Box Girder Bridge Design

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THIS PAPER discusses the coordinated design research program conducted under the sponsorship of the United States Steel Corporation, on the subject of steel box girder bridges.

The assigned objective of this investigation was the development of design theory, methods and specifications for steel box girder bridges of short to medium span lengths, having composite decks. The work has included both theoretical, computer, and model test studies, and has progressed to the point where a draft of a specification has been prepared by the investigators and a number of interested state and federal highway engineers, for presentation to the AASHO Bridge Committee.

The use of torsion boxes as flexural girders in bridges is but another extension of the advantageous application of closed structural sections as columns, arch ribs, truss members, or stiffeners for deck plates, where it is desired to achieve improved structural strength, economy, appearance, and resistance to corrosion. Even a cursory survey of current bridge literature will indicate a growing awareness of the potential importance of box girders.

Because they contribute a tremendous torsional stiffness to the bridge and consequently a better transverse (lateral) distribution of loads, box girders have significantly favorable effects on load-carrying capacity, and therefore on economy. In certain applications, also, they enable simplification of the bridge structure and enhancement of appearance over the conventional stringer bridge systems. Structural depths can be less, resulting in an attractive functional design in which corrosion is greatly reduced. The integrated use of steel piers for these boxes offers many possibilities for prefabrication of the total steelwork in the structure, and the eventual precasting of deck slabs may in future lead to further time savings in construction.

In the work of the author's firm, a compact formulation of the pertinent theoretical background for the design study was evolved. This included the theory for simple single-box spans, for twin and multiple box bridges, and for composite and orthotropic systems. Our present work is on extensions of the theory to cover continuous spans, curved spans, skew spans and generally irregular bridge patterns.

Using this theoretical background and an evaluation of past experience with different variations of the box concept, several potentially favorable systems were selected and comparative designs prepared, detailed and refined, and cost estimates were prepared.

In general, for spans in the 80 ft range, the steel composite box girder bridge superstructures were found to be approximately 10 percent cheaper than the best comparable designs of conventional composite rolled beam or girder spans. This economy increased with increasing span length.

ANALYSIS

In general two different methods of analysis are available for box girder bridge design.

The first method is that based on the theory of folded plates, and has been used by Mattock, Johnston and Scordelis in their investigations. Folded plates are widely used in building, roof, bin and bunker structures, and bridge engineers may therefore not be readily familiar with them. Nevertheless, a typical multi-box bridge as shown in Fig. 1 is a true folded plate system in that it is comprised of an assembly of flat plate strips (the bottom plate, the webs, and the deck) to form a prism. Loads are carried transversely by slab action to the nodes (folds, or intersections of the plates), and thence longitudinally by membrane action to the sup-

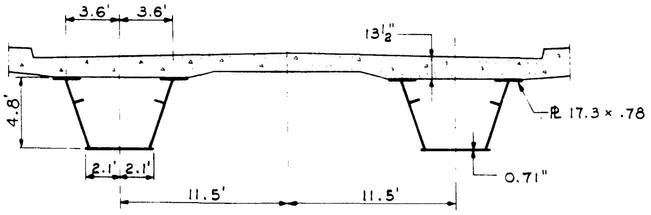

Fig. 1. Approach spans for Frederikstad Bridge over the Glomma, Norway. Span 103 ft. Two steel boxes with cast-in-place composite concrete slab deck

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ports. Obviously, at the supports transverse diaphragms are necessary for stability. The analysis of folded plate systems is covered in standard references,[1] and while complex in character, is susceptible to programming for computer solution. Where the folded plate system has intermediate transverse diaphragms within or between the boxes, the analysis becomes even more involved, and a more complex computer program has been devised for this by Scordelis.

