Cable stayed bridges: developments and perspective

Autor(en): **Muller, Jean**

Objekttyp: **Article**

Zeitschrift: **IABSE congress report = Rapport du congrès AIPC = IVBH Kongressbericht**

Band (Jahr): **12 (1984)**

PDF erstellt am: **13.07.2024**

Persistenter Link: https://doi.org/10.5169/seals-12305

Nutzungsbedingungen

Die ETH-Bibliothek ist Anbieterin der digitalisierten Zeitschriften. Sie besitzt keine Urheberrechte an den Inhalten der Zeitschriften. Die Rechte liegen in der Regel bei den Herausgebern.
Die auf der Plattform e-periodica veröffentlichten Dokumente stehen für nicht-kommerzielle Zwecke in Lehre und Forschung sowie für die private Nutzung frei zur Verfügung. Einzelne Dateien oder Ausdrucke aus diesem Angebot können zusammen mit diesen Nutzungsbedingungen und den korrekten Herkunftsbezeichnungen weitergegeben werden.
Das Veröffentlichen von Bildern in Print- und Online-Publikationen ist nur mit vorheriger Genehmigung der Rechteinhaber erlaubt. Die systematische Speicherung von Teilen des elektronischen Angebots auf anderen Servern bedarf ebenfalls des schriftlichen Einverständnisses der Rechteinhaber.

Haftungsausschluss

Alle Angaben erfolgen ohne Gewähr für Vollständigkeit oder Richtigkeit. Es wird keine Haftung übernommen für Schäden durch die Verwendung von Informationen aus diesem Online-Angebot oder durch das Fehlen von Informationen. Dies gilt auch für Inhalte Dritter, die über dieses Angebot zugänglich sind.

Ein Dienst der *ETH-Bibliothek*
ETH Zürich, Rämistrasse 101, 8092 Zürich, Schweiz, www.library.ethz.ch

http://www.e-periodica.ch

Cable Stayed Bridges — Developments and Perspective

Ponts à haubans — Développements et perspectives d'avenir

Seilverspannte Betonbrücken — Entwicklung und Zukunft

Jean MULLER
Chairman of Board
Figg and Muller Engineers Inc.
Courbevoie, France

Jean Muller received his Bachelors in Mathematics in 1943 and his Masters Degree in Civil Engineering from the Ecole Centrale des Arts et Manufactures, Paris, in 1947. He then worked for Freyssinet International, Paris, and was the Chief Engineer for Freyssinet Company, New York. From 1955 to 1976 Jean Muller worked for Campenon Bernard, Paris. Figg and Muller Engineers, Inc., of which he is Chairman of the Board and Partner in Charge of all Technical Design, was formed in 1978.

SUMMARY

Concrete cable stayed bridges were increasingly used for the last ten years in span ranges of 250 to 350 m. With existing materials and technology, span of 400 to 450 m can be crossed easily. For longer spans, steel and concrete should be used in composite structures. However, the most characteristic progress was accomplished in moderate span length, thanks to the three following items: choice of cross section in relation with aeroelastic stability; simplification of suspension system and stay anchors; use of existing and simple construction techniques already proven on conventional bridges. Important savings may be obtained through the use of cable stayed concrete bridges with spans of 150 to 200 m over conventional box-girder bridges.

RESUME

Les ponts à haubans en béton se sont développés rapidement depuis dix ans dans le domaine des grandes portées de 250 à 350 mètres. Avec les matériaux et la technologie actuels, on peut franchir sans problème des portées de 400 à 450 mètres. Au delà, il faut associer le béton et la charpente métallique dans des structures mixtes. Les progrès les plus caractéristiques ont, cependant, été accomplis dans les portées grâce aux trois éléments suivants: choix de la section transversale en fonction des efforts aéroélastiques; simplification dans la suspension et la réalisation des ancrages des haubans; utilisation de méthodes de construction simples et déjà éprouvées pour des ponts traditionnels. Des économies importantes sont possibles par l'utilisation de ponts haubannés dans des portées de 150 à 200 mètres, par rapport aux solutions traditionnelles de ponts à poutres en caissons.

ZUSAMMENFASSUNG

In den letzten zehn Jahren nahm die Anzahl seilvorgespannter Betonbrücken mit Spannweiten von 250 m bis 300 m zu. Brücken aus bestehenden Materialien und Technologien überspannen ohne Schwierigkeiten 400 bis 450 m. Die Verbundbauweise mit Stahl und Beton ermöglicht sogar noch grössere Spannweiten. Trotzdem, diese Bauweise fand hauptsächlich bei Brücken mit mittleren Spannweiten ihre Anwendung. Die folgenden drei Gründe haben dazu beigetragen: Wahl des Querschnittes unter Berücksichtigung der Stabilität für Windbeanspruchung; Vereinfachung des Aufhängesystems und der Verankerung; Verwendung von bestehenden und einfachen Konstruktionstechniken, deren Zweckmässigkeit im konventionellen Brückenbau bereits ausgetestet ist. Die seilverspannten Betonbrücken sind vor allem in Spannweitenbereichen von 150 m bis 200 m den konventionellen Kastenträgerbrücken vom wirtschaftlichen Standpunkt aus gesehen, überlegen.

1. HISTORICAL BACKGROUND

The first modern long span cable stayed bridge was proposed by Eugene Freyssinet in 1952 for crossing of the Seine River at Tancarville. The 2000 ft long main clear span was supported by multiple stays anchored in two short side spans with the contribution of outside anchorage structures to relieve the deck from excessive compressive stresses induced by the longitudinal components of the stay loads.

Tancarville bridge was finally built as a conventional suspension bridge and Freyssinet's scheme was only an anticipation of future developments.

