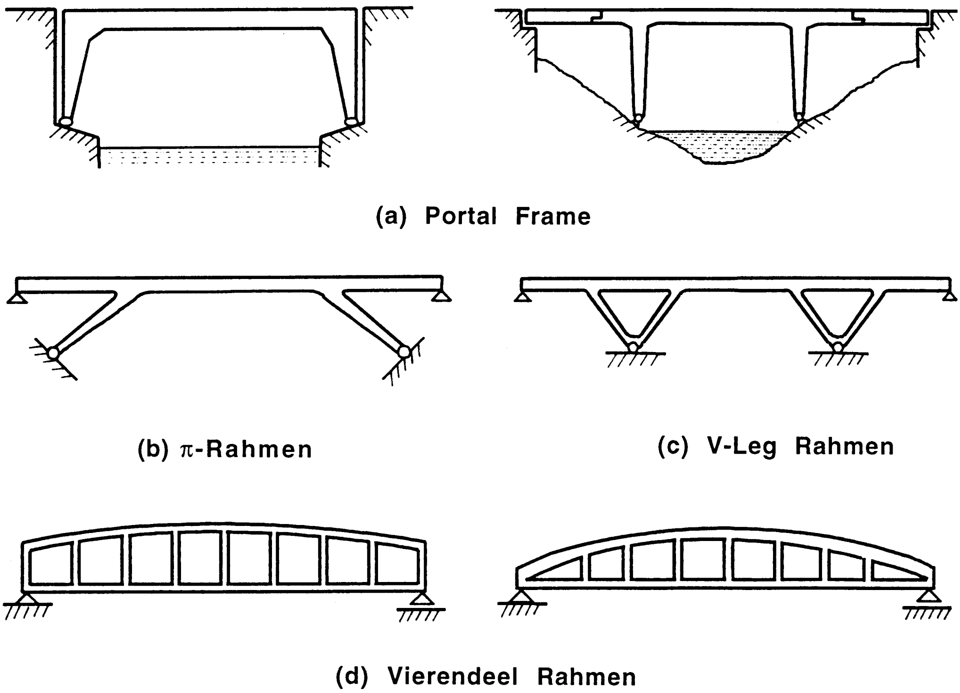
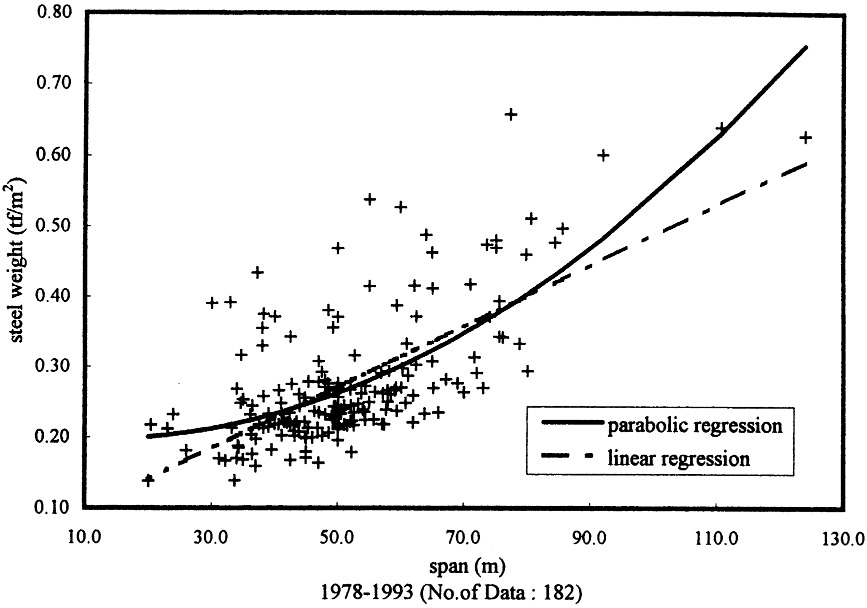
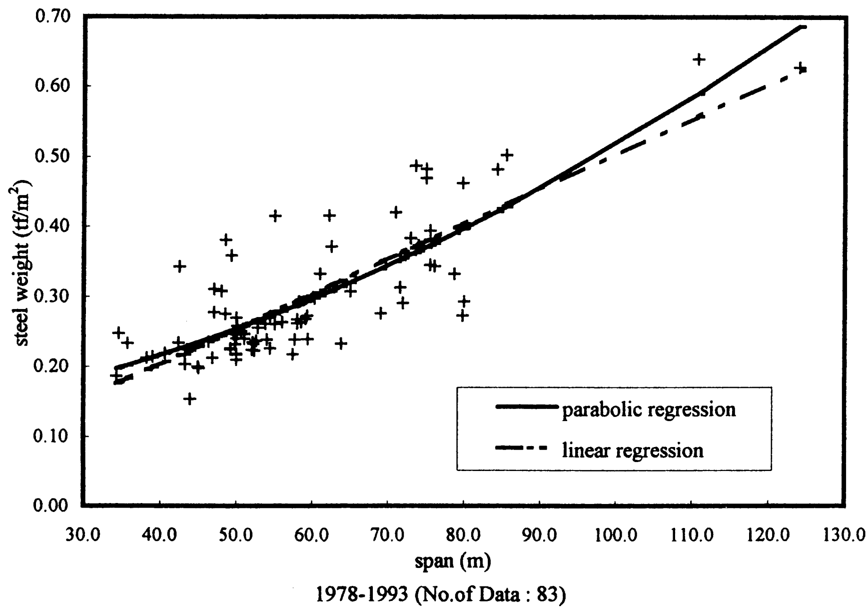


