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Renovation of Lions' Gate Bridge

Rénovation du pont Lions' Gate

Erneuerung der Lions' Gate Brücke

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SUMMARY

Rising capital costs of new construction are forcing bridge engineers to give serious consideration to renovation instead of replacement of existing bridges. This paper, which describes the renovation of Lions' Gate Suspension Bridge in Vancouver, Canada, identifies some of the defects common to bridges of 1930's vintage and discusses the steps taken in this case to remedy these defects and prevent their recurrence without unduly disrupting peak traffic flows on the bridge.

RESUME

La hausse des coûts de construction oblige les ingénieurs à examiner sérieusement la rénovation au lieu du remplacement de ponts existants. Cet article décrit la rénovation du pont suspendu Lions' Gate à Vancouver, Canada, identifie quelques-uns des défauts communs aux ponts des années trente et discute les démarches entreprises pour remédier à ces défauts et empêcher qu'ils ne se reproduisent, sans entraver de façon majeure la circulation sur le pont aux heures de pointe.

ZUSAMMENFASSUNG

Steigende Kapitalkosten für Neubauten zwingen Brücken-Ingenieure, Renovationen ernstlich in Erwägung zu ziehen, anstatt existierende Brücken durch neue zu ersetzen. Dieser Beitrag beschreibt die Renovation der Lions' Gate Hängebrücke in Vancouver, Canada, beschreibt einige häufige Mängel von Brücken der Dreissiger Jahre und erörtert die Schritte, die unternommen wurden, um diese Mängel zu beheben und ein Wiederauftreten zu verhindern, ohne den Hauptverkehrsfluss der Brücke unnötig zu unterbrechen.



1. INTRODUCTION

Lions' Gate Bridge was built in 1938 and has a total length of 1518m. The South approach road is located on a bluff and leads directly into the sidespan of the high level Suspension Bridge, which has a total length of 847m and a mainspan of 473m. At the termination of the North sidespan the bridge continues for another 669m over the North Viaduct with 25 spans ranging in length from 13m to 38m.

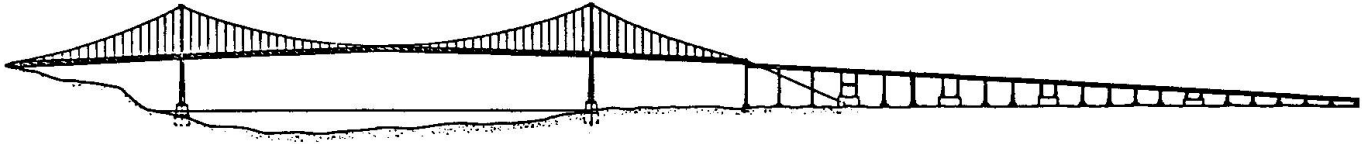


Fig. 1 Elevation Lions' Gate Bridge.

The North Viaduct was built of rivetted steel construction with a reinforced concrete deck supported on cross beams and longitudinal plate girders. The Suspension Bridge comprised a concrete filled steel grid deck supported by steel stiffening trusses and towers.

