PROCEEDINGS PAPER

The Bridge Spanning Lake Maracaibo

by Riccardo Morandi*

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SYNOPSIS:

This bridge now under construction across Lake Maracaibo is described in the following report, also included is a presentation of some of the principal technical data.

INTRODUCTION:

The problem of building a bridge across Lake Maracaibo does not in itself present grave difficulties, in spite of its excessive length (about six miles), elaborate foundations, and requirement of providing approaches for both the existing and future highway systems. The problem which immediately classifies the work as among the most demanding is the necessity that navigation pass beneath the bridge without limitations to frequency of traffic and, above all, the clearance requirements. Lake Maracaibo, one of the

*Professor, University of Rome
Rome, Italy

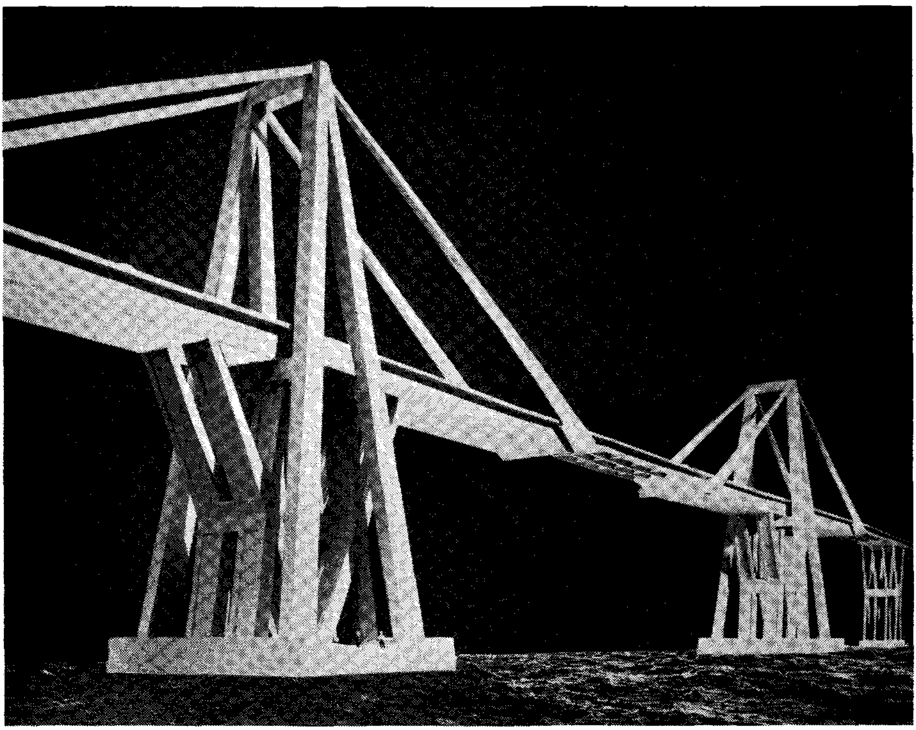

Fig. 1—Model of the Great Span

greatest petroleum centers of the world, has an immense volume of traffic.

The bridge will carry the traffic between the city of Maracaibo (more than 500,000 inhabitants) and the famous Panamerican Highway which runs the entire length of the continent.

The Venezuelan Government, which sponsored the competition for the design and construction of this important work, included in the rider pertaining to the second competion the fundamental characteristics (of the bridge). These characteristics establish the length of approximately six miles with additional requirements that there be, in the navigable channel in the center of the lake a free span with a length of 1,312 feet and a height of 148 feet.

Flanking this great central span there would be five spans, each of a length of 492 feet with the same height of 148 feet. The remaining portions of the bridge could be designed at the engineer's discretion.

The presentation of the theme seemed at first sight to lead to the conclusion that the central part of the bridge must be constructed in steel. The application of this solution, though having its merits, did not present any daring challenges considering the great suspension bridges already executed, especially in the United States.

It was necessary however to consider that the atmosphere of the Lake is particularly injurious to ferrous metals and therefore a bridge in steel would have involved considerable future maintenance expenses.

I asked myself if it were possible to effect this major span using prestressed concrete for its entire length.

The approach spans, 279 feet long, are within the limits of structures of which there are numerous successful examples.

We conceived for the center span a solution in which the span would be completed by means of three elements of already proven dimensions. They would be articulated in such a manner as to fulfill the requirement without resorting to any idea that had not been tried and tested by previous experience.

The Government of Venezuela became convinced through its technical departments that our fundamental solution of the theme was acceptable and it was selected. A most important factor from the economic point of view was that maintenance expenses would be reduced to a negligible minimum.

Subsequently, during the preliminary discussions for the design of the final project, the Venezuelan Government, above all for reasons of economy, modified the fundamental requirements of the project as follows:

—total length: 5 miles and 3,473 feet

—width of the bridge: 57 feet

—the free height above the average level of the lake at the navigable channel: 148 feet

—clear spans for the passage of vessels: 5 each of a length of 656 feet.