FIGURE 54.13 Types of Rahmen bridges. (a) Portal frame; (b) π-Rahmen; (c) V-leg Rahmen; (d) Vierendeel Rahmen.



(a)



(b)

FIGURE 54.14 Rigid frames (Rahmen). (a) Rigid frame (general type); (b) π-Rahmen.

54.4.9 Cable-Stayed Bridges

Figure 54.15 shows the weight of cable-stayed bridges. The data may not be sufficient for statistical analysis. The scatter is more significant at long spans.

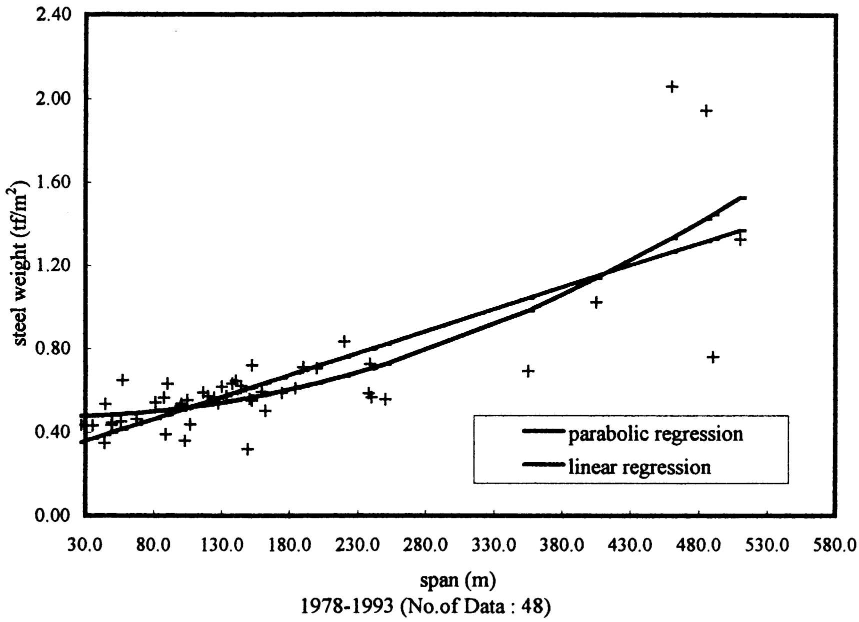


FIGURE 54.15 Cable-stayed bridges (steel deck).