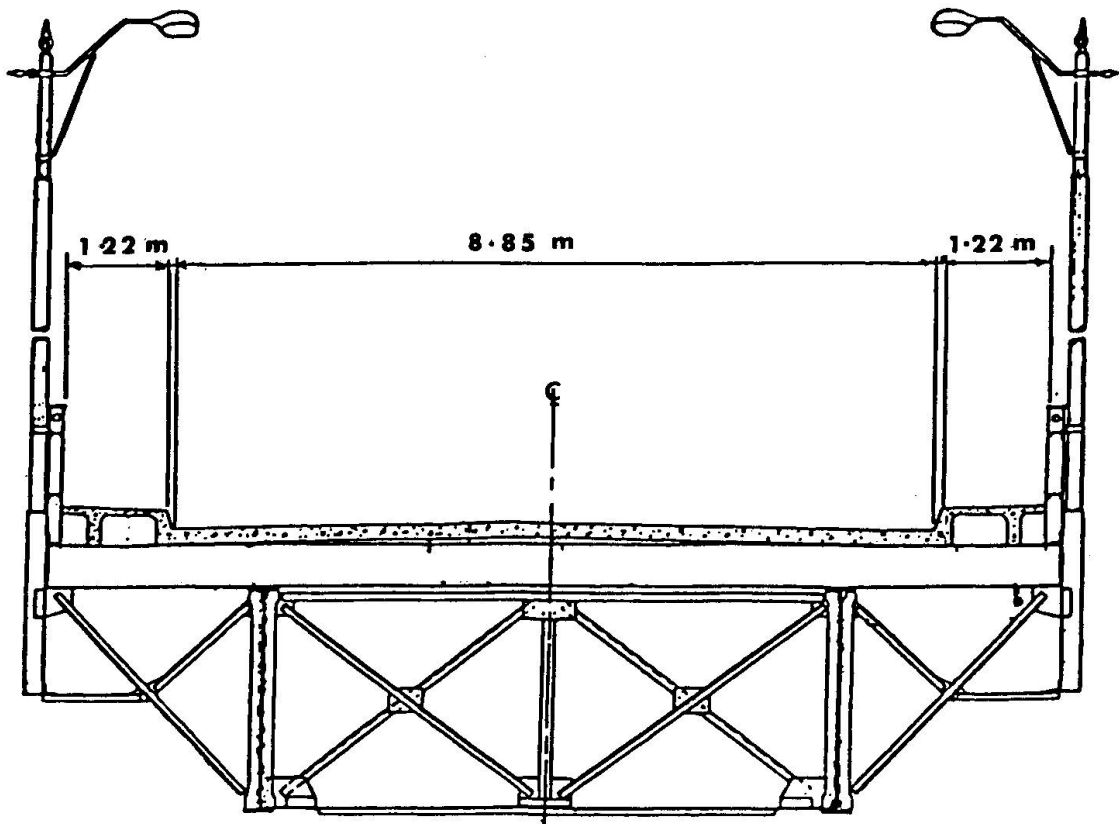


Fig. 2 Cross Section of North Viaduct

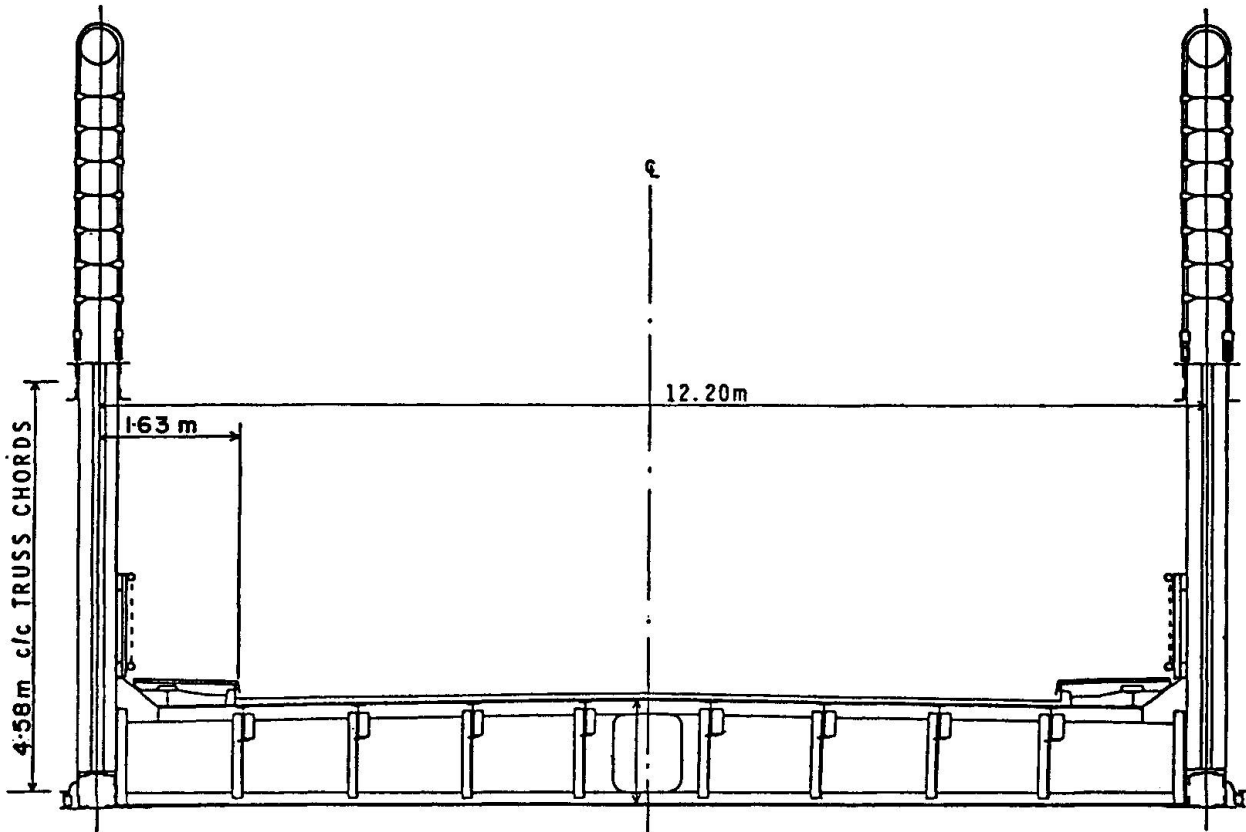


Fig. 3 Cross Section of Suspension Bridge.

