

A New Design For Torsion Resistant Suspension Bridges

HAROLD SAMELSON

THE PROPOSED design for improving torsional stiffness of the Manhattan Bridge was developed by the author as an alternate to published plans* for reducing the excessively high maintenance costs of the bridge. A preliminary simplified model incorporating the principal components of the proposed design was analyzed. The results indicated a decrease in torsional deflections approaching 90%. Finally, a rigorous check was made using the computer to analyze three dimensional models of two suspension bridges. The bridges were the same in overall dimension and member size, except that one was conventionally framed and the other contained elements of the author's designs. The result supported all of the conclusions drawn from the analysis of the simple model; in fact, torsional deflections diminished by more than 90%.

Harold Samelson is Structural Engineer, Control Data Corporation, New York, N.Y.

* *Engineering News-Record, October 1974.*

SOME BRIDGE STATISTICS

The Manhattan Bridge, a New York City landmark opened to traffic in 1909, is an East River crossing connecting the boroughs of Brooklyn and Manhattan. It is suspended by four cables which support a corresponding number of stiffening trusses. A typical cross section and elevation are shown in Fig. 1. The bridge carries two double-lane roadways on the upper level, between the outer pairs of trusses, and one three lane roadway between the two center trusses on the lower level. In addition to vehicular traffic, the bridge carries a dual pair of tracks for rapid transit cars, located in the outer bays of the lower level. Cantilever brackets support pedestrian walks located at each side of the lower level.

The superstructure has a main span of 1470 ft and equal side spans of 727 ft. The stiffening trusses are 27 ft deep and are supported by suspenders attached to the bottom of the lower chords. The inner bay is 40 ft, the outer bays are 28 ft, and the sidewalks are 12 ft, making a total width of 120