DESCRIPTION OF THE PROJECT:

The work was finally designed as follows: Starting from the shore nearest the city of Maracaibo (Punta Piedras):

1 span of 87 feet
2 spans of 153 feet
1 span of 216 feet
15 spans of 279 feet
1 span of 525 feet
5 spans of 771 feet
1 span of 525 feet

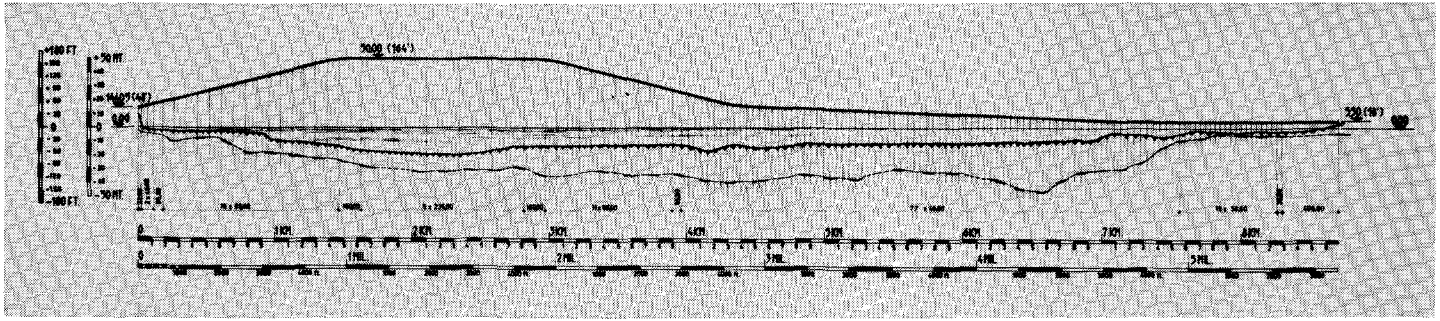

Fig. 2—Profile of the Lake Maracaibo Bridge

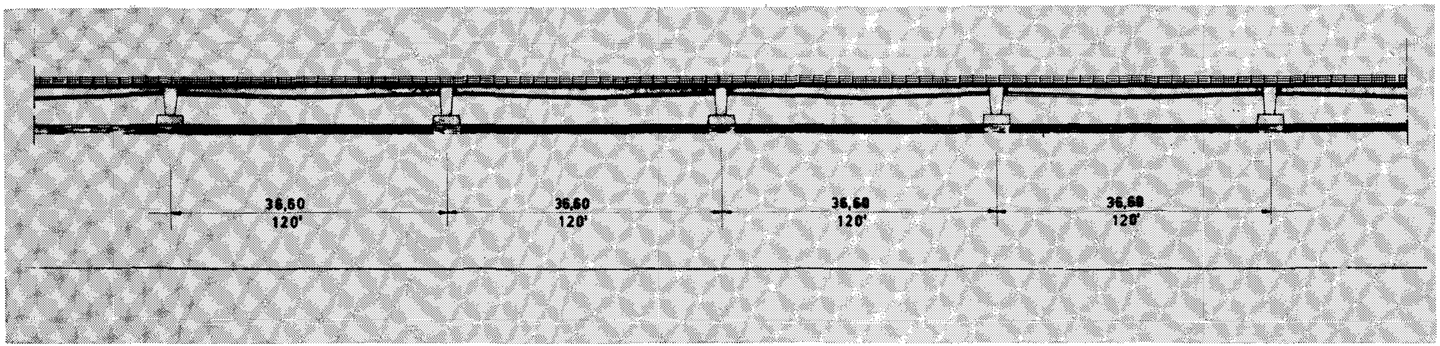

Fig. 3—Elevation 120 ft. Spans

11 spans of 279 feet
1 span of 216 feet
77 spans of 153 feet
20 spans of 120 feet
Approach of 1,335 feet

All of the 153 feet and of 120 feet spans consist of piers with their vertical axes composed of four reinforced concrete walls 2 feet thick. The width varied from 11 ft. 7 in. to 5 ft. 3 in., tied at the top by means of a pillow beam which supports the beam structures. The pier is restrained at its base by a rigid block which in turn is tied to the heads of the foundation pilings which extend to just above the water level of the lake.

Above the piers the horizontal road bed structure is tied at one end by means of a fixed support and at the other by means of an oscillating support. The road bed consists of four beams. They are tied together by the upper slab and by two transverse beams at the supports and by three additional intermediate transverse diaphragms.

The beams of the 151 foot span are characterized by the following dimensions:

—thickness of the slab: varying from 6-¾ in. to 10-⅝ in.

—maximum depth of the ribs: 8 ft. 2-¾ in.

—minimum depth of the ribs: 5 ft. 10-⅞ in.