The stiffening truss, being of a U shape in cross section (see Figure 3), has a low torsional rigidity. The towers are made of rivetted boxes and the girders and bents of the North Viaduct are rivetted steel plate girders. The South Main Tower is founded on rock, but all other foundations are spread footings on gravel.

The form of construction of this bridge is common to many medium span suspension bridges built in the 1930's in North America and elsewhere. Bridges of this vintage are now approaching a point in their lives where renovation or reconstruction must be considered.

This bridge forms an essential artery between the suburbs and downtown Vancouver. Construction of a new crossing was considered in the early 1970's, but was rejected by conservationists. With replacement ruled out, it became necessary to consider renovation.

Renovation of Lions' Gate Bridge is proceeding in three Phases:-

Phase 1	-	1974-5	Renovation of North Viaduct
Phase 2	-	1978-9	Repairs to North Cable Bent and Footing
Phase 3	-	1980-3	Renovation of Suspended Spans.

2. TRAFFIC ON THE BRIDGE

The bridge as built had a roadway width of 8.84m and carried two lanes of traffic. This was later increased to three lanes each of 2.95m as traffic volumes



built up. The traffic comprises only automobiles and buses (trucks were banned in 1973 in order to reduce live load) carrying commuters to and from downtown Vancouver. Due to user familiarity with the bridge and also to the high degree of control exercised by the Bridge Patrol Officers, who direct tidal traffic flow by lane signal lights, the traffic volumes passing over the bridge are very high (about 60,000 vehicles per day) despite the narrow traffic lanes. In winter about 60% of the vehicles on the bridge use tire studs. This fact, coupled with the high traffic volumes and the uphill grade for most of the bridge length, combine to create very severe wear of the bridge deck paving.

3. PLANNING FOR RENOVATION

Renovation of a bridge may be carried out under any one of three traffic conditions:-

1. - Renovation with normal traffic flow on the bridge.
2. - Renovation with the bridge closed to traffic.
3. - Renovation with one or more traffic lanes closed.

Certain bridge components may be renovated under condition 1, but any major work affecting the bridge deck requires condition 2, or 3. The choice between these alternatives depends upon the deck structure itself. Where a deck is supported by longitudinal stringers, the deck may usually be renovated or replaced one lane at a time, although a second lane will normally be required for access by construction machinery.

Thus on a bridge having 4 or more lanes, progressive lane renovation can be carried out at off peak periods without total bridge closures. However, if the deck structure is supported on transverse beams, as is the case for Lions' Gate Bridge, then full bridge closures are necessary for replacement of these components.

Because this bridge is a critical urban link, prolonged total bridge closures were out of the question. It was considered essential to maintain weekday peak commuter traffic flows in all lanes. Thus bridge renovation was planned around 6.50 hour night closures (23.30 to 06.00 hrs.) for work in the North Viaduct and 48 hour weekend closures for the Suspension Bridge renovation. This time constraint, requiring complete sections of bridge deck to be renovated and opened for traffic in such short time periods, added considerably to the design and construction problems of this project.

4. NORTH VIADUCT

4.1 Components Requiring Renovation

After 35 years of wear, the deck of the North Viaduct was in very poor condition. It comprised a 178mm reinforced concrete slab without wearing surface. Abrasion by traffic had removed the concrete cover and the top reinforcing steel entirely in places and furthermore cores showed cracks extending through the full slab depth. The supporting floorbeams were severely corroded while the plate girders and bents showed local corrosion where de-icing salts used on the road had accumulated.



4.2 Design for Renovation of the North Viaduct

Basically all of the problems in the North Viaduct stemmed from the bridge deck. Its main shortcomings were:-

1. - lack of wearing surface.
2. - insufficient road width.
3. - crevice corrosion due to drainage of de-icing salts from the deck onto rivetted support steel.

It was desirable to correct all of these deficiencies within the constraint of short bridge closures (as mentioned earlier), while at the same time increasing live load capacity of the bridge to bring it in line with modern design loads for a three lane bridge. Heavier traffic loads on a wider deck, acting at larger eccentricities from the girders and riding on a wearing surface which didn't previously exist, all tend to increase the forces on the support structure. Conversely, corrosion losses in the support steelwork required that the total effective load be reduced for safety. These opposing structural constraints had to be resolved by the design for renovation.

Consideration of the constraints on a structural solution for the North Viaduct led to two conclusions. Firstly, the new deck must have a much lower dead weight than the original in order to afford margins for wearing surface, increased width, traffic barriers etc. and secondly, the new deck and girder system must have increased live load bending capacity to handle a higher live load with a girder capacity reduced by corrosion.