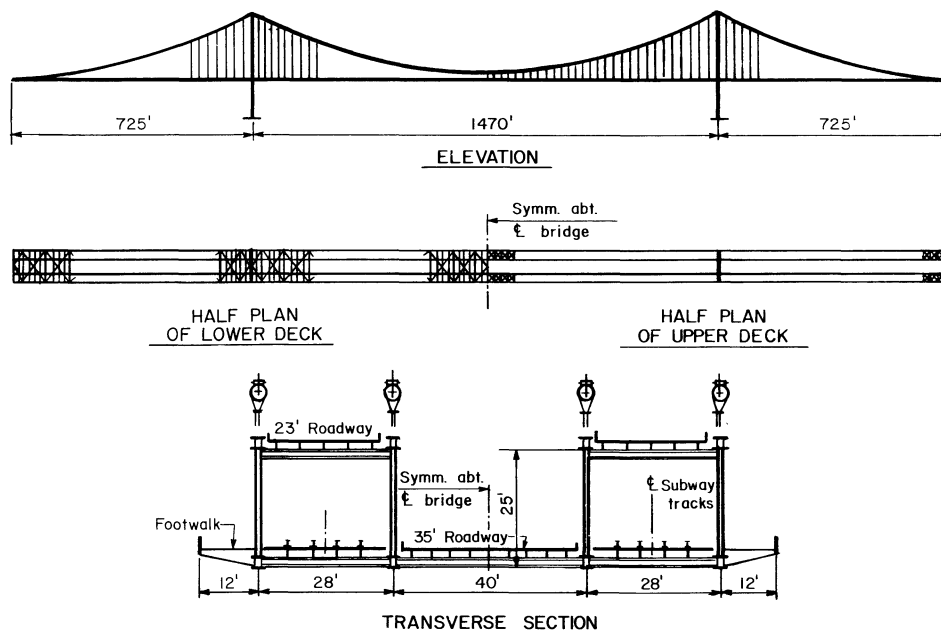
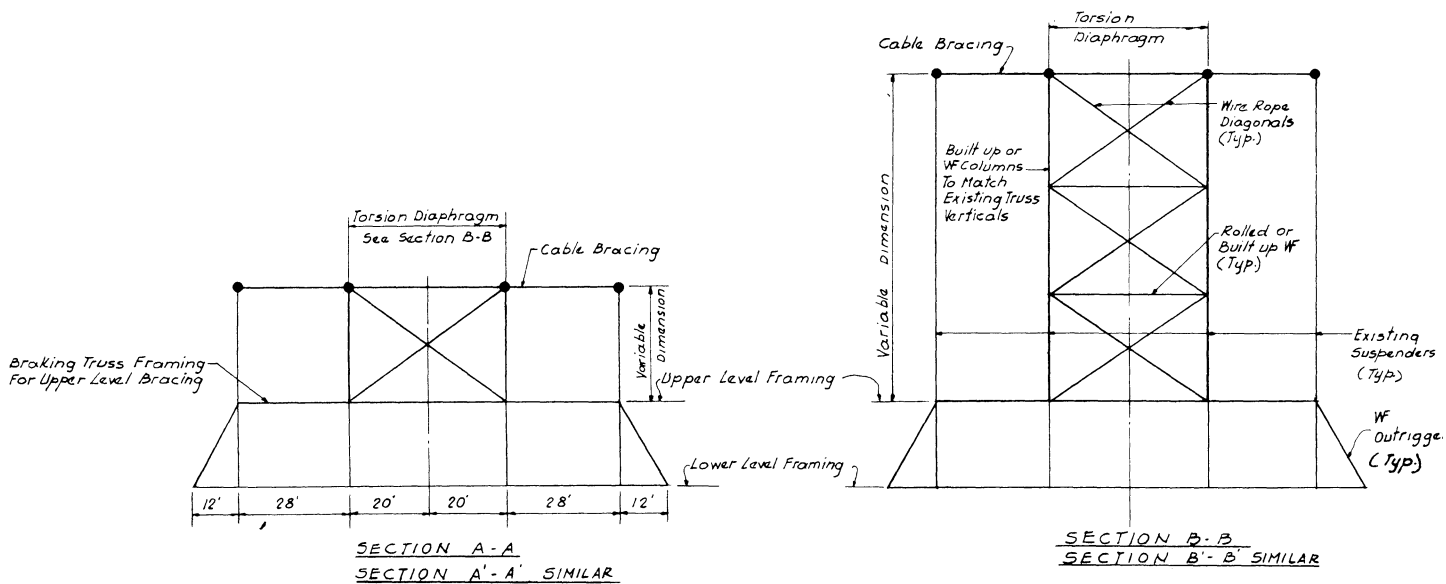
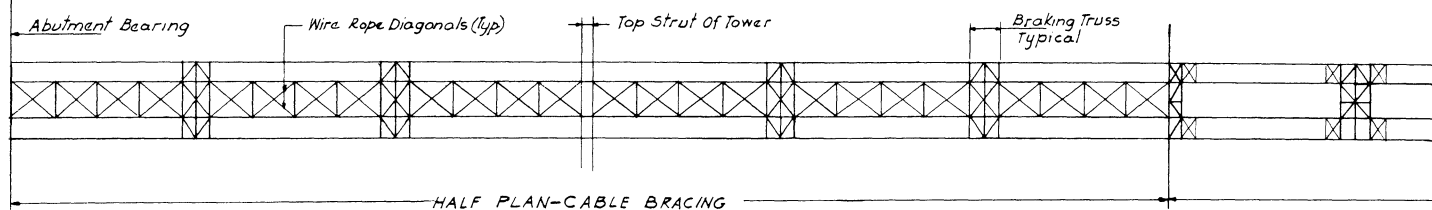
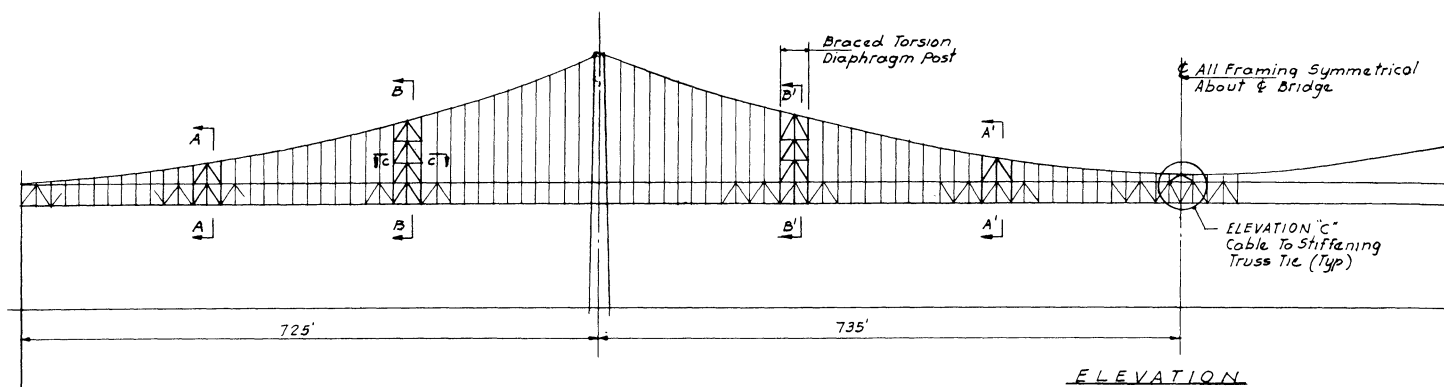