The quantities of the material are as follows:

—concrete of a minimum cube strength of 6400 lbs. per square inch: quantity 1.23 cu. ft. concrete per square foot of road bed.

—normal reinforcing steel: 4.6 lbs. per square foot road bed.

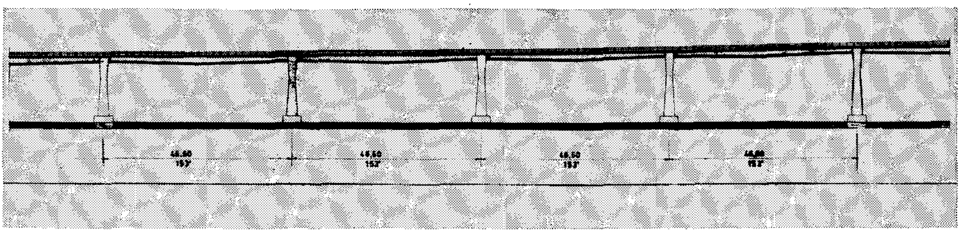

Fig. 4—Elevation 153 ft. Spans

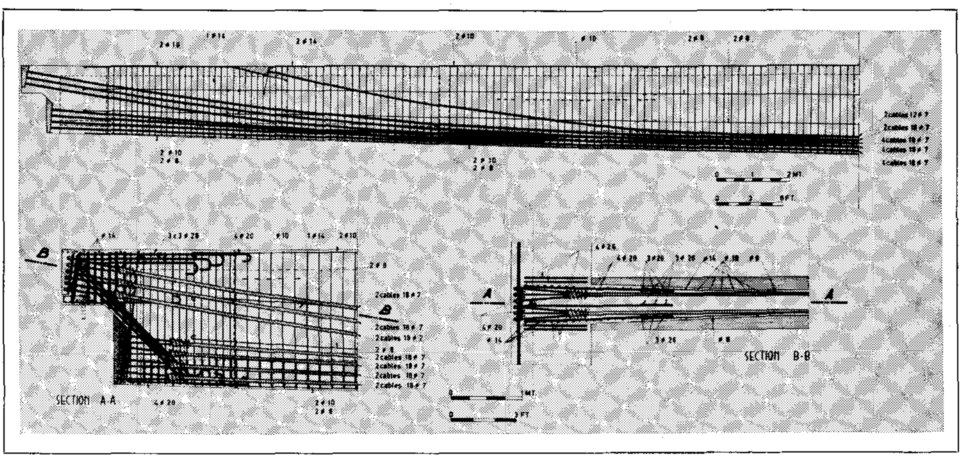

Fig. 5—Details 153 ft. Beam

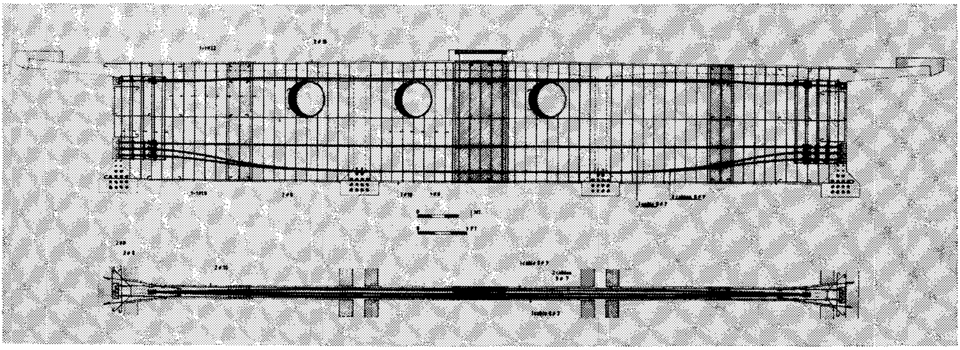

Fig. 6—Transverse Beam

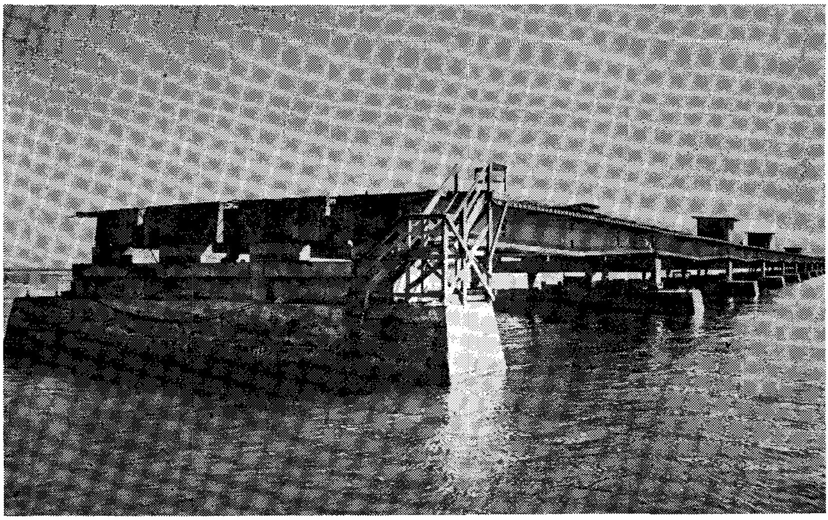

Fig. 7—Construction of 153 ft. Spans

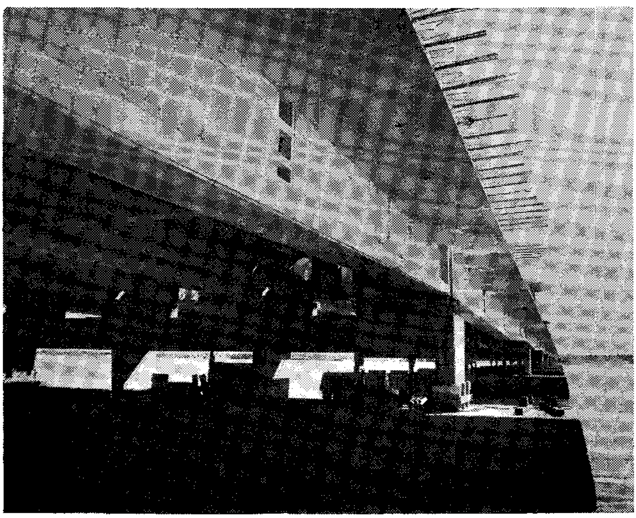

Fig. 8—Construction of 120 ft. Spans

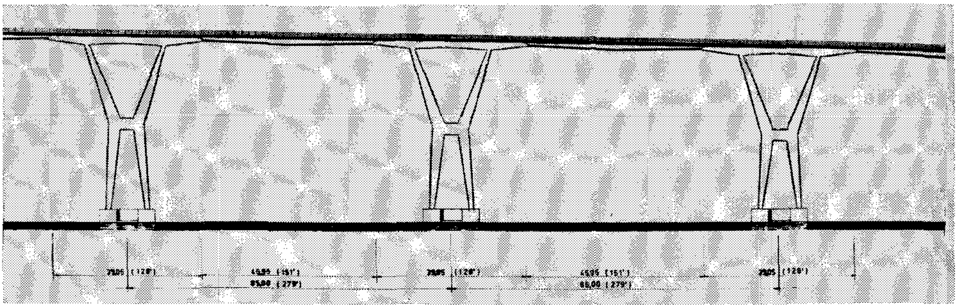

Fig. 9—Elevation 279 ft. Spans

—special prestressing steel, ultimate = 241,791 lbs. per sq. inch, an elastic limit at .2% offset = 206,233 lbs. per sq. inch: quantity 5.35 lbs. per sq. ft. of road bed.

Maximum stresses for the dead weight and live loads are in conformity with the American codes:

f_c = 2134 lbs/sq. in.
f_s = 128,000 lbs/sq. in.

Similarily for the beams of the 118 foot span:

—thickness of the slab: varying from 6-¾ in. to 10-⅝ in.

—maximum depth of the ribs: 6 ft. 6-⅝ in.

—minimum depth of the ribs: 4 ft. 11 in.

The quantities of the material are as follows:

—concrete having a minimum cube strength of 6400 lbs/ sq. in.: 1.18 cubic feet of concrete per square foot of road bed.

—Normal reinforcing steel IIa: 3 lbs. per sq. foot of road bed.