Johnston and Mattock[2] have analyzed many short- and medium-span, steel, multiple-box composite highway bridges without intermediate diaphragms, and with varying number of boxes and lanes of live load, from which they have derived a general, simplified lateral load distribution formula for the fraction W_L of a wheel load to be assigned to each box girder for determining live load bending moment, namely,

$$W_L = 0.1 + 1.7R + 0.85/N_w \qquad (1)$$

where

$R = \dfrac{N_w}{\text{Number of box girders}}$

$N_w = (W_c/12)$, reduced to the nearest whole number

$W_c =$ Roadway width between curbs (ft)

R shall not be less than 0.5 nor greater than 1.5.

This formula has been included in the draft of the proposed specifications. Tests by Mattock and Johnston[3] on quarter- and fifth-scale models have verified the accuracy of the computer based calculations.

A second method of multiple-box girder bridge analysis, which has been followed by the author's firm, Praeger-Kavanagh-Waterbury, and which has been extensively developed and used abroad, is that relating the bridge behavior to a grid of longitudinal and transverse beams, each of which may have torsional as well as flexural stiffness. The merit of this approach is that structural behavior of grids is more readily understood by bridge engineers, the favorable effect of intermediate diaphragms is more readily accounted for, and the complexity due to indeterminacy is reduced by availability of many approximation procedures (those of Engesser, Balog, Homberg, Hendry & Jaeger, Leonhardt, Guyon-Massonnet, Schöttgen, and others) or of more exact computer programs like STRESS or FRAN.

An insight into the structural action of these bridges can be gained by considering their behavior as grid systems, in which the following classification is useful.

GENERAL CLASSIFICATION

Figure 2 shows a general classification of box girder bridge systems, having as an important common element of structural action the lateral distribution of live loads applied eccentrically on the bridge cross section.

Figure 2a is a simple girder bridge with no lateral distribution through its deck slab, i.e., the load P shown is carried entirely by the right-hand girder, as shown by the dotted lateral distribution diagram. Figures 2b and 2c, on the other hand, are examples of grids or gridworks, comprising a planar array of longitudinal girders and transverse or cross beams (or frames), usually intersecting at right angles, but continuous through their intersections. The longitudinal girders in Figs. 2b and 2c are shown as plate girders, with considerable bending rigidity (stiffness) and small (usually negligible) torsional rigidity (stiffness). The transverse beam of Fig. 2b is, however, a torsionally stiff tube or box, which enables a better distribution of the load P to the girders. Figure 2c is the more conventional grid with both longitudinal girders and transverse beams having good flexural rigidity but negligible torsional rigidity. The grid imparts a better lateral distribution than that of Fig. 2a (without cross beams), which would