A suitable solution was found in the form of an orthotropic steel deck connected by diaphragms to the existing longitudinal girders in order to ensure composite behaviour under live load. This effectively reduced dead load well below previous values and also reduced girder live load bending stresses.

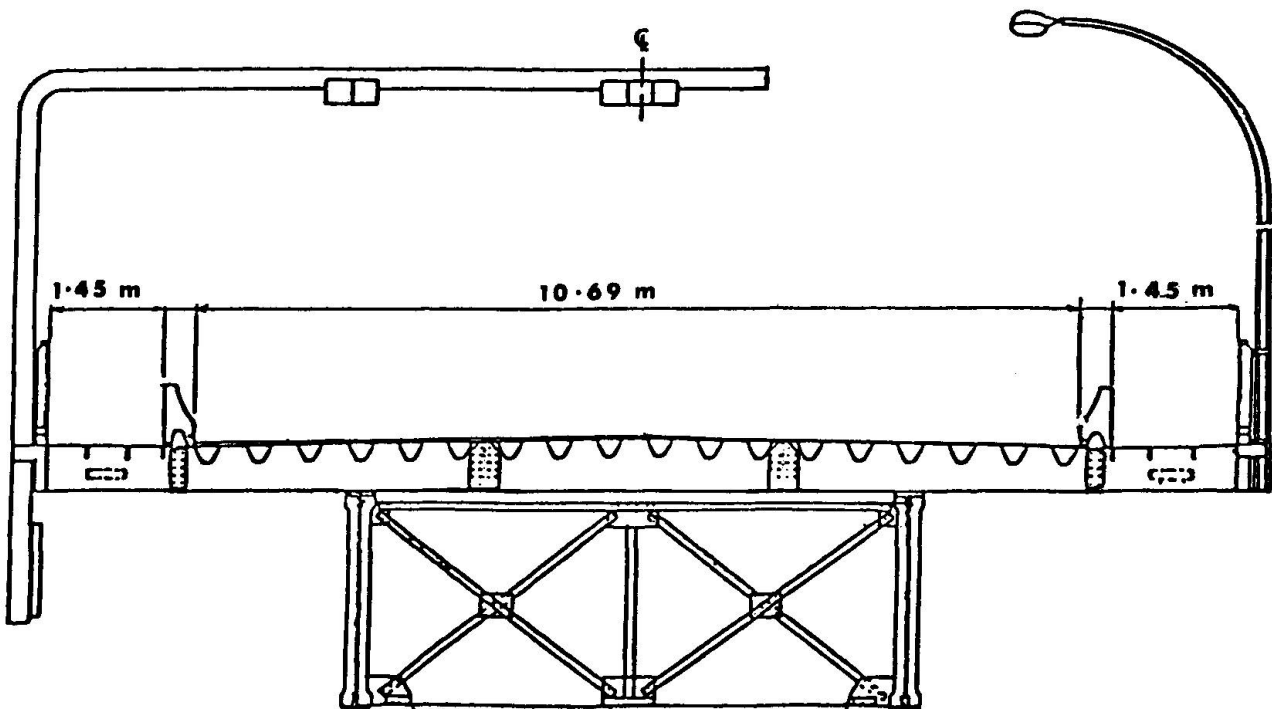


Fig. 4 Cross Section of Renovated North Viaduct



Fortunately, there was excess shear capacity in the existing girder webs. A 37mm wearing surface of epoxy asphalt was specified in the traffic zone with a 2mm epoxy coating on the sidewalks. A cross section of the renovated North Viaduct is shown in Fig. 4.

Epoxy asphalt has been found by experience in North America to be compatible with the flexibility requirements of orthotropic steel decks and to offer improved abrasion resistance in areas of high wear.

Many schemes were considered for combatting the corrosion attack on the viaduct support girders and bents. This had resulted in crevice corrosion of alarming appearance at the interface of the 8mm flange cover plates between rivets spaced up to 175mm apart. The corrosion product forming between the plates had forced the outer ones to bulge with permanent deformations up to 7mm. Fortunately, the most severe damage was in the tension flanges of the girders. Corrective measures considered for this problem included sealing every crevice (a lifetime's work!), encasing the steel structure in concrete and using sophisticated de-icing compounds on the bridge deck instead of salt.

All of these schemes had major drawbacks or limited chance of success. Finally, it was decided to measure actual corrosion losses at a few typical sections on the girder and to attempt to predict probable future section losses from this data. This approach proved useful. Despite the alarming appearance of the corrosion products, the actual section losses were found to be less than anticipated, ranging from 2 to 4% loss. Based on the most pessimistic corrosion predictions it was shown that a modest reduction in the corrosion rate, coupled with live load composite action by the orthotropic deck, was sufficient to ensure adequate load carrying capacity in the girder flanges for several more decades. The reduced corrosion rate was achieved by sealing the new deck with joint seals and ducting the de-icing salts away to ground level through a closed drainage system. Thus an impermeable "roof" was provided to reduce corrosion, furthermore the quality of the paint protection was increased by sandblasting and re-coating the steelwork to a uniform high quality.