—Prestressing steel ult. = 241,791 lbs/sq. in., an elastic limit at .2% offset = 206,233 lbs. per square inch; 4.70 lbs. per square foot of road bed.

Maximum stresses for dead weight and live loads are in conformity with American Codes:

f_c = 2134 lbs/sq. in.
f_s = 128,000 lbs/sq. in.

The 279 feet spans consist of a special system of trestled piers of the following description:

—A double plate of reinforced concrete placed on top of the foundation pilings and having the following plan dimensions: 52 ft. 4 in. × 14 ft. 11 in. and a height of 9 ft. 10 in., tied together by means of four reinforced concrete beams each 3 ft. 3-¾ in. × 8 ft. 6-⅜ in.

—A special trestle in the form of an "H" with four blades tied at their mid-point and at the top. They have a variable height but are arranged in such a way that the form and the slopes are equal.

—A prestressed concrete beam which ties the two sub-vertical arms of each trestle. This 128 ft. 1-½ in. long beam extends as a cantilever and supports at each end a 151 ft. drop in beam. (See Fig. 9)

The complete trestle consists of an elastic system calculated for:

—dead weight of the structure
—live loads
—wind
—temperature variation
—conditions of construction and assembly.

The maximum stresses are found to be as follows:

—for the parts in normal reinforced concrete:

f_c = 1422 lbs/sq. in.
f_s = 22,757 lbs/sq. in.