2. BROTONNE BRIDGE, FRANCE

Twenty five years later, Brotonne Bridge was opened to traffic. With a more modest span of 1050 ft over the same river - just 30 miles upstream of Tancarville - it still represents to-day the longest concrete cable stayed bridge before completion of the Sunshine Skyway Bridge in Tampa, Florida now under construction with a main clear span of 1200 ft. Between the conception of these two projects, Tancarnville and Brotonne, precast segmental construction with match marking joints was developed and its potential was made available for design and construction of long span concrete cable stayed bridges.

Brotonne Bridge's saliant features are:

2.1. The deck is made of a single box with internal stiffeners suspended on a single plane of stays and single concrete pylons. The safety of this scheme may be made as large as desired by proper choice of pylon dimensions and magnitude of reinforcement. In the case of Brotonne Bridge, the wind pressure causing instability would be in excess of 130 psf.

2.2. The deck of the main crossing is continuous over the transition piers with the approach spans while a moment transfer connection is provided between deck, pylon and main pier. This special static scheme greatly reduces the variation of live load moments in the deck which allowing cantilever construction of the main river span without temporary towers or strengthening devices.

2.3. Stays consist of prestressing strands encased in a steel pipe and pressure grouted after stressing. End anchorages in the deck are an extrapolation of conventional post tensioning hardware with provisions for future stay load adjustments. Each stay is continuous through the concrete pylon with an embedded sleeve pipe. The effect of bending stresses in the stays resulting from the change of sag and the deck deflections are minimized through the use of a thick pipe section near the pylons and the deck.

Damping devices are provided at deck level to control vibration.

The stays were installed without scaffolding with the help of rolling chairs similar to those of a ski lift.

After seven years of operation, Brotonne Bridge has shown to perform very satisfactorily. This year (1984) the stays were readjusted to compensate for all long term concrete strains and it is not anticipated that any further adjustment will ever be required. (see the finished bridge by night fig. 5)

3. COATZACOALCOS BRIDGE, MEXICO

A concept similar to Brotonne Bridge is applied to the construction of Coatzacoalcos Bridge in Mexico. With dimensions comparable to Brotonne Bridge (main span length is

945 ft and deck width is 59 ft),the cast-in-place deck is suspended on a single centerplane of stays which in turn transfers the deck load to the main delta framed pylons.
The description of this interesting structure and its related developments are reported by others in this Congress.

4. A NEW PROPOSED PYLON AND STAY SCHEME FOR MOONEY MOONEY CREEK BRIDGE, AUSTRALIA

Brotonne Bridge features single center pylons supporting a single plane of stays.

Coatzacoalcos Bridge features in fact a single plane of stays and a double pylon system.

When the author was asked in 1980 to review the design of the Mooney Mooney Creek Bridge in Australia for the Department of Main Roads of New South Wales, a new challenge had to be met. Substantial mining subsidence effects had to be considered while the deck width of 100 ft to accomodate six lanes of traffic was substantially wider than of previous references. The scheme proposed for this concrete cable stayed bridge was based on the following options: (Fig 1.)

- A torsionally resistant deck section with a curved intrados and transverse webs at 20 ft intervals, the same interval as the stays.

- Single pylons placed at the deck centerline supporting two families of radiating stays located in two inclined planes.

This scheme was found to be efficient to insure the elastic stability of the pylon and stay system while minimizing the harmful effects of differential settlements of the foundations.

In spite of its attractiveness, this project was not built because cost studies had shown that for that particular site where no restrictions were imposed on the location and number of piers, a conventional box girder design was more economical, at the time.

5. CONCRETE CABLE STAYED BRIDGES IN THE UNITED STATES - PREVIOUS EXPERIENCE WITH SEGMENTAL CONSTRUCTION

Today the largest concrete cable stayed bridge in North America is the Pasco Kennewick Bridge in the State of Washington, designed by Pr Leonhardt and Arvid Grant and built by Peter Kiewet and Sons Co. with a main span of 980 ft.

The new Sunshine Skyway Bridge (presently under construction over Tampa Bay, Florida), incorporates many new developments in the field of precast segmental construction. It is therefore of interest to briefly review the experience gained in that field since the design of the Florida Keys Bridges. Several new items were introduced at this occasion:

- Pretensioning of the roadway slab.

- Assembly of precast segments on a truss in complete continuous spans.

- Longitudinal post tensioning created by tendons located inside the box girder but outside the concrete walls of the section. Such tendons are placed inside polyethylene ducts and pressure grouted after stressing. Proper overlapping of the tendons of each span over the successive piers achieves full continuity for all loads over several spans on a total length of about 1000 ft.

- Riding on the as-cast surface with no waterproof membrane or/and pavement.

- Dry joints between match marked segments are used with no epoxy.

After the succesful experience of the four segmental bridges in the Florida Keys which represent a total deck area in excess of 2,200,000 SF, several other structures were designed and succesfully built.