Fig. 1. Typical cross section and elevation



MANHATTAN BRIDGE

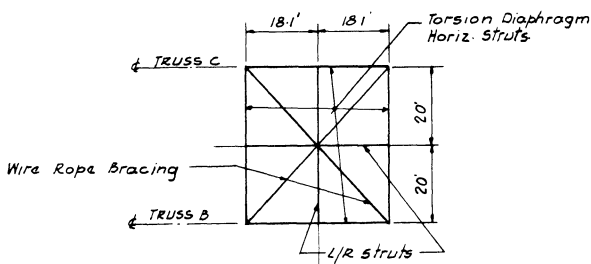
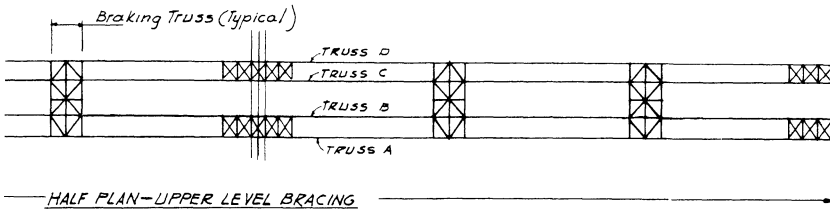
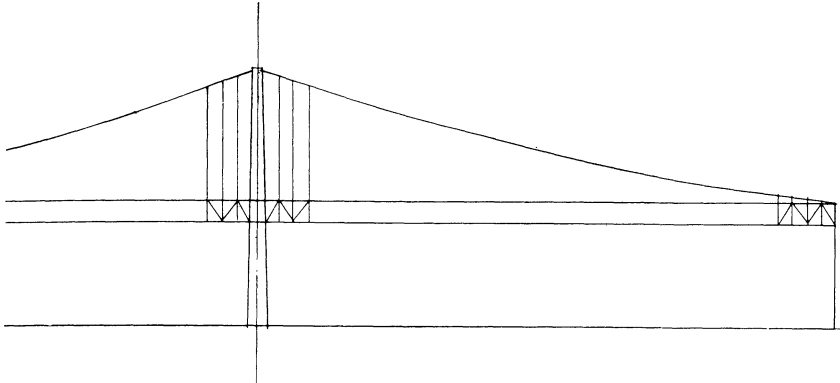
PROPOSED STRENGTHENING
TO REDUCE TORSIONAL DEFLECTIONS