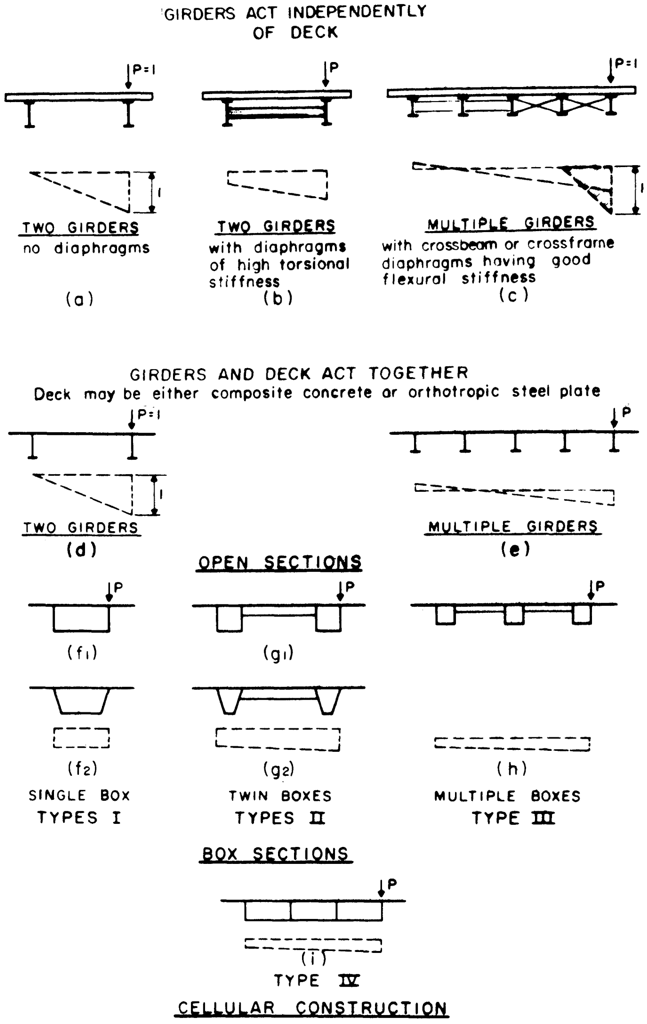

Fig. 2. Lateral load distribution

be as shown superimposed as a shaded area. The distribution is even better in Figs. 2g to 2i where torsionally stiff (box) longitudinal girders are used. Thus, the main characteristic of grids is that their lateral distribution (and therefore their efficiency in causing all elements to participate in the load-carrying function) depends largely on both the flexural and torsional stiffnesses of the longitudinal girders and the traverse beams. Of course, other secondary factors, such as the spacing of girders and the number of transverse beams, also affect the distribution. There are in practice wide ranges of magnitudes of these stiffnesses, and some preliminary insight into the separate effects can be obtained by considering the respective limiting values.

When the transverse beam is lacking and the slab itself has little shear stiffness, the simply supported case of Fig. 2a is obtained. This would also be equivalent to having a grid of non-continuous transverse beams hinged at each longitudinal girder.

Where the grid of Fig. 2c has continuous transverse beams (or frames) with some flexural rigidity, the lateral distribution diagram will normally be curved. When the flexural rigidity of the transverse beam or frame becomes infinite (i.e., the beam or frame is rigid flexurally), the distribution is a straight line. This latter distribution is then analogous to that obtained under eccentric load in a group of piles having a rigid pile cap, and is the basis for simple and useful approximations.

Another class of bridge gridwork is one wherein the deck acts together with the longitudinal girders or transverse beams, either as a composite concrete deck or an orthotropic deck of steel plate with ribs welded thereto in two directions. In continental nomenclature these are referred to as plate grids, and may exist in the form of open sections, Figs. 2d and 2e, or closed (box) sections, Figs. 2f to 2i. The latter box sections are of primary interest here, and they classify themselves naturally into three main types:

Type I—Single boxes (Fig. 2f)
Type II—Twin boxes (Fig. 2g)
Type III—Triple or multiple boxes (Fig. 2h)

The single box, Type I, Fig. 2f, is in a rather special category since it is no longer basically a grid, but rather a single box girder carrying its loading to the supports in flexure and in torsion. Where the torsion is of the St. Venant type (uniform, and the structure is free to warp), the static analysis would be relatively simple; however, restraint against warping may exist (non-uniform torsion) and can cause secondary longitudinal direct stresses of some magnitude. A special theoretical treatment of the single box (Type I) is therefore necessary, as opposed to the grid or orthotropic analyses adaptable to the other systems, Types II and III.

A special classification is shown in Fig. 2i as Type IV, Cellular Construction, involving interconnected plate box grids (egg-crate, closed top and bottom). It may be noted that when the number of boxes is large, a cellular construction analogous to sandwich construction empolyed on aircraft work is arrived at.

Grid theory quickly leads to a number of simple observations. Thus, it is almost intuitive that in a multiple box bridge the lateral distribution for a load at an edge (fascia) box girder is more markedly improved by grid action than would be the case for a load on a box girder near the center of the roadway. Also, the lateral distribution achieved by grids is of primary importance for eccentric live loads which produce torsion; dead loads which are uniformly distributed laterally produce no torsion. The bridge span will therefore also determine the applicability (economy) of grid design. For long spans, say 200 ft or over, dead loads are predominant and concentrated live loads less so, and thus lateral distribution is of reduced importance. For very short spans, say below 50 ft, the lateral distribution effect is diminished for normal widths of roadway.