Other improvements incorporated in the renovation design for the North Viaduct included a protective guard-rail between automobiles and pedestrians (made of galvanized steel to minimize weight), a new electrical distribution and emergency power system and improved access beneath the bridge for maintenance.

5. SUSPENSION BRIDGE

5.1 Components Requiring Renovation

The defects occurring in the Suspension Bridge were of a more complex nature than those in the North Viaduct. Bridge components were in general in better condition, but the structural defects were more significant.

Starting with the foundations, it was discovered that the footing of the North Cable Bent, located at the North end of the Suspension Bridge, had settled unevenly over the years and was inducing large secondary stresses in the tower legs. Furthermore, continued slippage of the main cables in the saddle at the top of this tower had aggravated the situation. See Figure 5.

The stability of this tower is critical to the safety of the entire bridge. Other significant structural defects in the Suspension Bridge included live load bending overstress in the stiffening truss and inelastic stretch in the main cables which caused main tower out of plumb and secondary bending in the

stiffening truss. The suspended spans also suffered from the same basic problems as the North Viaduct due to crevice corrosion in the support steelwork and towers plus decay of the deck structure due to corrosion and wear. In this case the deck construction is steel tee grid infilled with concrete. This deck has no wearing surface and is unacceptably slippery when wet. Furthermore, the deck is not waterproof and corrosion between the tees and on the top of the floorbeams tends to cause the tees to pry loose from one another and the support steel.

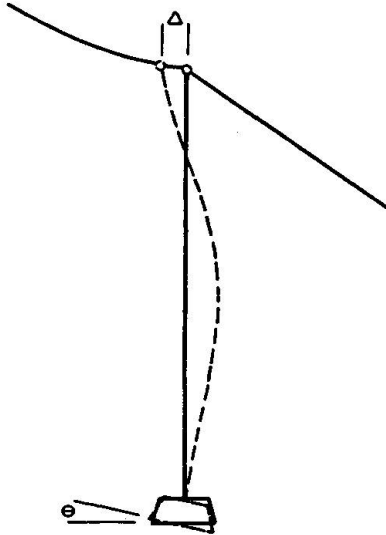


Fig. 5 Schematic View of North Cable Bent

The objectives of the renovation in this case were:-

1. - to secure the North Cable Bent in a safe and stable condition.
2. - to provide a new wider, waterproof deck with a wearing surface and improved drainage.
3. - alleviate the bending overstresses in the towers and stiffening trusses.

5.2 Design for Renovation of the Suspension Bridge

The first objective of this phase of the renovation was to restore the North Cable Bent to a stable condition prior to commencing other work in the suspended spans. Bridge strand tiebacks were installed between the North anchorage and the top of the bent in order to prevent further slippage of the clamp among the main cables. After this was completed, the footing was underpinned to prevent further settlement and then rotated to relieve secondary bending in the column. The steps in this process are illustrated schematically below:-