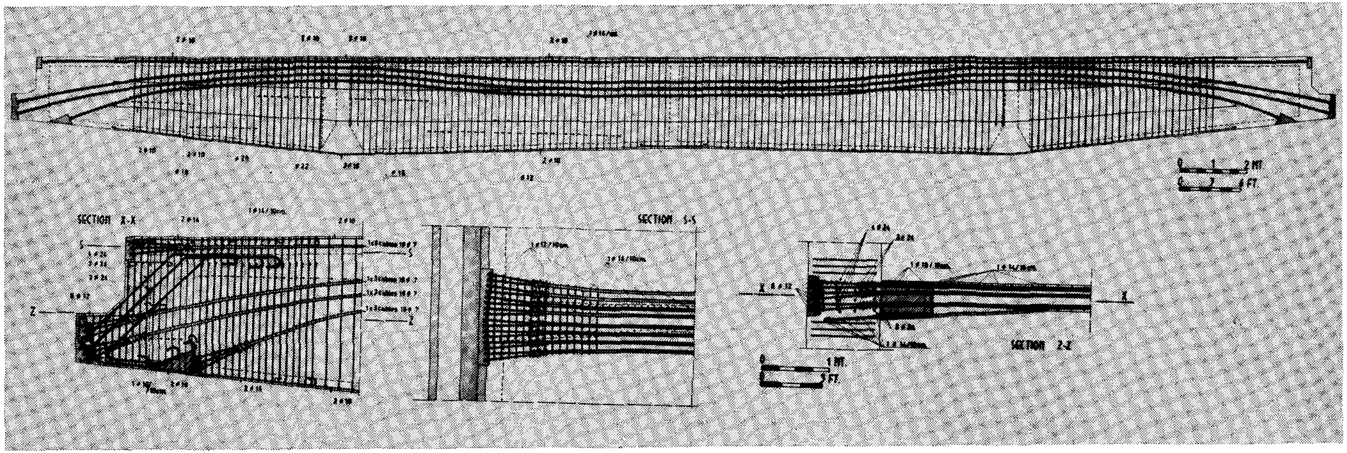

Fig. 10—Cantilever Beam for 279 ft. Span

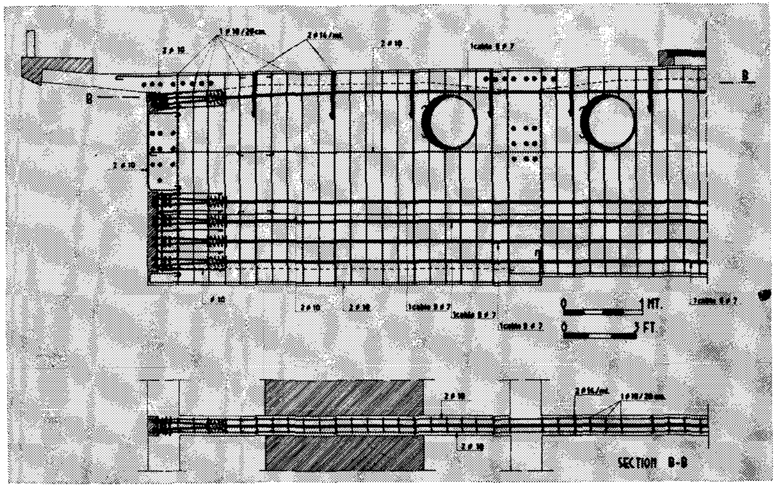

Fig. 11—Transverse Beam

—for the parts in prestressed concrete:

$f_c = 2133$ lbs/sq. in.

$f_s = 128{,}000$ lbs/sq. in.

The quantities of material employed for the road bed (excluding the trestles) are:

—Concrete: 1.80 cubic foot per square foot of road bed.

—Normal reinforcing steel: 8.78 lbs. per square foot of road bed.

—Special prestressing steel: 5.66 lbs. per square foot of road bed.

The 771 foot Spans

This span consists of a complex of six beams, each 620 ft. 3 in. long. They were designed as continuous beams with six restraints of which four are governed by the oblique struts intersecting each other in the form of "XX". The other two restraints are the two ends supported by the tension member that ties them and passes above the double antenna system in the form of an "A". This "A" frame is supported by a great plate placed at the level of the lake, which is also the base of the entire pier complex which in its turn is supported by the foundation pilings. (See figure 13)

The free ends of each continuous beam are tied by simply supported drop-in beams having a theoretical span of 151 feet, identical to those used for all the other spans.

The base plate, the "A" antenna system and the "XX" frames are all constructed in normal reinforced concrete.

The continuous beam is prestressed internally by steel cables and externally by the horizontal component of the oblique antenna tension members. The latter are prestressed to compensate for the tension caused by the dead load deflection of the cantilever beams. This means that the only lowering of this support is that caused by moving live loads. This was accomplished by determining the lengthening of the tension member due to the dead weight and then prestressing to compensate for it.