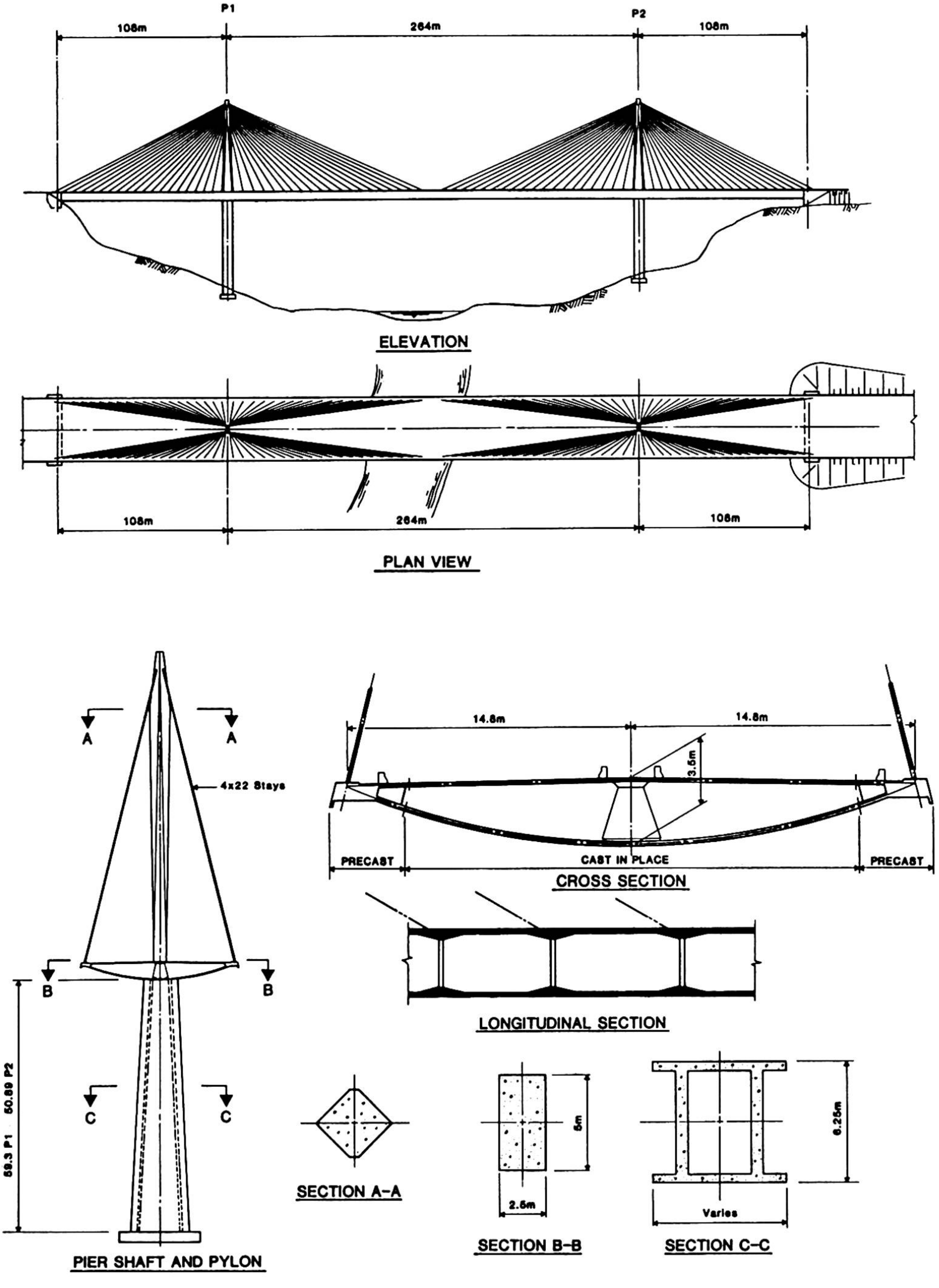


FIG. 1. PROPOSED CONCEPT FOR MOONEY MOONEY CREEK BRIDGE

Of particular interest are:

- Wiscasset Bridge, Maine.

Climatic conditions dictated the use of epoxy in the joints and of both a waterproof membrane and a bituminous pavement over the concrete deck slab.

Dauphin Island Bridge, Alabama.

With a 400 ft main span built of precast segmental construction. The contractor accepted the challenge of building this main span to stringent specifications to allow riding on the as-cast surface as was specified for the approach spans. The result has been very satisfactory.

- Linn Cove Viaduct, North Carolina.

Of moderate dimensions only, this structure symbolizes however the utmost geometric complications with the most stringent environmental constraints. All construction proceeded from the deck with the exception of minor foundation work and the use of precast segmental construction has proven capable of fully meeting this challenge.

- Mark Clark Expressway in Charleston, South Carolina.

With a construction budget of 250 million US dollars, this large project implies several structures of unusual interest:

- a precast cable stayed crossing with a clear span of 800 ft over Cooper River,
- a precast box girder bridge with a clear span of 400 ft over the Wando River,
- difficult foundation conditions over a waste disposal area,
- urban interchanges,

all structures being located in a seismically active zone.

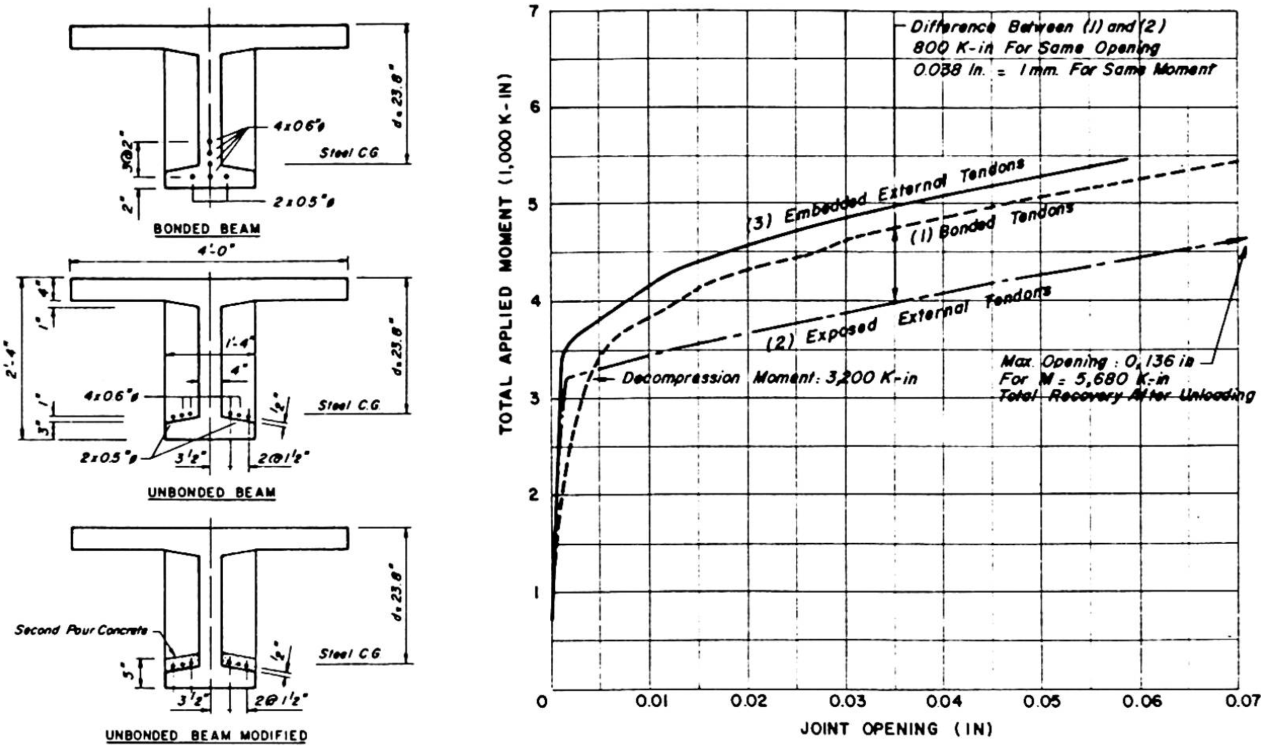
To ascertain the suitability of our concepts of precast segmental construction with external tendons to sustain seismic loads, a comprehensive testing program was implemented with particular attention being focused on redundancy and ductility of the structures.