54.5 Regression Equations

The two lines in the distribution figures shown previously in Figures 54.3 through 54.13 are the mean values obtained by linear regression using the least-squares method. They are linear and parabolic. It seems that the parabolic curve does not always give a better prediction. Table 54.2 gives the coefficients of the regression equations to give designers the information necessary for estimating steel weight and assessing designs.

54.6 Comparisons

The weight distributions in Figures 54.3 through 54.13 are compared from various points of view in the following.

54.6.1 Composite and Noncomposite Girders

Figure 54.16 is a comparison of the means given by the linear regression for the noncomposite plate girder bridges shown in Figure 54.3 and the composite plate girder bridges in Figure 54.4. The figure also shows a similar comparison for box-girder bridges (Figures 54.5 and 54.6). Clearly composite girders are more economical than noncomposite ones.

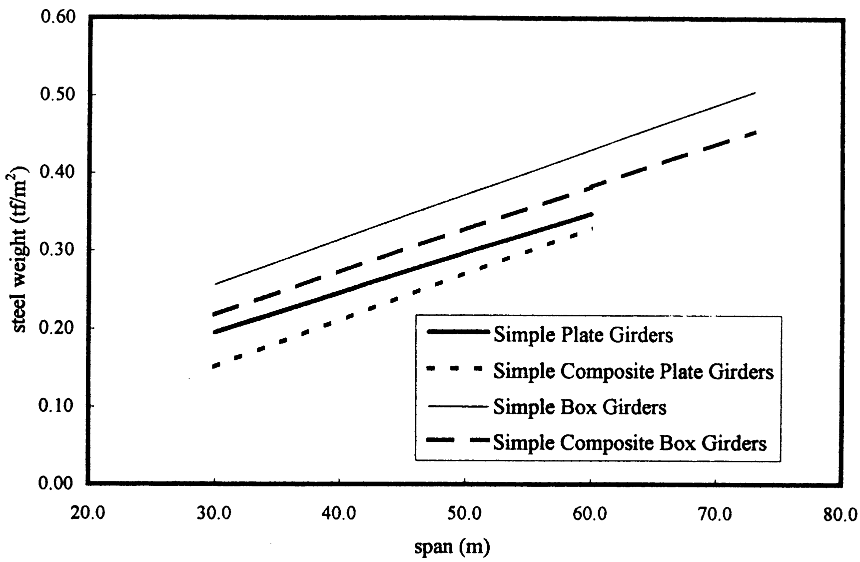


FIGURE 54.16 Comparison between composite and noncomposite plate girders.

54.6.2 Simply and Continuously Supported Girders

The difference caused by variation in support conditions is shown in Figure 54.17 for plate and box girders. The figures shown are for bridges with RC slab and steel decks. It is judged that continuous girders are more advantageous when the spans are long. There is no significant difference between simple plate and box girders for steel deck bridges. Continuous box girders can be used in long-span bridges.