For the investigation of the tension members we examined the influence of the elastic deformation of the antenna in the case of asymmetric live loads which also determine asymmetric reactions on the antenna itself. A similar investigation was carried out for the temperature variations of the system consisting of the antenna tension members and beams.

To give an idea of the range of stresses in the cables, their maximum and minimum values are as follows:

—minimum tensile stress: 6027 tons

—maximum tensile stress: 6586 tons

The tension members consist of patented cables developed by the firm of Felton and Guilleaume.

A member of particular interest is the transverse beams placed at the ends of the cables whose function is that of distributing the reaction of those cables uniformly across the entire width of the road bed. In these we observe extremely high shear forces for which we compensated by placing a great number of prestressed cables with sharp curvature.

The beam system, length of 620-ft. 3 in. (see fig. 14) is a box structure with high transverse rigidity. The thickness of the box's components are, an upper slab varying from 6-¾ to 10-⅗₀ in. walls and the lower slab of a minimum thickness of 9-⅞″. This is supported by a "X" sub-structure with its restraints con-

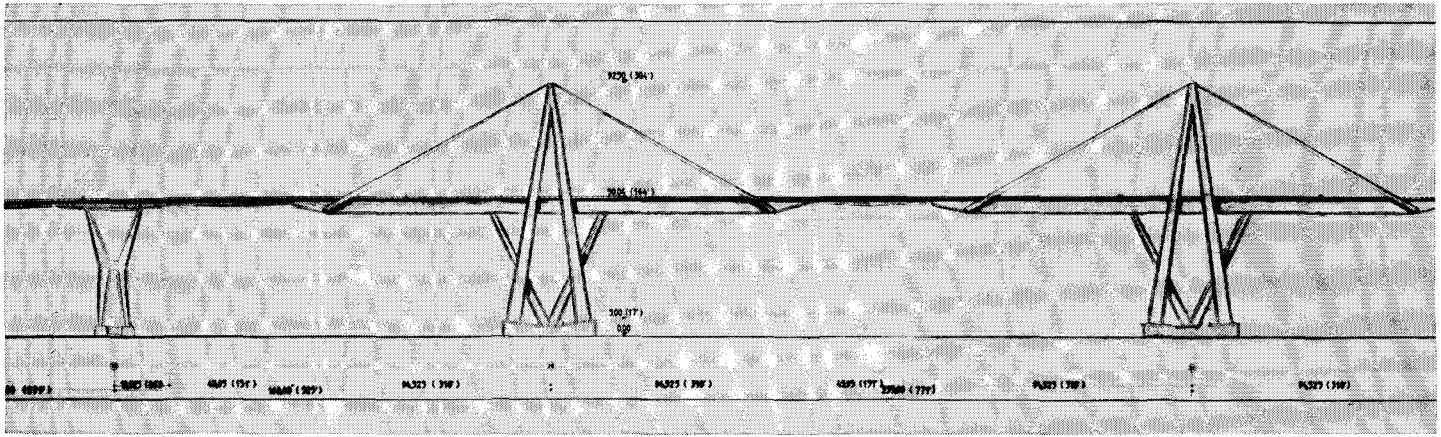

Fig. 12—Elevation 771 ft. Spans

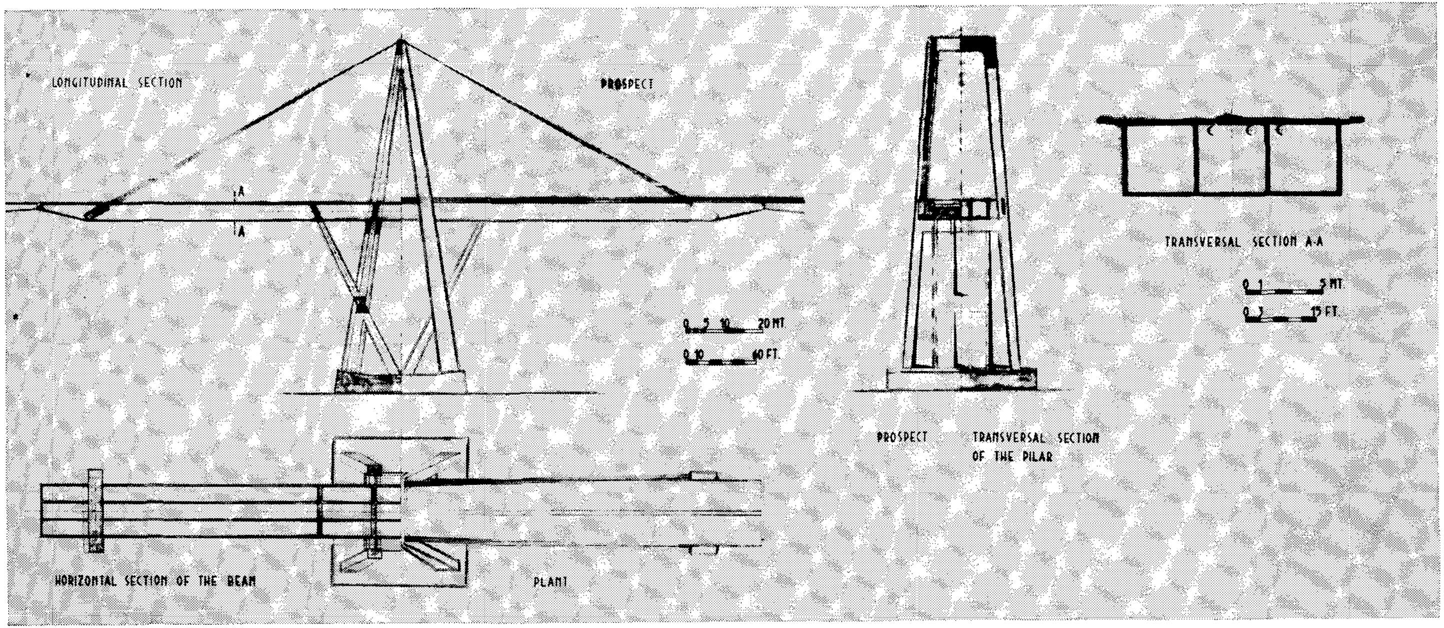

Fig. 13—Details of 771 ft. Span

sidered as connections with respect to the distribution of the bending moments along the length of the beam itself.

The maximum stresses found in the beams are identical to those already described for the other minor beams—as follows:

—compression:
$f_c = -2134$ lbs/sq. in.
—tension:
$f_c = +114$ lbs/sq. in.
$f_{steel} = 128{,}000$ lbs/sq. in.

The quantities of material are as follows:

—Concrete of a minimum cube strength of 6400 lbs/sq. ft.: 3.28 cubic feet per square foot of road bed.
—Normal reinforcing steel: 12 lbs. per square foot of road bed.
—Prestressing steel, ult. = 241,781 lbs/sq. in., elastic limit at .2% offset = 206,233 lbs. per square inch: and a quantity of 4.90 lbs. per square foot of road bed.

The "XX" system, constructed of reinforced concrete with characteristics similar to those in the "H" system, was calculated as an elastic system with following hypotheses:

1st phase: stresses in the system with hinged joints between beam and pier.
2nd phase: stresses induced by the actual rigid tie between the beam and pier.

Conditions of Loading:

—dead weight of the structure
—live loads
—shrinkage
—braking
—temperature variations
—wind

The following stresses resulted:
$f_c = 1707$ lbs/sq. in.
$f_s = 25{,}602$ lbs/sq. in.

THE FOUNDATIONS:

Lake Maracaibo has a depth of water variable from a maximum of 52 ft.-6 in. (for the navigable channel) to a minimum of 6 ft.-¾ in. along the projected crossing.

The lake floor consists of slimey sand. At a depth variable from a maximum of 121 ft.-5 in. below the average level of the lake to a minimum of 32 ft.-10 in., the solidity of the sandy terrain increases. It was agreed to define as firm ground, soil that which resists 20 blows of a standard penetration test.