For purpose of comparison, three identical beams were tested and instrumented first up to design load and in the elastic range and further loaded to ultimate capacity. These beams represented at the scale of 1 to 5 a typical 150 ft span made of a single box section 46 ft wide and 10 ft deep with match cast segments and dry joints. Although the simply supported model beams were not intended to duplicate exactly the actual continuous deck particularly insofar as tendon anchor blocks, multiple keys and loading arrangement were concerned, the test program proved very valuable.

- The first beam (bonded beam), used as a reference has the tendons inside the concrete section and grouted on their full length.
- The second beam (unbonded beam) has the tendons draped along the web but external to the concrete.
- The third beam (unbonded modified beam) was tested to ascertain the benefit of a second stage casting which would allow the tendons to be bonded to the bottom flange of the beam after stressing to sustain the applied loads.

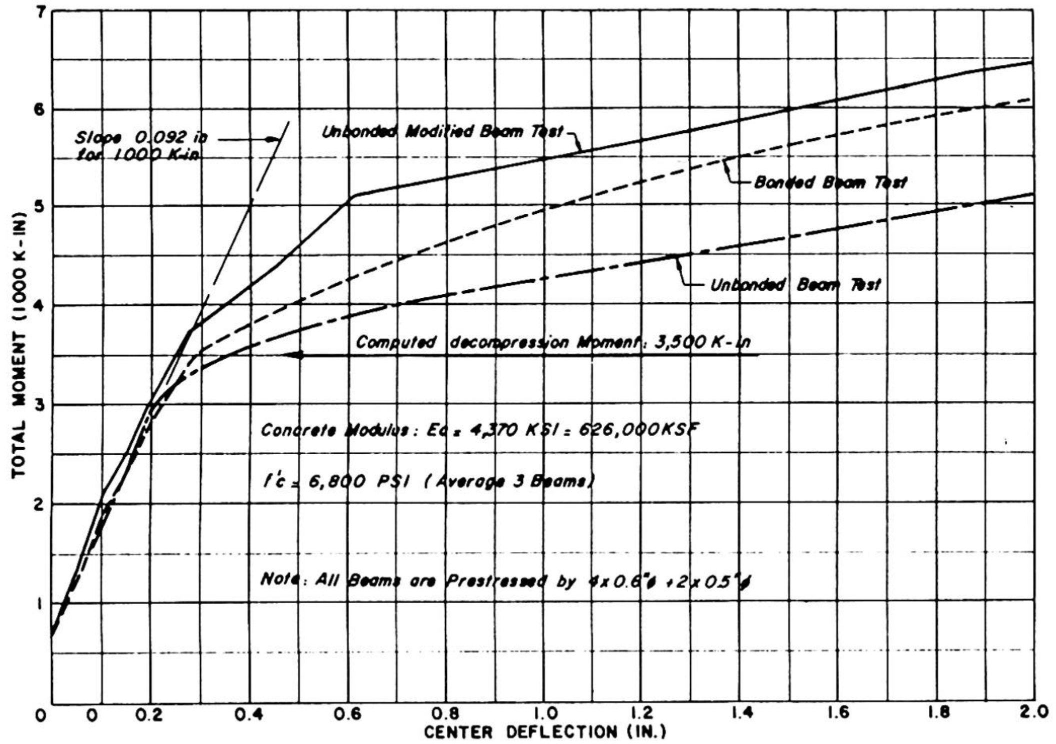
The enclosed diagrams show the relative behaviour of the three test beams and allow to draw the following conclusions: (Fig 2)

- All beams perform identically up to and including design load (load which produces the decompression of the bottom fiber at the most critical joint). For this load, the deflection at mid span was 0.3" for a 30 ft span or 1 : 1200 of the span length.



(a) DIMENSIONS OF THE THREE TEST BEAMS

(b) OPENING OF JOINT BETWEEN SEGMENTS VS TOTAL APPLIED MOMENT



(c) LOAD VS DEFLECTION CURVES

FIG. 2. COMPARATIVE BEAM TESTS.

- Beyond the design stage, the unbonded beam is the most flexible and unbonded modified beam is the most rigid. However, after reaching the state of joint opening, the slope of the moment/deflection diagram is substantially the same for three beams. This is confirmed by the diagrams of applied moment versus opening of joint between segments.

- Moreover, a complete elastic recovery was experienced after loading of the beams up to 1.7 times the design load in spite of the substantial joint opening of the critical joints (0.14 in = 3.5 mm).