Furthermore, the more closely the box girders are spaced, the better the lateral distribution. In general, also, as the number of intermediate transverse beams (diaphragms) increases, the lateral distribution improves, but practically the number of transverse beams is normally set at zero, or one (at the center of span), or a maximum of three (at the quarter points), for economic reasons. In the absence of transverse beams, the "grid" seems to disappear; however, an "equivalent" intermediate diaphragm is employed to represent the stiffness of the slab. For usual grids, the bending stiffness of the transverse beams, if used, need only be about one-fifth that of the longitudinals to produce an effect approximately equal to that of an infinitely rigid transverse member.

An important fact in understanding grid action is the recognition that the transverse beams are basically continuous beams on multiple supports which are elastic with respect to deflection and rotation. The spring constants, unfortunately, vary at different points of the girder span; for example, the linear spring constant at a point is obtained from the deflection of a girder by a 1 lb load at the point, and thus varies from a minimum at the center of span to a maximum at the supports. From this it is evident that the lateral distribution decreases to zero as one approaches the supports. This forms the basis for numerous approximations ranging from those assuming a more-or-less linear variation of the distribution from the center of span to the supports, to those which replace all cross beams by an equivalent one at center span with augmented stiffness.

As in all highly indeterminate systems, box girder grids possess a high reserve against overload, since their action may cause only one or two sections to reach a yield condition. A limit design (plastic analysis) is therefore possible.

The studies reported here, which are in their advanced stages, indicate that the effect of warping of the box sections is only important in single box bridges, and even there can be reduced or eliminated by the use of internal diaphragms.

It is possible to derive (and the author's office has done so) analytical techniques for simple curved multi-box bridges, with or without transverse diaphragms, and to reduce these to a computer program. The use of grid analysis and the STRESS and FRAN programs, with modifications, appears also to offer supplementary opportunities for analysis of *any* types of simple or continuous curved box bridges, skewed bridges, or even multi-box bridges of highly irregular shape, such as with non-parallel girders or other combinations of skewness, non-circular curvature in plan, or geometrically irregular placing of transverse beams. With such systems the use of transverse beams or diaphragms is almost mandatory for purposes of erection.

DESIGN FACTORS

In successful past design and construction efforts centering around relatively short span steel box girders, major attention has been given to single boxes for one- or two-lane bridges, and multiple boxes (usually two or three) for two-lane and larger roadways. Figures 3 through 18 are examples of box girders in bridge construction.

Composite deck slabs of reinforced concrete have been found most economical, but recently attention has been directed to precast deck units made composite either by high-tensile bolting (to develop frictional shear) or by high-tensile bolting as a supplement to epoxy mortar bonding as a shear developer. This is the so-called VK system used in Germany (Fig. 17). Occasionally, the precast slab is prestressed in the transverse direction, using post-tensioning cables.

The size of the boxes is limited by the shipping clearances normally required to be within standard traffic lane widths of 11 to 13 ft, and the headroom under bridges of 14 ft-2 in. or slightly more.

Appearance and fabrication considerations dictate the use of box bridges with rectangular or trapezoidal boxes as shown in Fig. 19. Both provide high torsional stiffness, and the selection of one or the other is a matter of practicality of fabrication of the box, and the subdivision of transverse slab spans. The trapezoidal box usually requires a heavier bottom plate and may require a heavier slab to span the top. To reduce the span of the slab, resort is sometimes taken to an additional longitudinal stringer at the centerline between the cross frames.