It was determined that at 32 ft.-10 in. below firm ground the resistance of the standard penetration test increases to 50 blows. It was finally agreed to consider the piles fixed to two meters below firm ground. The notable variation in the depth of the lake and in the depth of the firm ground directed us towards diverse solutions for the various foundations of the bridge.

At the zones nearest the shores and therefore of lesser depth it was sufficient to resort to short piling, using normal prefabricated piles of a maximum safe bearing capacity of 300 tons.

For the deeper foundations on the other hand, larger piles were studied with larger bearing capacities (variable from 500 to 700 tons) built as follows:

A metal sleeve of a diameter of about 4-½ feet is driven into the floor of the lake to the required depth, in some cases 150 feet below the level of the lake. Then a prefabricated pile of a slightly smaller diameter than that of the metal sleeve is introduced into the sleeve. This pile consists of a hollow cylinder with 7 inch thick walls. Finally, the metal sleeve is extracted and cement is injected into the zone between the ground and the pile, completely saturating this area.

Every foundation pile group is tied together by a large plate of reinforced concrete. This footing is designed to transmit the horizontal and vertical actions derived from the superstructures in a uniform manner upon all the piles of the foundation. The foundation for the major spans are still in experimental stage to determine their resistance to extremely high horizontal forces.

THE SYSTEM OF PRE-STRESSING:

All prestressed structures of the road bed, the beams and slabs, have been prestressed using the Morandi system. (see fig. 14) I have used this system, commonly known in Europe as the Italian system, in numerous important structural works and I have had a successful experience with it for more than 12 years. I review briefly here the characteristics of the system which was designed to satisfy the following requirements:

1) To impart equal tension to each of the single wires of the cable.
2) The possibility of realizing, with the same system of anchorage, cables of diverse sections.
3) The possibility of applying the prestressing by degrees, and to recalibrate the tensions and therefore greatly facilitate the unlocking.
4) The possibility of determining the exact tensions in the wires without unlocking them, for the following purposes:
   a) The immediate verification of the tension imparted in order to control eventual losses of tension during locking.
   b) Deductions from tensions read owning to friction which can be verified along the cable.
   c) Verification of the tensions before the recalibration in order to unlock only those wires which require correction, giving in general a control of the performance of the plastic flow of the material.
5) Security of locking and high resistance to oscillating forces.
6) Lightness and economy of the anchorage.