- The ultimate capacity of the three beams was obtained by crushing of the top slab. The bonded beam was specifically a bending failure with strand breakage while the ultimate behaviour of the unbonded beams was influenced by the combination of maximum moment and maximum shear in the critical section (a condition never found in the actual continuous bridge deck).

- Both unbonded beams developed an ultimate moment which was the same as that of the same beam with fully bonded tendons. These experimental studies were confirmed by computer analysis.

As a conclusion, it may be stated that post tensioning by external tendons produces safe structures with the desired ductility and redundancy called for in seismically active areas. The analysis of such structures may be performed with existing design tools (computer programs). From a construction view point, external tendons are economical and easy to install. Most of the technological problems associated with tendons in the concrete (such as bursting or lamination of the concrete member and grout leakages) may be avoided while construction supervision is most simple.

6. CABLE STAYED BRIDGES IN THE UNITED STATES - THE SUNSHINE SKYWAY BRIDGE

Much of the experience briefly reported in the preceeding paragraph was applied to the design of the new Sunshine Skyway Bridge now under construction over Tampa Bay, Florida.

Principal dimensions and design features are as follows: (see Fig 3.)

6.1. Span lengths of the main 4000 ft center unit (between expansion joints at the transition with the high level approaches)

140 - 3 x 240 - 540 - 1200 - 540 - 3 x 240 - 140 ft.

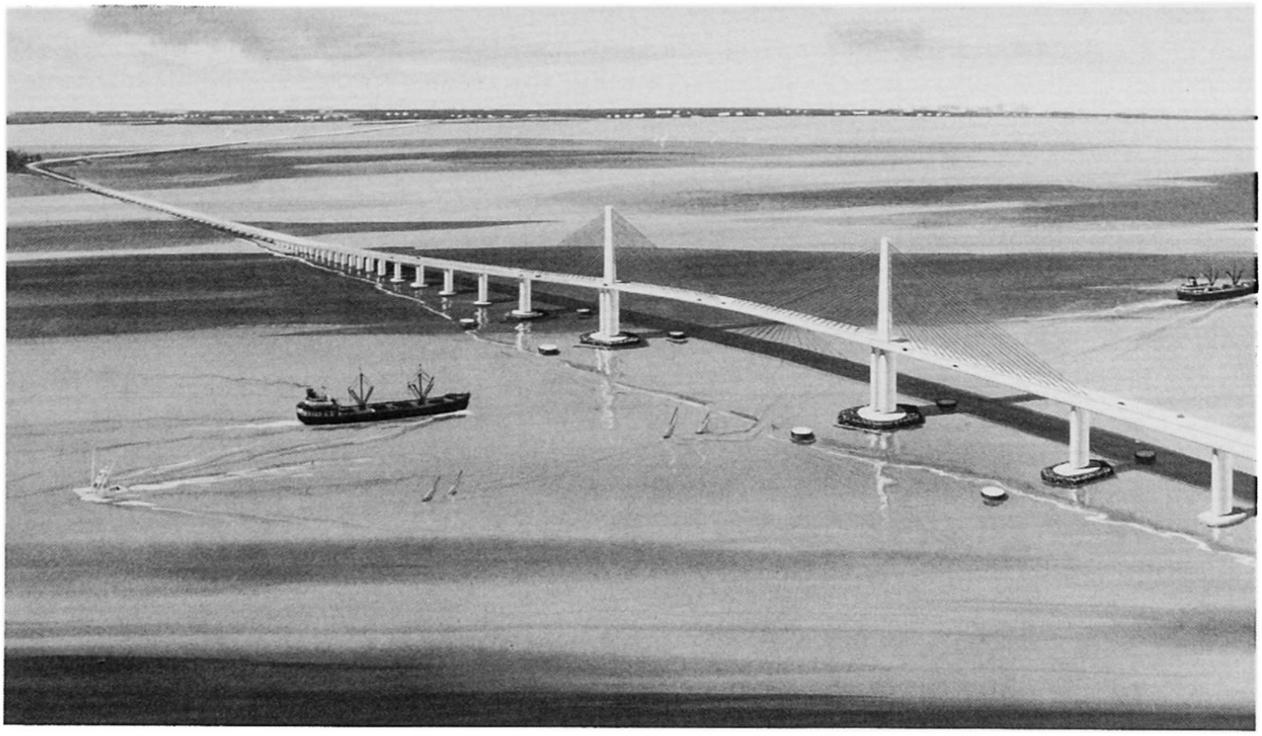
6.2. Main piers: massive foundation on drilled shafts supporting twin elliptical reinforced concrete cast in place box piers (12 x 38 ft). The individual flexibility of the piers allows for deck volume changes while the combination of twin piers affords a great bending capacity.