And finally a note on maintenance. Much has been written abroad about the advantages of the closed box in relation to protection provided by the interior steel. All protruding edges, angles, bolt heads, etc., which in themselves are starting points for corrosion, are within the box and protected from the weather. A closeable access manhole, and solid web end closures (cross beams), insure the maintenance of a watertight and vaportight interior. The exterior steel surfaces are smooth flat expanses of plate steel offering no local points for incipient corrosion, and providing an excellent base for protective finishes.

In fact, since approximately 60 percent of the steel surfaces are in a protected interior environment, and all exposed surfaces are flat, a strong case may be made for a reduction in the normal minimum plate thicknesses required by the bridge specifications.

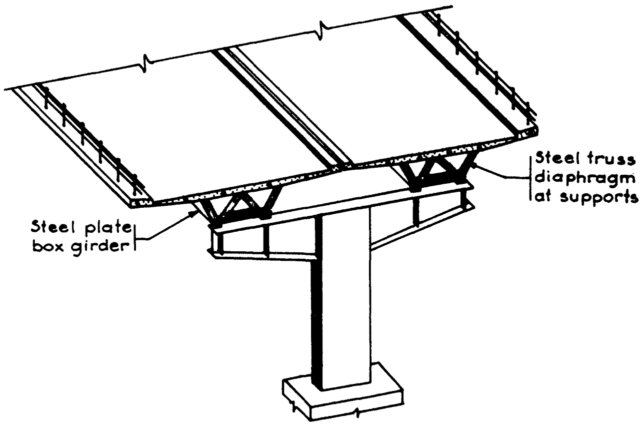

Fig. 3. Elevated highway in Genoa, Italy

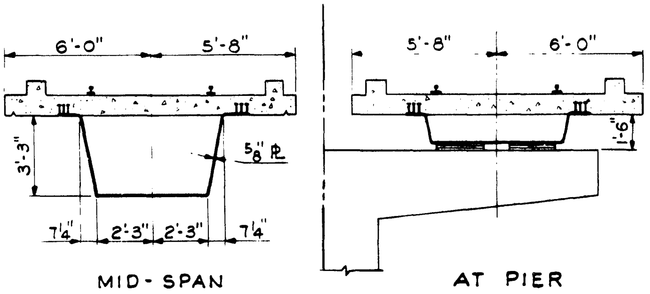

Fig. 4. Proposed structure for elevated rapid transit system, San Francisco Bay Area. Span 85 ft. A single steel box girder with a composite cast-in-place concrete deck slab. The depth of box is reduced at pier supports. When superelevation is required, unequal web depths are used at the supports

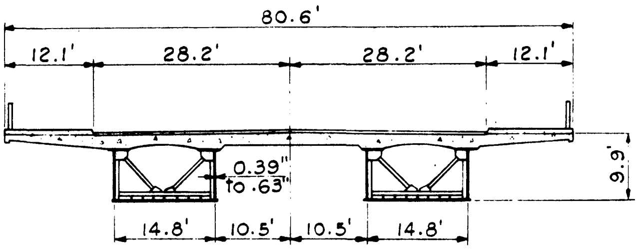

Fig. 5. Schloss Bridge, Mulheim-on-Ruhr, Germany. Spans 138 ft–145 ft–138 ft. A three-span continuous twin steel box with composite concrete deck. The deck is prestressed both laterally and longitudinally

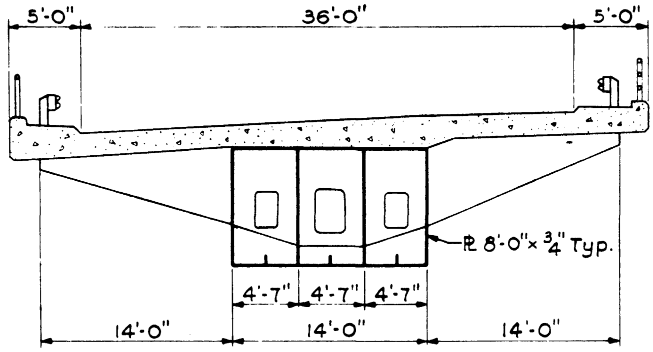

Fig. 6. Fylde Junction Higher Bridge, Great Britain. Spans 7 @ 130 ft and 4 @ 97.5 ft. Three-cell box with cantilever arms supporting a reinforced concrete deck slab