ADDITIONS TO BASIC FRAMING SYSTEM

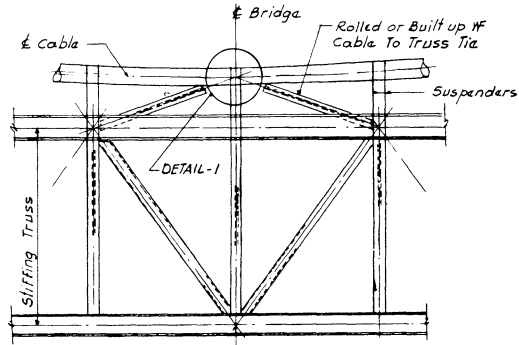
- a. CABLE BRACING AND BRAKING TRUSSES
- b. BRACED TORSION DIAPHRAGMS
- c. BRAKING TRUSSES ON UPPER LEVEL BRACING
- d. CABLE TIE TO STIFFENING TRUSS AT CL OF BRIDGE

FUNCTIONS OF FRAMING ADDITIONS

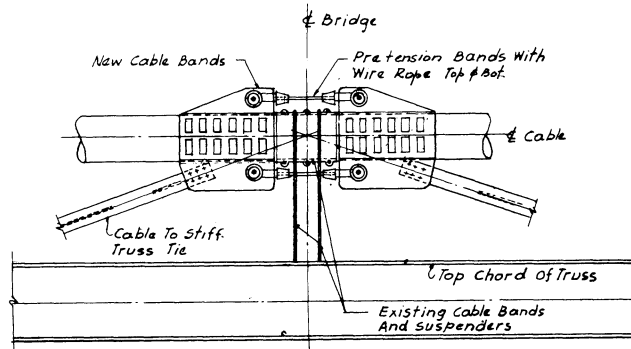
- a. TORSION DIAPHRAGM COUPLES BRACED CABLES TO LOWER LEVEL DIAGONAL BRACING PROVIDING EXTREMELY HIGH RESISTANCE TO TORSIONAL LOADS OF SUBWAY CARS
- b. CABLE BRACING TRUSSES FORCE PARTICIPATION OF ALL CABLES IN RESISTING TORSIONAL LOADS
- c. BRACED TORSION DIAPHRAGM POSTS ACT AS SHEAR CONNECTORS BETWEEN CABLE AND STIFF TRUSS THEREBY DECREASING SIGNIFICANTLY THE VERTICAL DEFLECTIONS OF THE BRIDGE
- d. CABLE TIES TO STIFF TRUSS AT CL OF BRIDGE PERFORM AS SHEAR CONNECTORS WHOSE ACTION IS DESCRIBED IN ITEM "c"
- e. BRAKING TRUSS IN UPPER LEVEL INTEGRATES THE BRACING BY VIERENDEL ACTION THEREBY STRENGTHENING THE BRIDGE AGAINST TORSIONAL DEFLECTION



SECTION C-C (TYP)



ELEVATION C



DETAIL-1

Fig. 2. Proposed strengthening to reduce torsional deflections

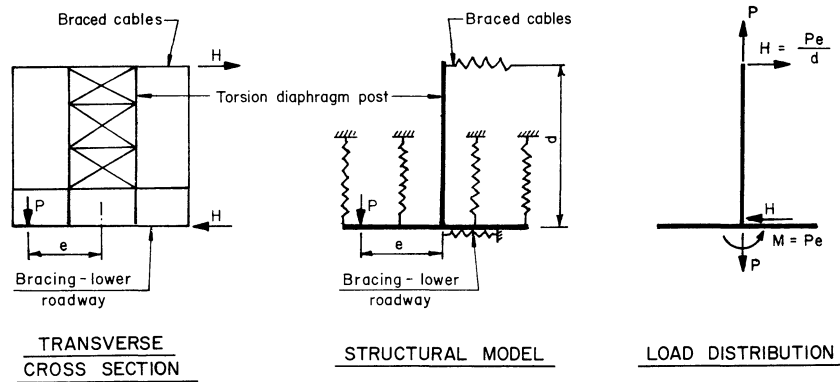


Fig. 3. Diaphragm action of post

ft. A plane of lateral bracing is attached to the bottom of the lower chords for the total length of the bridge. Upper level planes of lateral bracing were originally attached to the bottom of the upper chords in the outside bays. This bracing system was entirely removed from the bridge after frequent and persistent failure convinced authorities that mere strengthening and replacement of members would not solve the problem.