6.3. Pylon: single box reinforced concrete cast in place shaft.

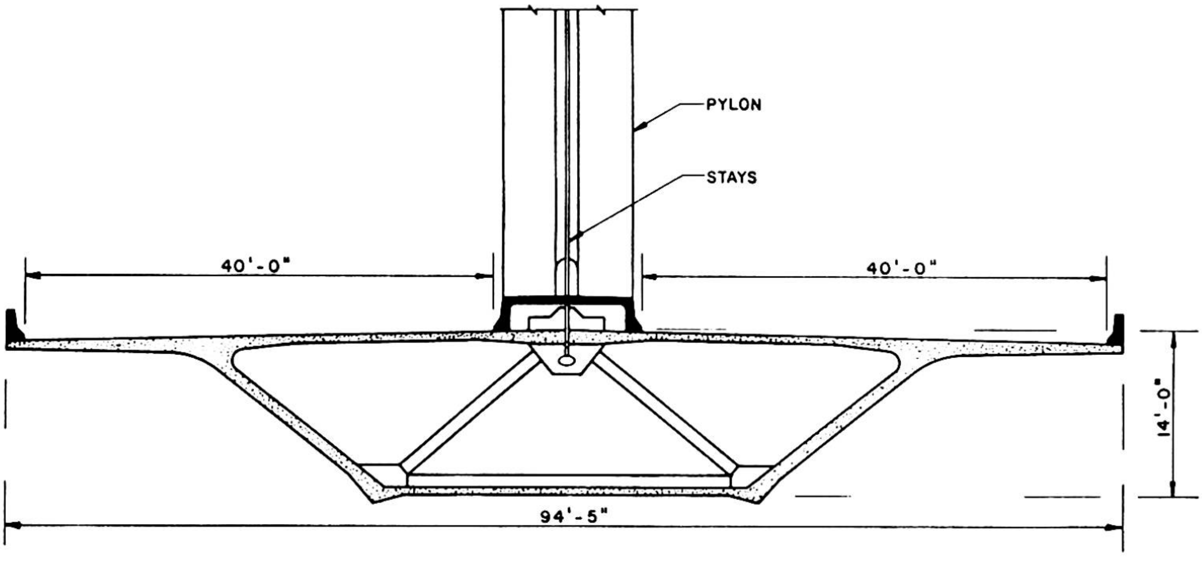
6.4. Deck section:

- single box 95' wide 14' deep,
- deck slab and bottom slab: 8" thick web
- thickness 12" to 15" vertically prestressed
- section properties. area A = 156 SF
  moment of inertia I = 4078 ft.

6.5. Stays: single plane at bridge centerline with stays made of 60 to 80 x 0.6" strands encased in a steel pipe and pressure grouted. Stage stressing after completion of the decks includes a provision to place permanently the steel casing and the grout column under compression to minimize the effect of live load and fatigue due in particular to local bending near the anchors.



(a) RENDERING OF THE FINISHED BRIDGE



(b) TYPICAL CROSS SECTION

FIG. 3. SUNSHINE SKYWAY BRIDGE - TAMPA, Florida, U.S.A.

6.6 Stay layout: stays are placed at 24 ft intervals at deck level and a fan layout is used like in Brotonne Bridge. The angle of the stays with regard to the deck varies between 22 degrees and 47 degrees. There is a significant economy in the weight of stays afforded by the fan layout over the harp layout with all stays parallel. Also the normal load in the deck due to the componant of stay loads is significantly reduced.

6.7. Construction methods: segments are fully precast and placed in balanced cantilever first in the 240 ft approach spans and then in the main span. This results in 3 closure joints for the main cable stayed structure:

- one in each transition span 420 ft from the main pier and 120 ft from the main pier and 120 ft from the transition pier,
- one at mid-span of the main crossing.

6.8. Prestressing layout: In the cable stayed span, segments are prestressed in the precasting yard in the transverse and vertical direction. In the longitudinal direction, a limited amount of prestress at top slab level allows construction in balanced cantilever before placing the first permanent stays.

The longitudinal prestress in the main span which is required to offset the combined effect of live load moments, temperature gradients and deck concrete creep and shrinkage is provided by a series of external tendons laid above the bottom slab and draped inside the box section to be successively anchored in the stay anchor block at roadway slab level in the median strip between inside barrier walls.A full continuity between stays and tendons is thus realized in the main span much in the same manner as in a suspension bridge.

7. BEHAVIOUR OF DECK UNDER ECCENTRIC LOADING AND ELASTIC STABILITY OF LONG SPAN CABLE STAYED BRIDGES

7.1. Scope

Brotonne and Sunshine Skyway Bridge decks both use a box section with a large torsional rigidity. Other schemes have been used or are contemplated where two lateral planes of stays support a relatively flexible deck (of concrete or of composite steel and concrete construction) with minimal or even negligible torsional rigidity.

It is not the intent of the author to ascertain the proper merits of the two concepts but rather to emphasize two particular points of importance pertaining to the relative behaviour of the two schemes under eccentric loading on one hand and the elastic stability of the deck on the other hand.

The comparison is simplified by using the analogy of a beam on elastic foundation.

7.2. Behaviour of the deck under eccentric loading

For a bridge with a single plane of stays, the torsion is entirely resisted by the concrete box section. For a bridge with two lateral plans of stays and a flexible deck, the torsion is resisted by the difference in stay loads between both planes of stays.

Taking the example of Skyway Bridge, the comparison would be the following for the effect of eccentric live loading: (three lanes on one half bridge only).

The transverse deck rotation at mid-span is:

- box and single plane of stays : 0.0040
- flexible deck and double plane: 0.0072

An exact analysis including the effect of deck moment shows infact the second bridge to have 4 times more transverse rotation than the first bridge.

7.3. Elastic stability of deck

The deck is subjected to high compressive stresses due to the componant of the stay loads and as such liable to buckling. With the beam on elastic foundation analogy the critical buckling load would be:

$$N = 2\sqrt{kEI} \qquad (\text{k spring constant EI flexural rigidity})$$

and a simple derivation shows that the equivalent unsupported length for buckling is $l = \frac{\pi a}{2}$ which is precisely half the wave length of the curves characteristic of the beam on elastic foundation. Numerically, the comparison between the two bridges is as follows:

(unit in feet)	Box deck Single stays	Flexible deck Double stays
. Deck moment of inertia	4000	300
. Radius of gyration	5.10	1.53
. Characteristic length	192	99
. Unsupported length	300	155
. Slenderness ratio	59	101

The increased rigidity of the box section is evident and this is particularly important in the case where one stay would be accidentally lost (derailment, accident or fire for example).

8. RECENT DEVELOPMENTS IN MODERATE SPANS

Essentially used for long spans (in excess of 800 ft) where box girder bridges are no more competitive due to their rapidly increasing weight, the cable stayed concept proves now its merits for shorter span lengths (in the range of 500 to 700 ft). This was recently confirmed by the results of the bidding of the Neches River Bridge in Texas with a 640 ft. main clear span. An alternate design with a concrete cable stayed box girder deck proved to be the most economical scheme over all other conventional steel or concrete solutions.