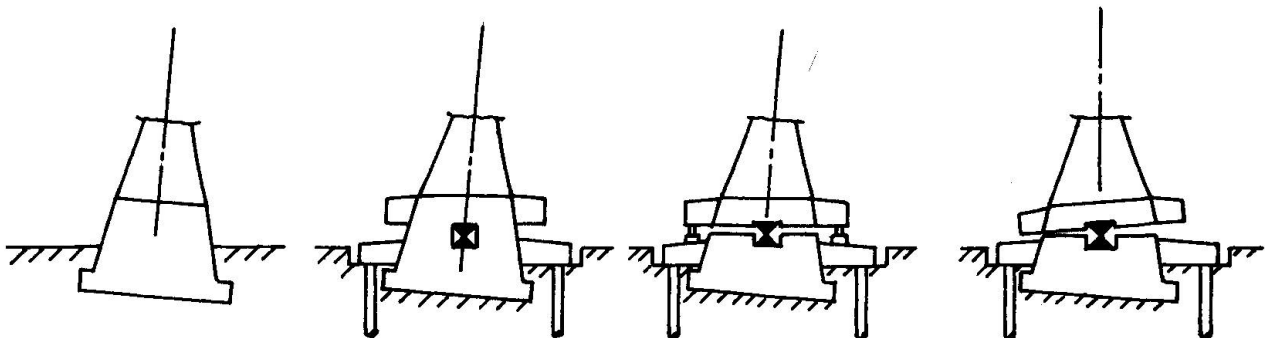


Fig. 6 Stabilization of North Cable Bent



It seemed natural to renovate the deck in the suspended spans in a similar manner to the North Viaduct using an orthotropic deck and epoxy paving, and this is in fact being done. However, there were a number of difficulties in framing this deck into the existing stiffening truss and floorbeam system within the constraints of short bridge closures and the requirement to provide adequate corrosion resistance and long term strength in an already overloaded stiffening truss. Furthermore, widening the road deck could only be achieved at the expense of cantilevering the sidewalks outside the stiffening truss, where they significantly reduced the aerodynamic stability of the cross section. In light of the poor behaviour in wind of U shaped trusses, decreases in aerodynamic stability were regarded as undesirable. Aerodynamic model tests of the full bridge, carried out at the National Research Council of Canada [1], showed that aerodynamic stability could be attained, but at the price of fairings over some of the mainspan.

Upon consideration by the Owner of all these factors, including aerodynamics, maintenance, strength, ease of renovation etc., it was decided not to install a renovated deck within the existing truss but to design a new truss integral with a wider orthotropic deck. This decision permitted the new truss to be sized and detailed specifically to suit the requirements of renovation. It was dimensioned sufficiently shallow to fit entirely below the deck, which participates in the vertical bending of the truss. The bending stiffness of the new truss system is less than the original. However, the aerodynamic stability of the new section is made superior to the existing by closing the new truss into a box configuration and thus improving the torsional stiffness by a large factor. A cross section of the new configuration is shown below.