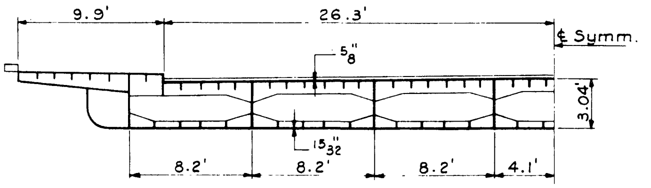

Fig. 7. Nishi-Ohashi Highway Bridge over Nagahori river, Japan. Span 103 ft. A multi-cell steel bridge with a 2.2 in. asphalt wearing surface

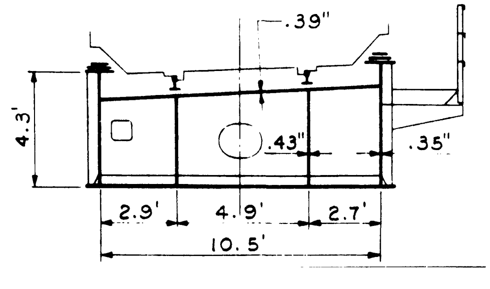

Fig. 8. Railroad bridge over Alsstrasse, M-Gladbach, Germany. Span 80 ft. A three-cell steel box with rails bearing directly on upper flange of box

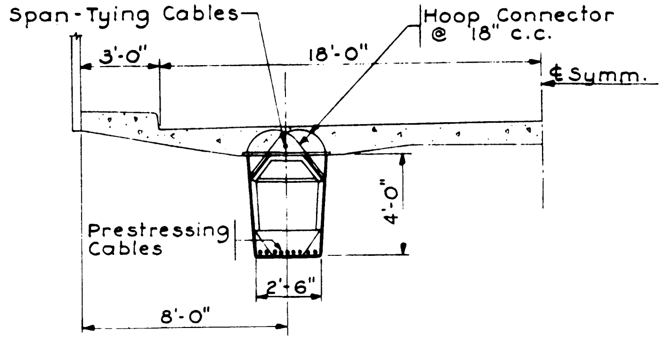

Fig. 9. Brits Highway Bridge, Transvaal, South Africa. Spans 83 ft–83 ft–83 ft–83 ft. Two closed steel box girders continuous for four spans. The box girders are strengthened by prestressing cables and composite cast-in-place concrete deck

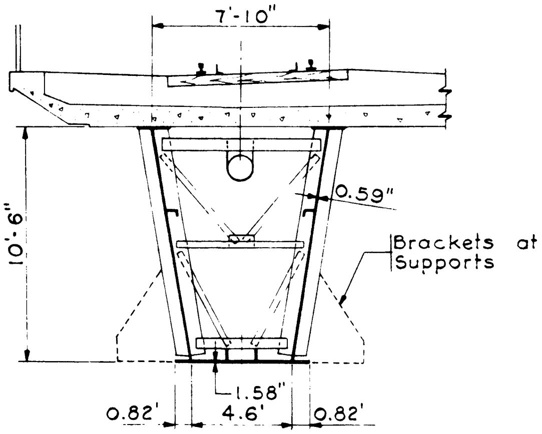

Fig. 10. Standardized Czech railroad bridges. Span 152 ft-6 in. A single steel trapezoidal section with precast concrete deck. The deck is connected to the box by high strength bolts to achieve composite action. This standard section may be used for single and multi-track railway bridges