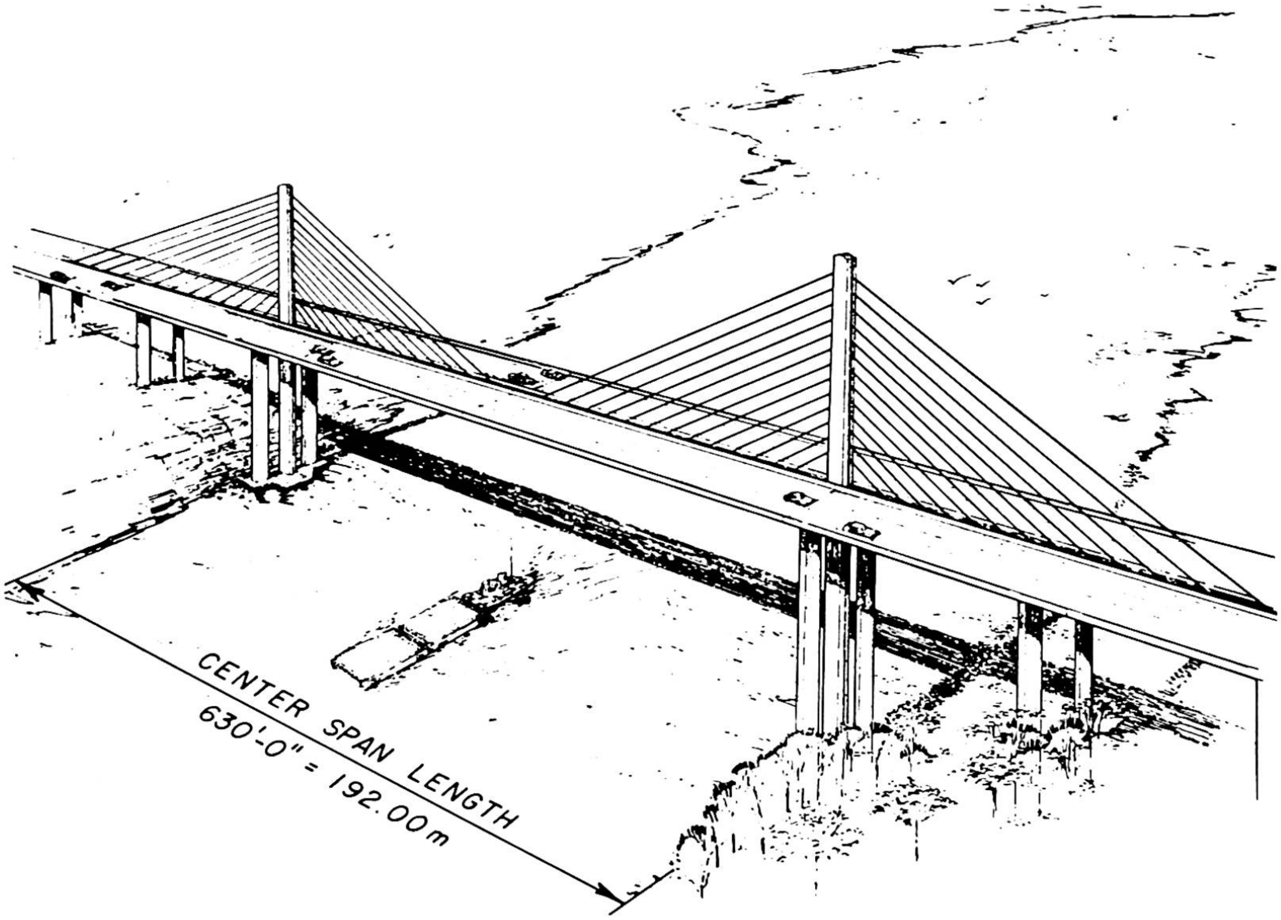
Similar conclusions were reached for other projects such as the Cooper River Bridge in South Carolina or the James River Bridge project in Virginia during the design stage after careful cost studies.

Probably the key reason for this trend is the use of new simplified design concept and construction process.

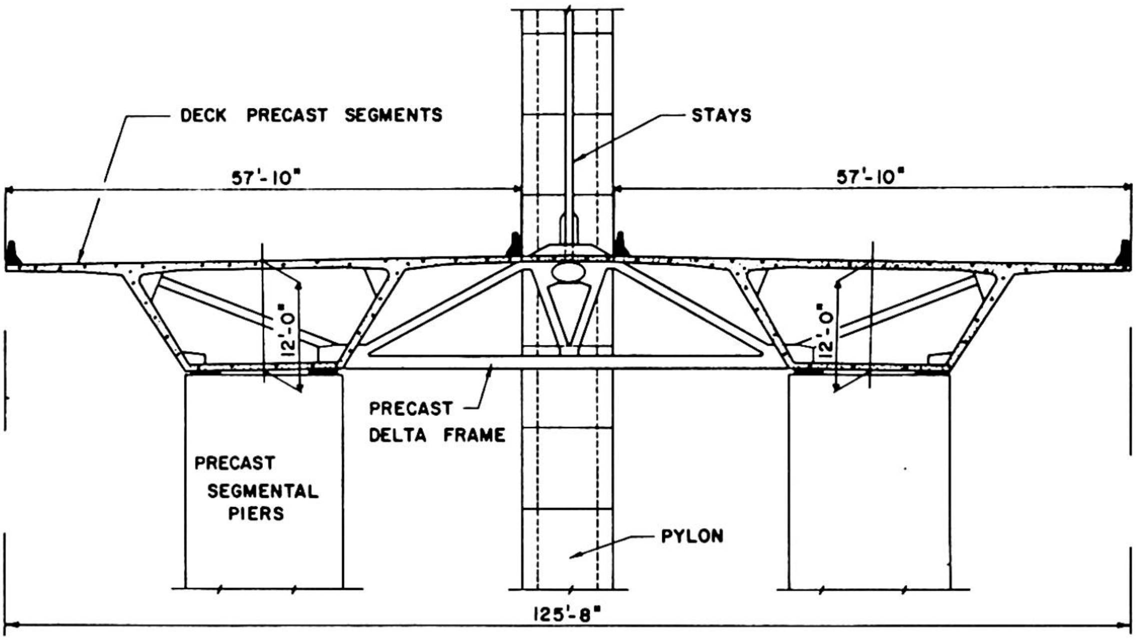
The main span is now considered as a natural continuation of the approach spans both for the choice of deck cross section and for the method of constructing the deck.