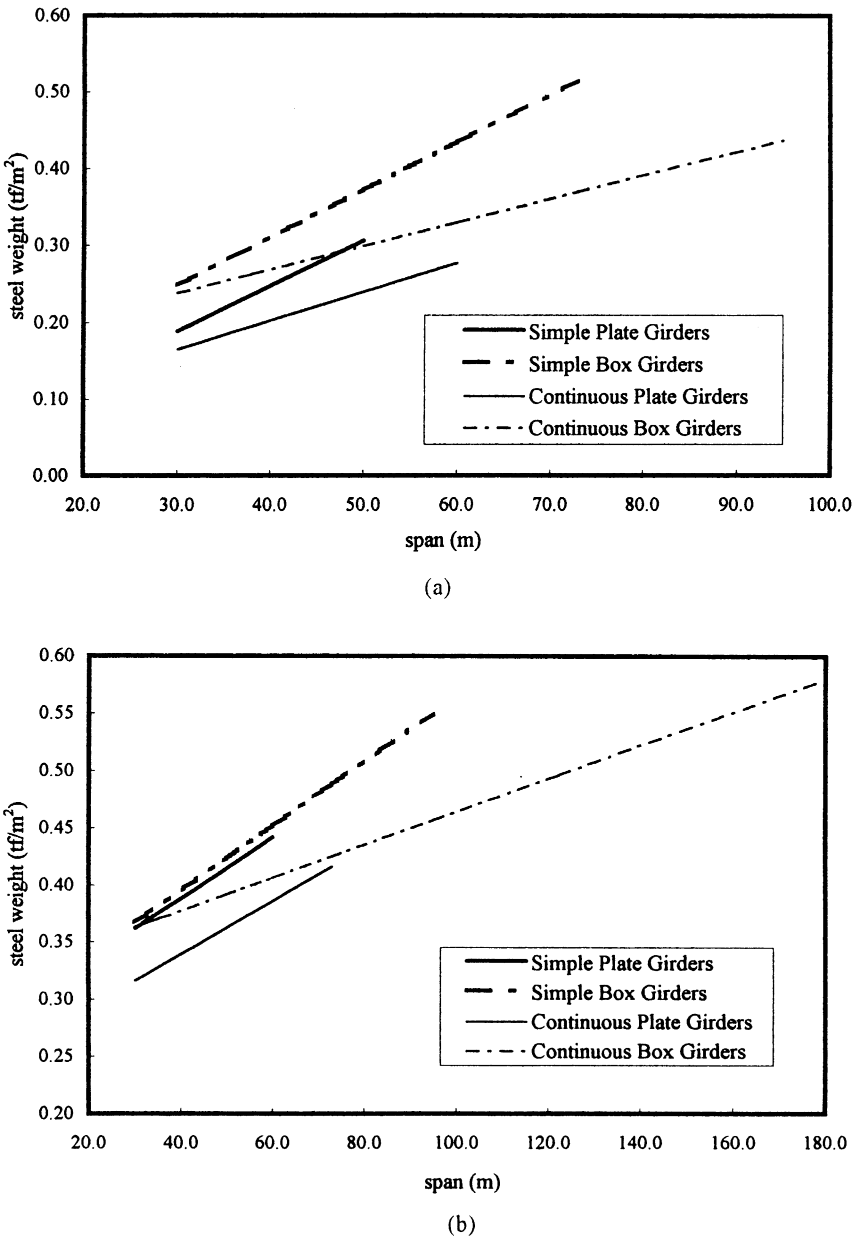


FIGURE 54.17 Comparison of girder bridges. (a) RC slab deck; (b) steel deck.

54.6.3 Framed Bridges

Six types of framed bridges are compared in Figure 54.18. The Nielsen bridge is the heaviest. The Nielsen and Lohse bridges, as well as the trussed Langer, are best suited to long spans.