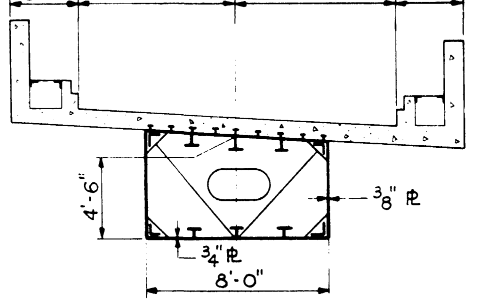

Fig. 11. Curved roadway ramp, Port of New York Authority Bus Terminal, New York City. Spans 58.5 ft–52 ft–73 ft. A continuous single steel curved box with a cast-in-place deck slab. Part of this structure was built on a horizontal curve with a 67-ft radius. The top flange plate conforms to the cross slope of the roadway. The bottom plate is horizontal, normal to the roadway section

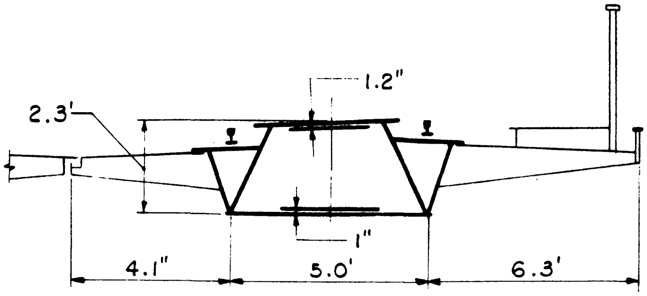

Fig. 12. Railroad bridge over Autobahn, Kirchweyhe (Bremen), Germany. Spans 56 ft–56 ft. The rails bear directly on the steel box without use of ties or ballast. Each box is fully shop prefabricated

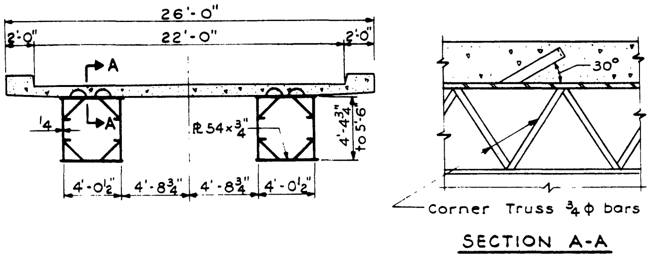

Fig. 15. Two-lane highway bridge, King County, Washington. Span 110 ft. Two boxes with cast-in-place concrete deck slab. Pairs of shear connectors made of 2 × ¼-in. flat bars welded at a 30-degree angle to the top plate achieve composite action. Corner trusses are used to make assembly extremely rigid

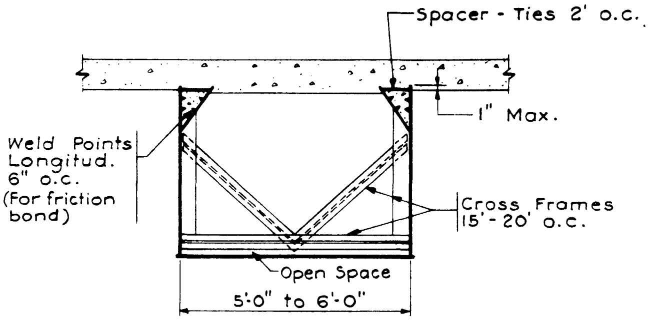

Fig. 13. Box UV girders (Hadley). This box girder with corner plates forming continuous V-shaped troughs filled with concrete illustrates an unusual method proposed by Hadley for connecting the composite deck to the steel box