DEFICIENCIES OF THE ORIGINAL DESIGN

Before introducing the proposed design, a brief review of the major deficiencies of the original design will be presented. Concisely, the bridge's problems stem from the following sources:

1. Inadequate torsional rigidity of the superstructure.
2. Low torsional stiffness of the inner pair of cables.
3. High torsional loads resulting from transverse eccentricity of trains.
4. Inadequate resistance to changes in cable geometry caused by moving loads.

The lack of superstructure torsional rigidity is caused primarily by the absence of an upper level lateral system and the relatively stiff transverse frames necessary to distribute the applied torque into the upper and lower lateral systems. Consequently, the applied torque is resisted pri-

marily by the cables, which are inefficient in torsional resistance because the inner pair contributes only 17.5 percent of the torsional stiffness of the outer pair. The available torsional stiffness can be expressed as a percentage of that which would be theoretically possible if each pair of cables were located at the outside stiffening trusses:

$$\% \text{ Available} = \frac{117.5}{200.0} \times 100 = 58.7\%$$

The foregoing discussion of the bridge's problems provides the background necessary to introduce a design for their correction.

PROPOSED SOLUTION

The key to the proposed solution is the recognition of the great potential for torsional resistance in the horizontal stiffness of the cables and the braced framing of the lower roadway. A coupling of these two systems by diaphragm posts provides a mechanism to substantially increase the torsional stiffness of the bridge.

The plan for revisions to the bridge is pictured in Fig. 2. The principal additions and their functions are as follows:

1. Cable bracing and bracing trusses.
2. Braced torsion diaphragms.
3. Cable tie to stiffening truss at center line of bridge.

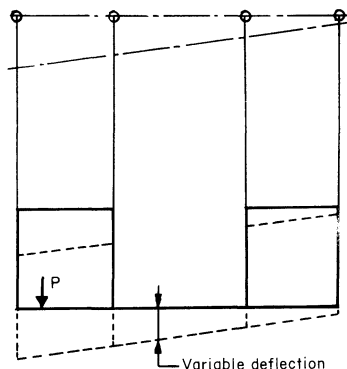


Fig. 4. Cross-sectional deflection of existing bridge

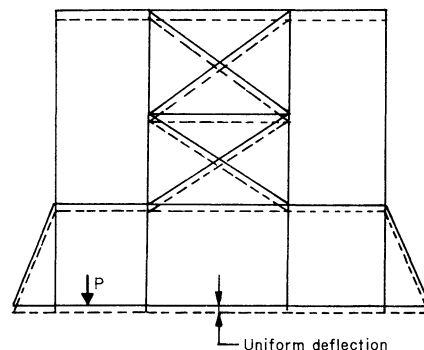
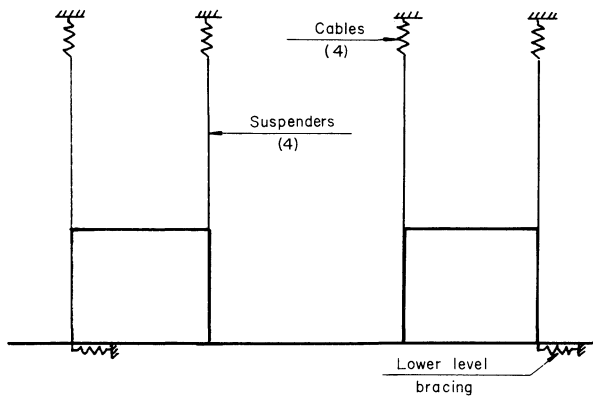
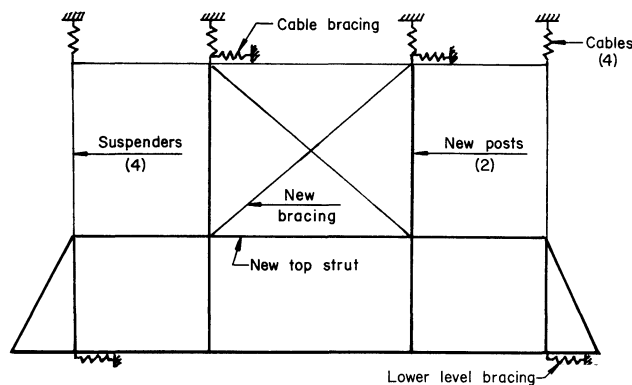