In the frequent case of twin structures each carrying 2 or 3 traffic lanes for width of 35 to 55 ft., the approach spans are conveniently built with two separate parallel box girders of constant depth. Precast segmental with span by span construction has proven well suited to that type of project.

The same structure may in fact be used to construct the main cable stayed span (see Fig. 4 the example of James River Bridge). A series of transverse frames located at the section where the stays are anchored into the deck will allow the loads of both box girders to be transferred to the center plane of suspension. This scheme requires less quantities of materials than the equivalent single deck on the full width. The investment in special equipment is also significantly reduced.



(a) ISOMETRIC VIEW OF THE FINISHED BRIDGE



(b) TYPICAL CROSS SECTION

FIG. 4. JAMES RIVER BRIDGE PROJECT, VIRGINIA

The erection scheme becomes now very simple: the transition spans up to the main piers are constructed in the same fashion as the approach spans. The main span proceeds thereafter in one directional cantilever towards the center while stays and transverse frames at installed at each step of construction.

This concept is believed to be competitive over conventional girder designs for spans as short as 400 ft.

9. CONCLUSIONS

Primarily used initially for long spans, the cable stayed concept will certainly find in the near future many applications in shorter spans.

With present materials properties (concrete and steel) a 2000 ft. clear span can be built entirely in concrete. Beyond this point, steel or an association of concrete and steel should be more economical.

In the range of very short spans, pedestrian bridges have already been built with a cable stayed deck. Recently, Professor Walther of Lausanne has prepared a design for a cable stayed highway bridge in Switzerland with a main span of only 97m. (318 ft). The deck is a solid slab with a maximum thickness of 0.55m (22 inches) supported on each side by a series of stays anchored over an H framed pylon. The bridge is now under construction (1984). The deck is cast in place on a very simple and inexpensive travelling formwork.

In both fields of very long spans and of short spans, the future of cable stayed bridges looks bright.

Progress will undoubtly take place as more experience is gained in the following areas:

- choice of static scheme (proportions of flanking spans, number and position of intermediate piers, connection between deck and pylon).

- proper association of steel and concrete for composite designs.

Logical in its concept, the cable stayed structure has already acquired an excellent record of performance.

With simple and functional shapes, the structure may be given the added touch of an aesthetically pleasing work of art.

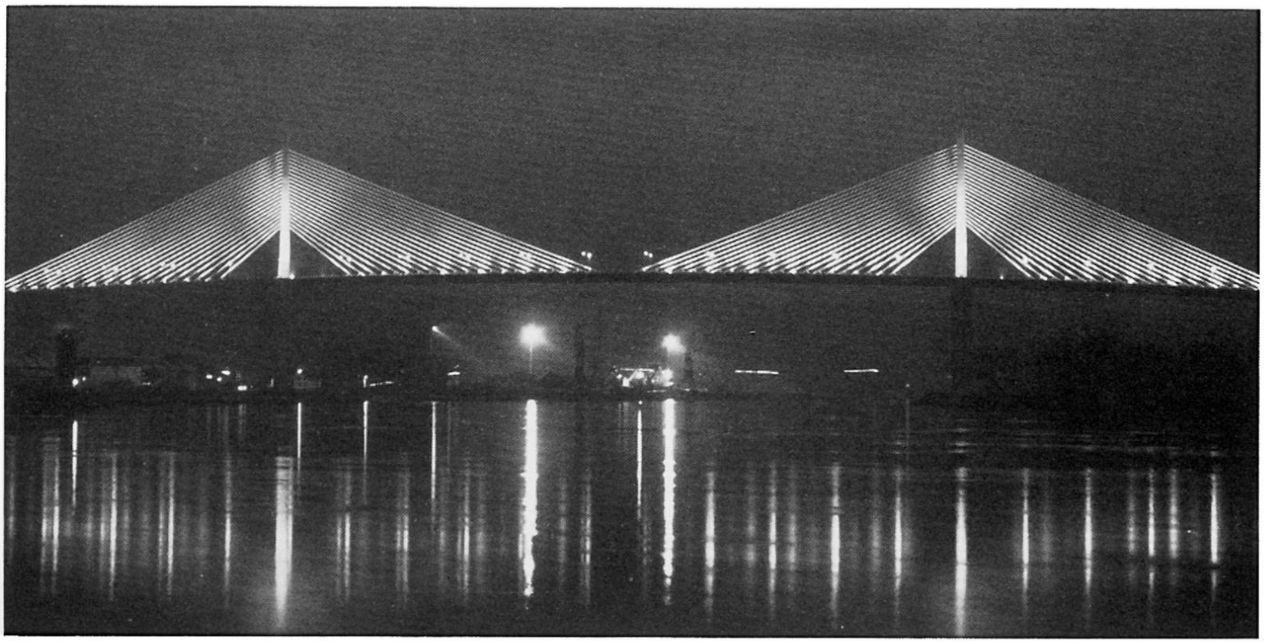


FIG. 5 BROTONNE BRIDGE BY NIGHT