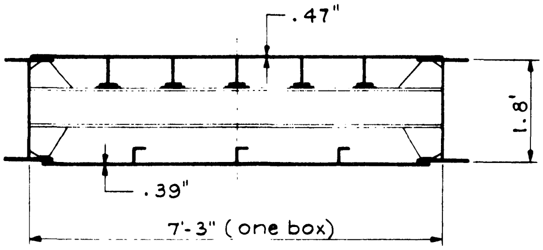

Fig. 16. Highway bridge over R. R. on Nanterre-La Garenne Rd., France. Spans 55 ft–38.25 ft–55 ft. This continuous bridge is composed of several shallow one-piece steel boxes separated by non-rigid ties. The deck is 4-in. concrete laid over a ¾-in. bituminous surface

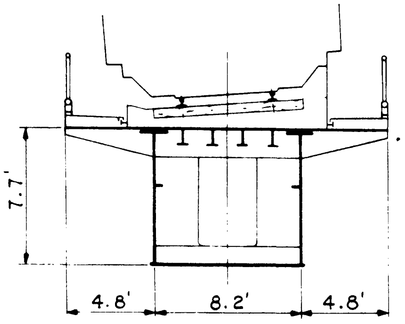

Fig. 14. Railroad bridge over Stresemannstrasse, Hamburg, Germany. Spans 132 ft–148 ft. A two span continuous single steel box with stiffened steel deck

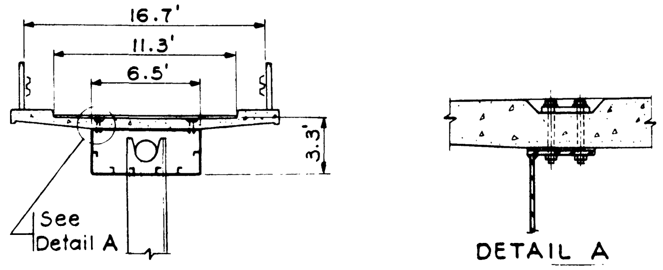

Fig. 17. Curved viaduct ramp, Hannover, Germany (1961). Span 67 ft. A continuous single steel box, curved in plan, with precast concrete deck slab. The slab is connected to the box by high strength bolts to achieve composite action by friction. Part of this structure was built on a horizontal curve with a radius of curvature of 30 ft

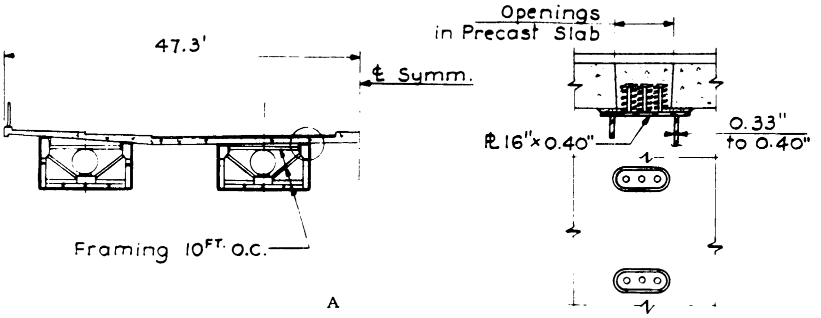

Fig. 18. Emil Schulz Bridge, Berlin-Lichterfelde, Germany (1964). Span 157 ft. The boxes are jointed by three lateral frames at the quarter points and the centerline to form a grid. Stud shear connectors with small spirals connect the precast concrete deck slab to boxes

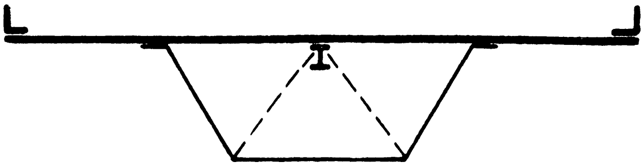

Fig. 19. Means of reducing slab span across box

CONCLUSION

All factors point to an expanded, favorable and economic application of steel composite box bridges for simple and continuous short spans, and the extension of such use to bridges which may be highly skewed, curved, or grossly irregular in its geometric arrangement of box elements.

ACKNOWLEDGMENTS

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