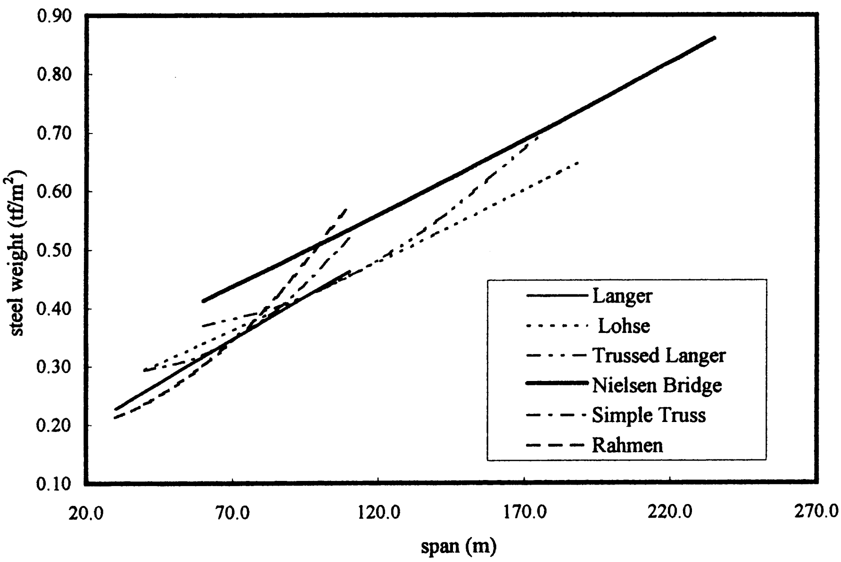
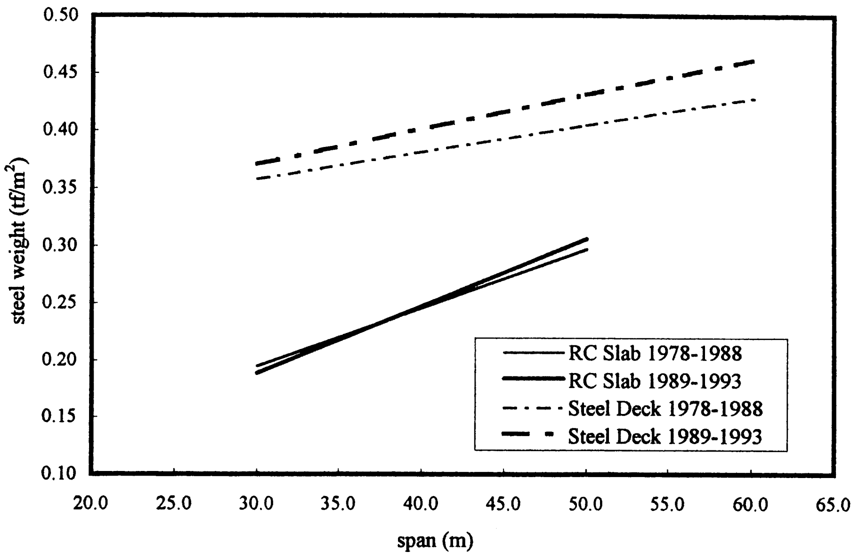


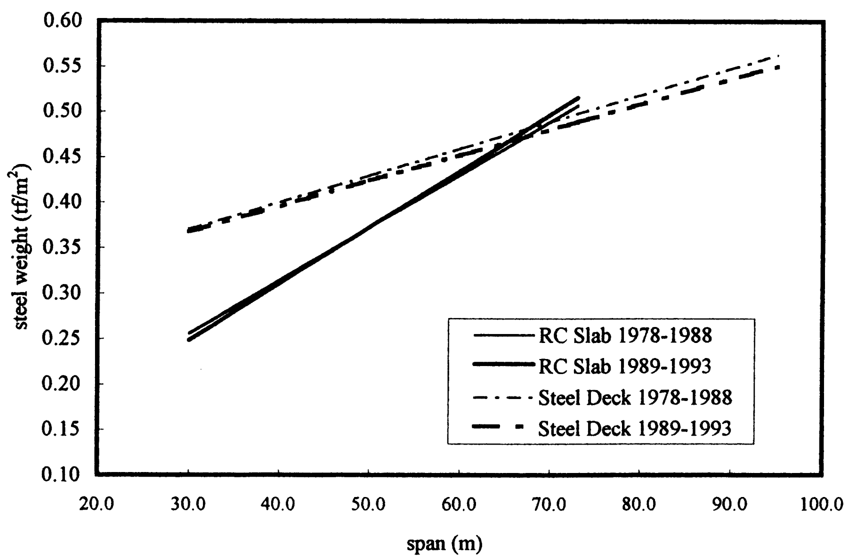
FIGURE 54.18 Comparison of framed bridges.