Fig. 5. Cross-sectional deflection with torsion diaphragm post



$$\begin{aligned} K \text{ OF VERTICAL SPRING} &= 10^k / \text{FT.} \\ K \text{ OF HORIZONTAL SPRING} &= 100^k / \text{FT.} \end{aligned}$$

Fig. 6. Model of existing cross section



$$\begin{aligned} K \text{ OF VERTICAL SPRING} &= 10^k / \text{FT.} \\ K \text{ OF HORIZONTAL SPRING} &= 100^k / \text{FT.} \end{aligned}$$

Fig. 7. Model of cross section with torsion diaphragm post

The torsion diaphragm couples braced cables to lower level diagonal bracing, providing extremely high torsional resistance. In addition, the torsion diaphragm posts and the cable tie to the stiffening truss act as shear connectors between cable and stiffening truss, significantly increasing the vertical stiffness of the bridge. The cable bracing and bracing trusses force participation of all cables in resisting torsional loads. Figure 3 illustrates the relevant mechanics of the torsion diaphragm post. The horizontal springs represent the stiffness of the braced cables and the lower roadway framing, while the vertical springs represent the stiffness of the cables. The horizontal stiffness is large in comparison to the vertical (30:1), thereby assuring a major portion of the applied torque to be distributed to the horizontal springs. Since the torque distribution to vertical springs is negligible, the following equation closely approximates the conversion of vertical action into horizontal reaction (refer to Fig. 3):

$$\text{Acting Torque } (P \cdot e) = \text{Reacting Torque } (H \cdot d)$$

It follows that the response to applied torsion is predominantly equal vertical deflection of the cables—the horizontal deflection being small by comparison because of the high spring stiffness in that direction. The principle of redistribution of torsion to the stiffest path is the key to understanding why the proposed revisions are so effective in strengthening the bridge.

Figures 4 and 5 demonstrate the effectiveness of the torsion post in reducing the vertical deflection caused by torsional loads. The stiffening trusses in the “Bridge As-Is” (Fig. 4) participate only partially in distributing unbalanced load to the cables because they deflect unevenly, i.e., the trusses near the applied load undergo large deflections (they participate), whereas the others undergo small deflections and consequently do not effectively participate. On the other hand, the “Bridge With Torsion Diaphragm

Post” (Fig. 5) deflects uniformly, indicating equal participation of the trusses in distributing unbalanced load to the cables. The net result is that the “Bridge With Torsion Diaphragm Post” resists load with considerable less deflection.

Figures 6 and 7 show simplified models for which computer analyses were made to check the validity of the assumed actions. The solution indicated an 87% reduction in torsional deflection, an encouraging figure which was checked by a detailed three-dimensional computer analysis. The principal results of that analysis are presented in Fig. 8, which contains a plot of the exterior stiffening truss