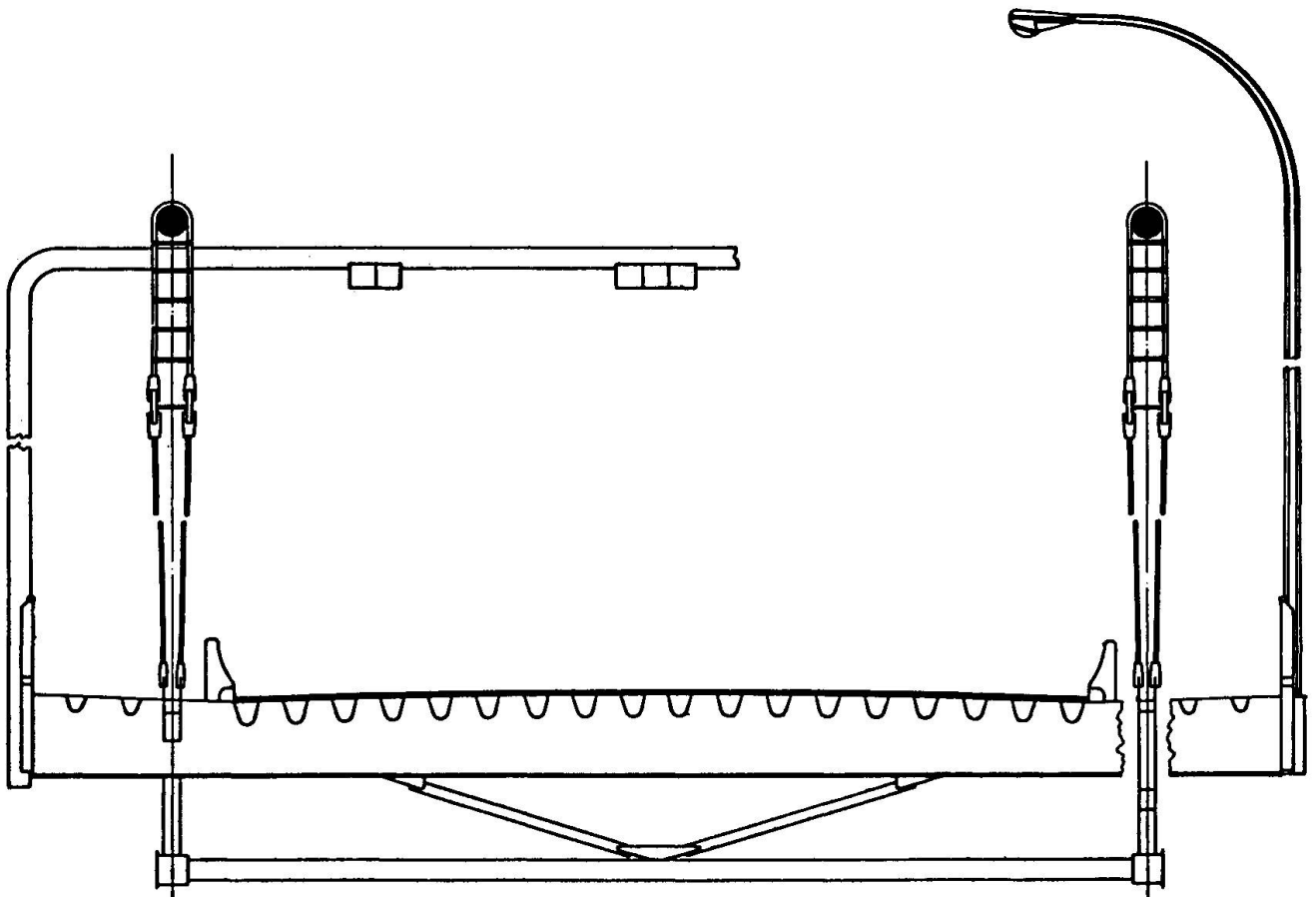


Fig. 7 Suspension Bridge New Stiffening Truss Section



In order to save enough weight to permit asphalt paving to be added, and also to minimize corrosion and simplify maintenance, truss members are welded rectangular hollow sections. Welded splice design posed some problems due to the anticipated low fatigue strength of one sided welds inevitable with tubular construction. However, prototype joint fatigue tests [2] conducted at Universitat Karlsruhe indicate that adequate fatigue resistance can be obtained, in most cases with one sided fillet welds.

At first analysis, the tower out of plumb due to cable stretch appeared to be a serious problem. Combined tower stresses including secondary bending exceeded design allowables. However, after a careful assessment of ultimate loads and displacements, it was demonstrated by a load factor approach that adequate live load factors against collapse could be attained provided appropriately low load factors were used on the predominant dead load components of tower load. This approach avoided the necessity of massive reinforcement of the towers. It only proved necessary to replace some rivets with high strength (A490) Bolts to increase the capacities of some connections.

6. DESIGN OF CONSTRUCTION FOR RENOVATION

For intermittent renovation of this type, the traffic closure is short and finite and the bridge must be ready to receive traffic at the end of the closure. This constraint dictates that:-

1. - the new deck be prefabricated to the maximum extent.
2. - the new deck be pre-paved.
3. - connection details be simple and tolerant of adjustment.

Maximum prefabrication implies completing everything possible before the actual closure commences. In this case paving, drains, traffic barriers, sidewalks, lighting, fences etc. were all installed on the deck sections ready to lift into place before commencement of the closure.

New orthotropic decks must be pre-paved before erection because traffic cannot pass safely over unpaved steel. For the North Viaduct, the panels were fully pre-paved prior to erection against steel paving stops at the end of each section. This discontinuity will be avoided in the suspension bridge by pre-paving to half thickness only prior to installation and then applying the remaining paving upon completion of the whole length of deck.

The method by which the new deck panels connect to the existing structure requires careful detailed design. For successful performance they must be quick to install but tolerant of adjustment in several directions. This is particularly necessary when connecting to existing structure because "as built" dimensions may differ from those shown on the original drawings or, as was discovered on Lions' Gate Bridge, settlement of the foundations may have caused distortions and misalignments in the structure.

For the North Viaduct, connection to the top flange of the existing plate girders was made by removing four existing rivets and bolting a nominal 40mm thick shim pack to the top of the girder with countersunk bolts. The height and tilt of the top surface of the shims could be adjusted by adding or removing shims, tapered if necessary. Once at the correct level and bolted down, the countersunk bolts afforded a flat surface, permitting the new deck cross beams to be moved laterally or longitudinally to the appropriate position before welding down. This simple device thus afforded linear and rotational movement in each of the three axes and permitted complete freedom of adjustment.