54.6.4 RC Slab Deck and Steel Deck

Figure 54.19a shows a comparison between the mean values of plate girder bridges with RC slab and steel decks. Bridges with steel decks are naturally much heavier than those with RC slab decks because the weight of the decks is included.



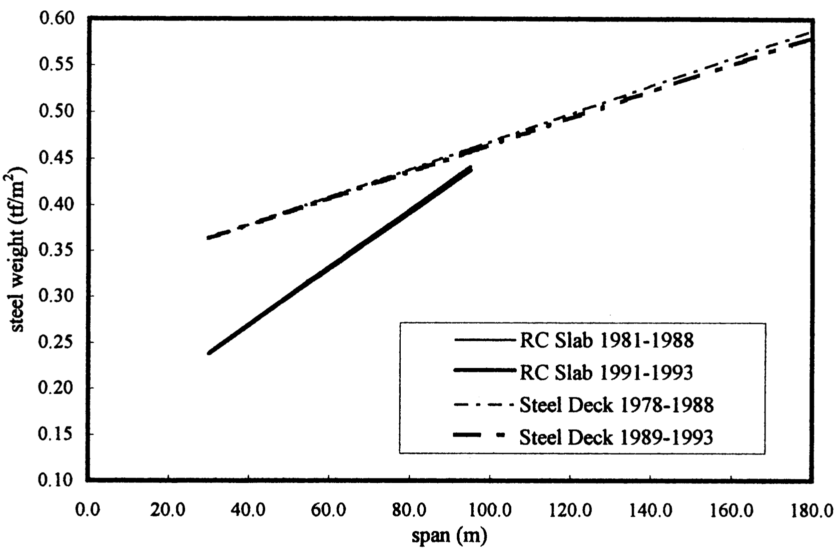
(a)



(b)

FIGURE 54.19 Comparison between RC slab and steel deck bridges. (a) Simple plate girders; (b) simple box girders; (c) continuous box girders.

A similar comparison for the box girder is shown in Figure 54.19(b). The difference gets smaller as the span length increases implying that steel deck bridges are economical when spans are long.



(c)

FIGURE 54.19 (continued)

54.7 Assessment of Bridge Design

54.7.1 Deviation

The distribution of the weights can be expressed by standard Gaussian techniques giving a mean value of 50 and a standard deviation of 10 as shown in Figure 54.20. The mean value $X(L)$ is calculated by the regression equations in Table 54.2 and converted to 50. The standard deviation σ can also be obtained from the regression equations table (Table 54.2), and converted to 10 using standard Gaussian procedures.

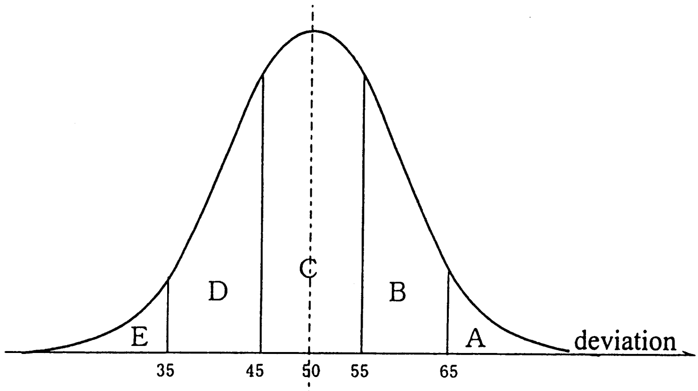


FIGURE 54.20 Classification of distribution.

The deviation (H) of the designed steel weight (X) is obtained using the equation

$$H = \frac{X - X(L)}{\sigma} \times 10 + 50 \tag{54.1}$$

H can be used as an index to compare the designs statistically and perform simple assessments of designs.