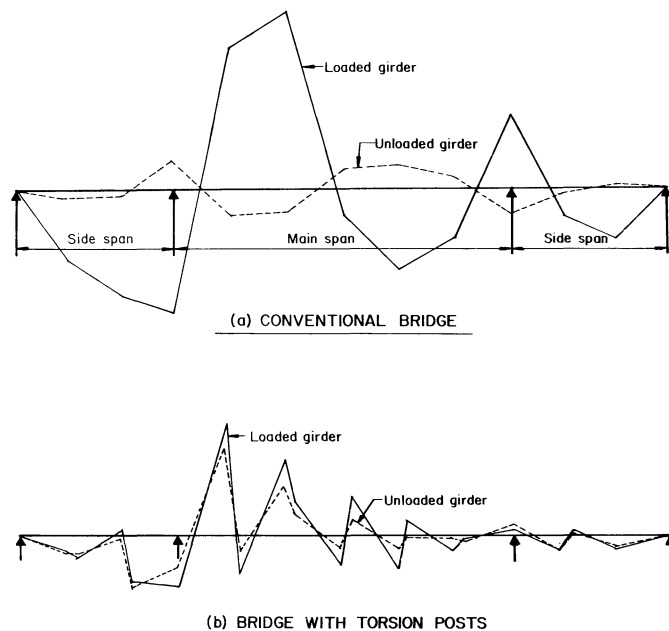


Fig. 8. Girder moments

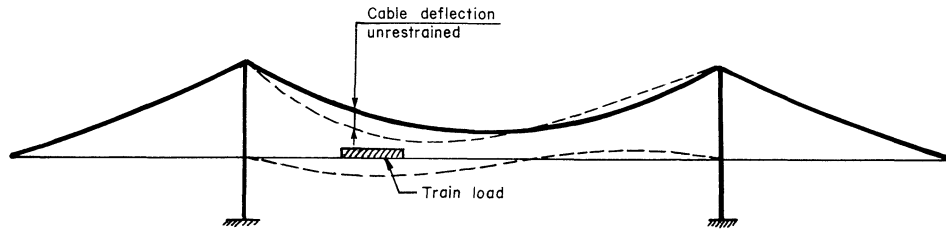


Fig. 9. Main span deflection of existing bridge

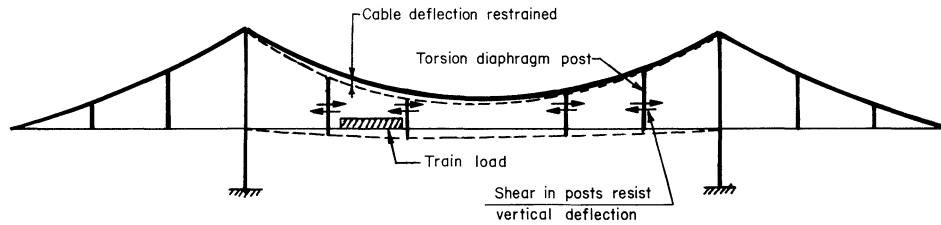


Fig. 10. Main span deflection with torsion diaphragm post

moments for two bridges; one is conventional and the other has torsion posts. The results clearly indicate the following:

1. Truss participation and load distribution to the cables are dramatically improved by the torsion post.
2. The torsion posts function effectively as shear connectors to reduce stiffening truss moments and deflection. This action, shown in Figs. 9 and 10, effectively reduces change in cable geometry by resisting the longitudinal sway caused by unbalanced load. The effect is to increase the vertical stiffness of the bridge.

Finally, Fig. 11 shows how the diaphragm posts resist by torsion the tendency for differential longitudinal displacement of the cables.

The concept of the torsion post has been presented as a means of stiffening the Manhattan Bridge. However, it can be economically and effectively applied to other types of suspension bridges where high resistance to deflection from unbalanced load is required. Present day practice places this stiffness locally into the superstructure, whereas the design presented takes advantage of the large depth from cable to truss to achieve better economy.

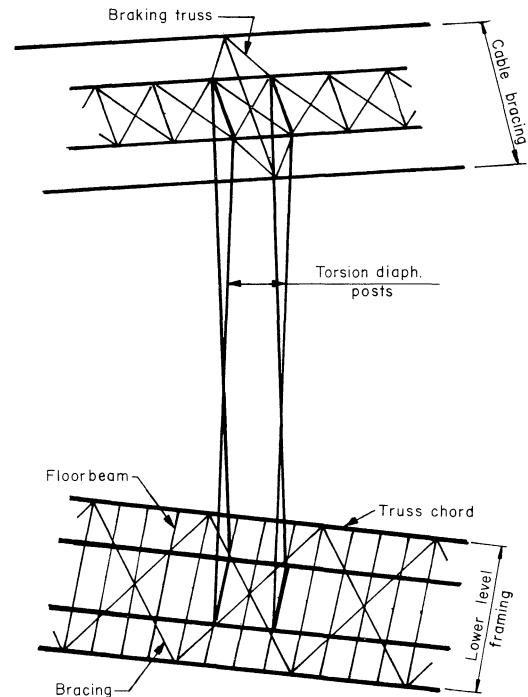


Fig. 11. Torsion action of post