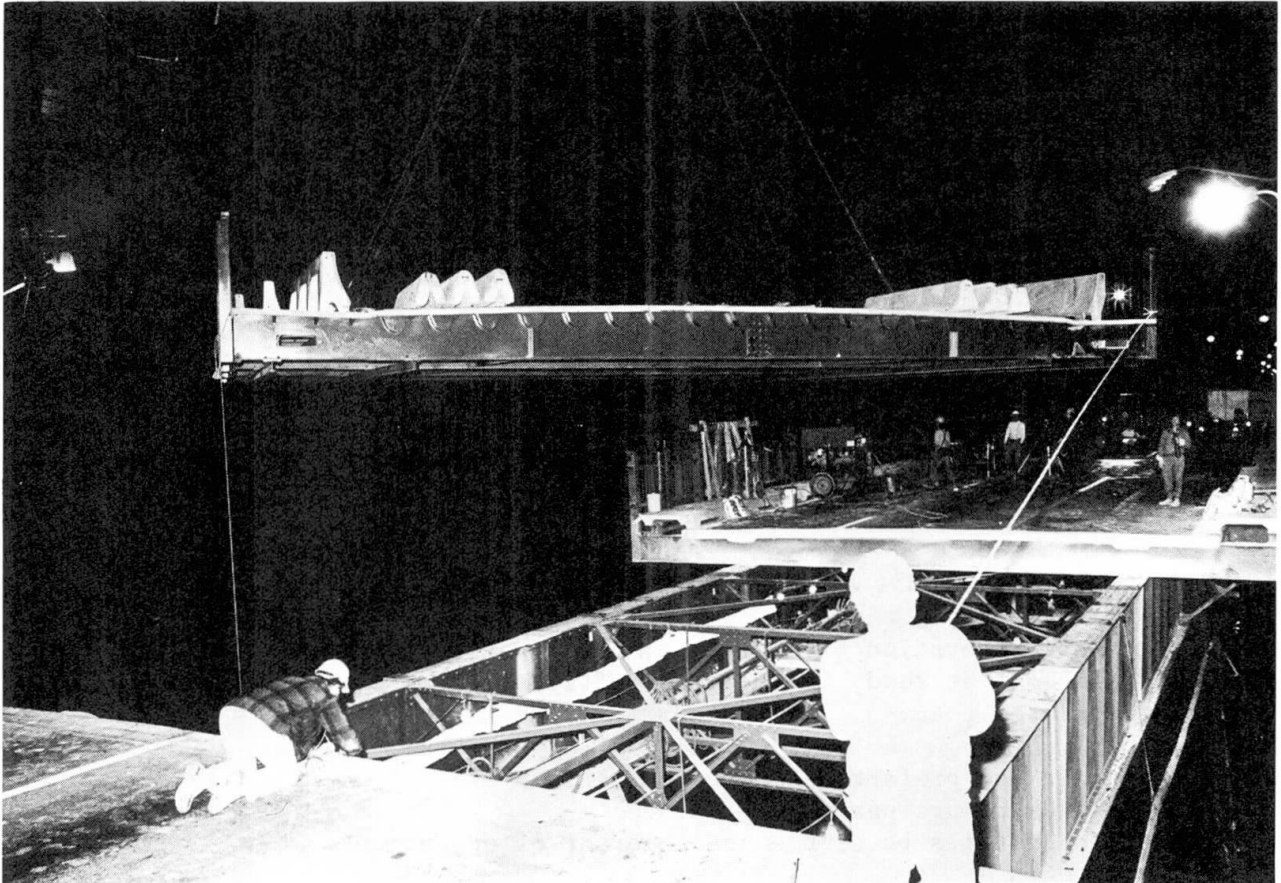


Fig. 8 Section of North Viaduct during Installation.

Other detail problems peculiar to renovation included:-

- maintaining load carrying capacity in the partly renovated deck system. This problem is particularly acute when replacing the stiffening truss of a suspension bridge.
- assuring smooth traffic flow over the joint between old and new sections. It was discovered that, when running at capacity, bridge traffic is very sensitive to minor discontinuities in the deck and serious traffic back ups can develop if a bump, perceived or actual, is introduced.
- precautions against major equipment failure during bridge closures. When working against the clock in short bridge closures the problem of machinery breakdown is very real and potentially serious. One approach is to demand back up machines for all key items of equipment. However, this is very expensive and perhaps unrealistic. One alternative, which was used on the North Viaduct renovation, is to have light modular temporary deck sections available adjacent to the site ready for immediate installation by a light crane should an emergency develop. This approach at least ensures that the bridge will be capable of carrying traffic after an equipment breakdown, although the vehicle flow over the temporary sections may be considerably less than over the permanent deck system.



7. PUBLIC INFORMATION

The importance of this aspect of renovation cannot be overemphasized. The bridge user is always curious about what is happening to the bridge, and if he is made aware of precisely what changes are being made and what the end result will be, then he becomes involved in the process and is more tolerant of minor delays and irritations. For all stages of renovation of Lions' Gate Bridge, a three fold public information system is being used. This consists firstly of media advertising giving a full description of the work to be done and defining the extent of traffic closures. The second phase comprises mailings to local businesses containing calendars of bridge closures. Finally, bulletins are supplied to local radio stations at 15 minute intervals as the end of the closure approaches so that the public is informed of the anticipated opening time for the bridge.

8. CONCLUSIONS

After forty years of wear and corrosive attack, this bridge had reached a point where maintenance problems were mounting and it was necessary to review how many more years it would remain servicable. Removing the bridge from service for repair for more than a few hours was ruled out, as was total replacement.

This paper shows that with ingenuity and careful design it is possible to successfully renovate a bridge under these circumstances.

With rising capital costs of new construction and an unwillingness by the public to support large scale new projects, it is becoming more important to consider the benefits of recycling major bridges.

When renovation of this structure is complete, it can anticipate an extended useful life as long or longer than its life to date. Furthermore, future decay will be minimized by careful attention to corrosion free details and improved access for maintenance.

9. ACKNOWLEDGMENTS

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