54.7.2 Assessment of Design

An example assessment of a typical design is discussed in the following. The labor and maintenance cost of bridges have become a major consideration in all countries. To solve this, a new design concept is proposed using only two girders with wide girder spacing. Figure 54.21 is one of the two-girder bridges that were constructed in Japan. It is a two-span continuous bridge with each span length 53 m. The road width is 10 m and the girder spacing 6 m. In this bridge, the section of the girder is not changed in an erection block to reduce welding length, thus reducing the labor cost.

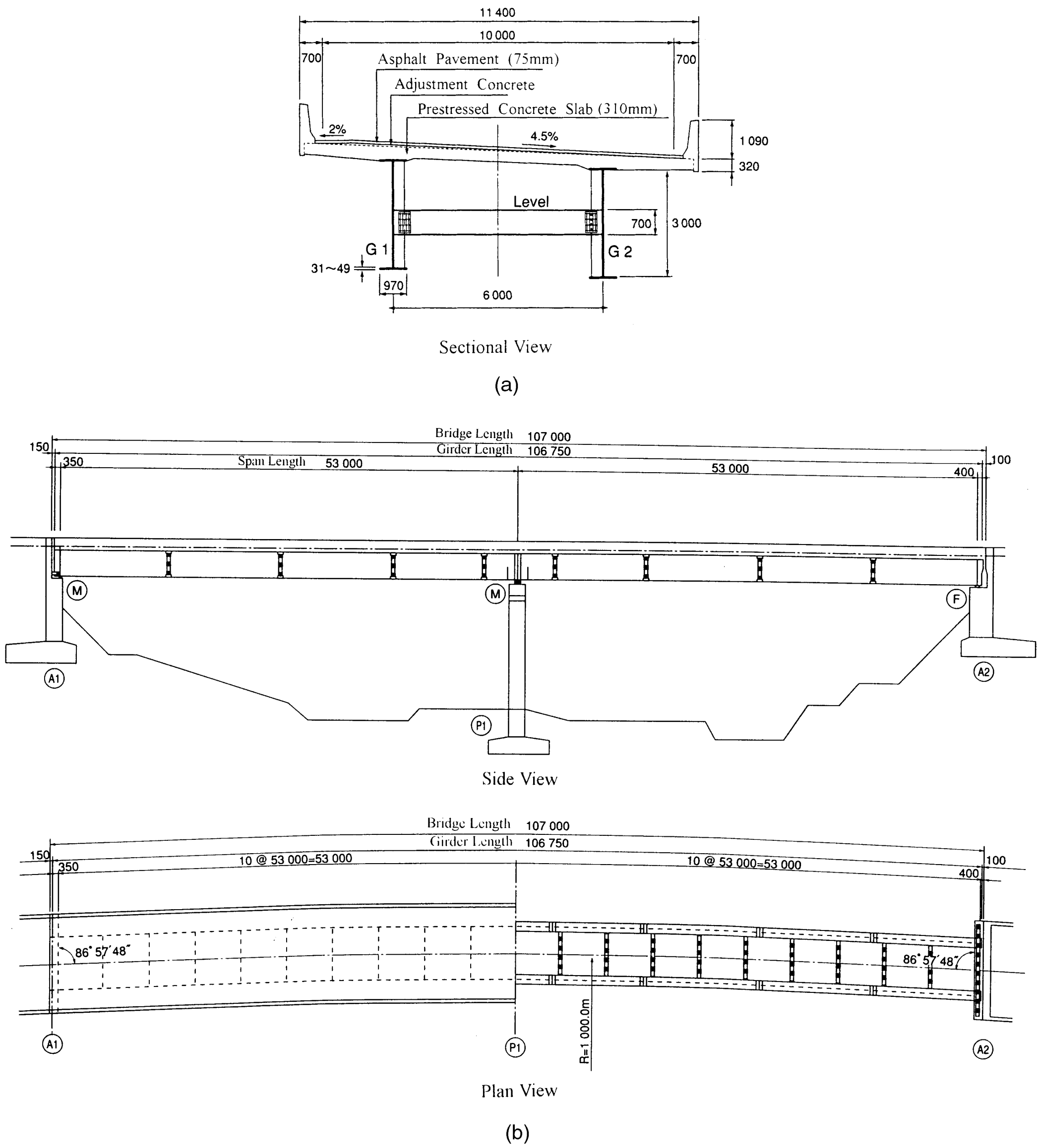


FIGURE 54.21 General plan of two-girder bridge. (a) Sectional view; (b) plan view. (*Bridges in Japan 1995-96*, JSCE)

The steel weight of this bridge is plotted in Figure 54.22. The deviation in this case is H = 62.8 (Rank B) using Eq. (54.1). In the calculation, the mean and the standard deviations are shown in Table 54.2. Note that most of the continuous bridges in Figure 54.22 are three-span continuous bridges. In addition, the design of this bridge follows the new code [1]. Those make the deviation for this case tend to be higher. From these deviation values the steel weight of a similar bridge can be estimated.

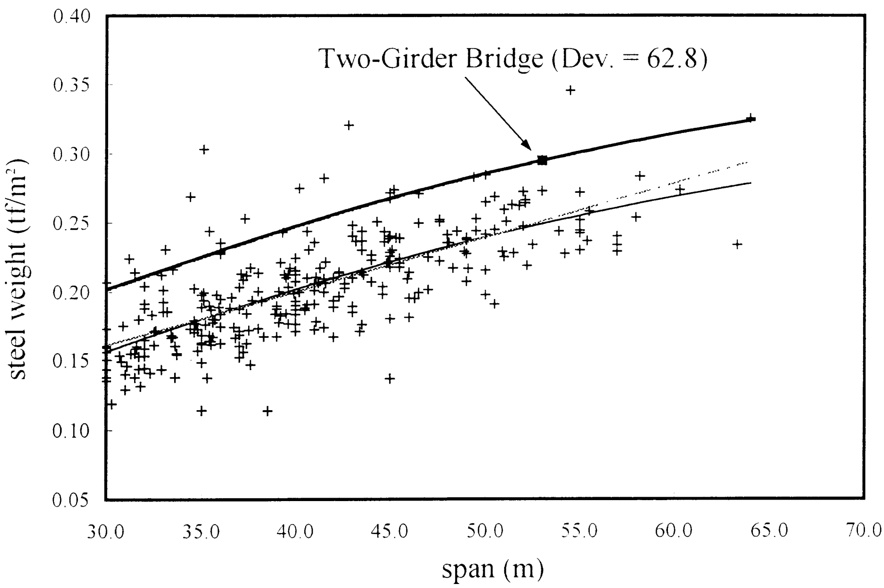


FIGURE 54.22 Two-girder bridge in continuous bridges.

54.8 Summary

The steel weight of bridges is a general indication of the design which tells an overall result. It reflects every influential design factor. A database has been put together to allow assessment of designs and prediction for the steel weight of various types of highway bridges. The distributions are plotted and shown for each type of bridge. From the figures, comparisons are made from various points of view to see the differences in each type of bridge. The regression equations for mean weight are derived, from which designers can estimate the steel weight for their own design or see economical or safety features of the bridge as compared with others.

References

1. Japan Road Association (JRA), Specifications for Highway Bridges, Vol. 1 Common Part, December 1996 [in Japanese].
2. Japan Road Association (JRA), Specifications for Highway Bridges, Vol. 1 Common Part, February 1990 [in Japanese].
3. Japan Association of Steel Bridge Construction (JASBC), Annual Report of Steel Bridge Construction, 1978 to 1993 [in Japanese].
4. Toma, S. and Honda, Y., Database of steel weight for highway bridges, *Bridge Eng.*, 29(8), 1993 [in Japanese].