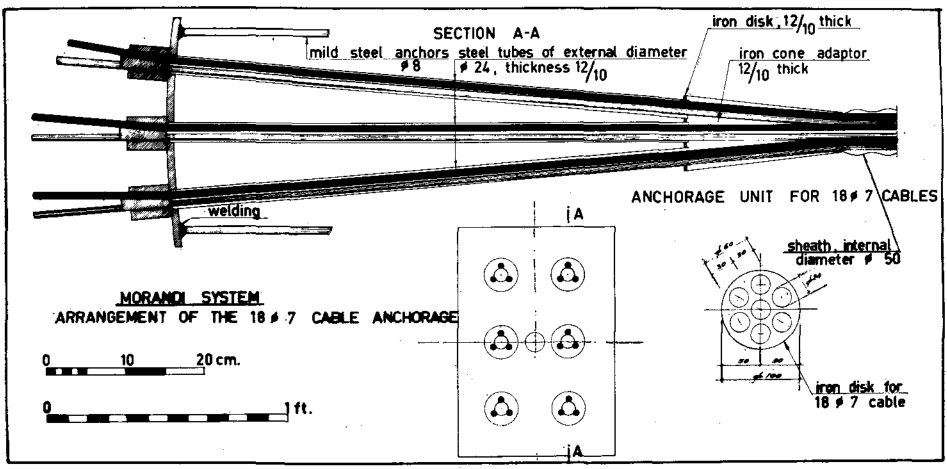

Fig. 14—Anchor Details of Prestressing System

7) Rapidity of the tensioning operations and ease of handling of the equipment.

The tensioning and locking equipment consist of:

a) A light horizontal jack having an anular compression chamber for the tensioning of three wires at a time. The weight of a complete jack for tensioning three cables of 5 mm diameter is 26.5 lbs. for tensioning 3 cables of 7 mm diameter, 48.5 lbs.

b) A lock for 3-5 mm or 3-7 mm cables, consisting of a hard steel cylinder in whose bore are introduced the three steel wires. Along the walls of each bore are grooved three channels, in each of which one wire of the trio is accommodated. In the bore of of the cylinder between the 3 wires, a pin of soft steel, having along its sides 3 grooves of a convergence exactly equal to the canals of the cylinder and in a coincident position.

c) Anchorage plates to distribute the forces transmitted to the cylinders at the head of the structure, with as many 20 mm diameter holes as there are three-wire groups comprising the cable. Plus a subsidiary hole to permit the injection of grout along the cable.

The following therefore is the sequence of the prestressing operations. After having fixed the terminal plates into the concrete at the ends of the structure, the anchorage block for each group of three wires is introduced, the pin is fixed into the block and the jack is operated after the three wires have been introduced into the anular chamber. Thereupon the three wires are firmly grasped at the head of the jack by means of a specially designed pin. In view of the extreme ease of operation of the equipment it is possible to proceed in a very few seconds to the stressing and locking of the three wires.

The jack is provided with a special movable ring nut having the function of holding the cylinder against the plate (during the stressing operation), or, to free the cylinder in order to shift it back along with the wires (operation of direct reading of the tensions), or, finally, to relock the cylinder to the plate for the eventual successive operation of unlocking of the wires and recalibration of the tensions (operation of checking of tensions).

CRITERIA FOR CALCULATION OF THE PRE-STRESSED STRUCTURES

I)—Calculation of friction losses:

Starting from the point of anchorage the percentage of the decrease of the tension is calculated taking into account the normal friction forces as well as the effects of friction in the curved portions and the losses of tension in the anchorage.

The coefficients of friction were assumed in accordance with the Italian Code and are as follows:

nature of the sleeves or surfaces surrounding the cables	coefficient of friction in a straight line fd 1000	coefficient of friction in curve fc
smooth concrete:	5	0.5
sheet metal:	2.5	0.3
lubricated sheet metal:	1	0.2

The results obtained are:

A loss of tension owing to friction up to mid-span for the 151′ beam (metal sleeve): about 16%. Of the total loss about 6% is concentrated at the anchorage.

II)–Calculation of tension because of plastic flow and shrinkage of the concrete:

Given the section of concrete, let:

ϵ_s = unit deformation for shrinkage.

μ_E = final value of the plastic deformation of the concrete.

E_c = modulus of elasticity of the concrete.

e_v = distance of the center of gravity of the cables from the center of gravity of the ideal section (concrete + steel).

J_v = distance of the center of gravity of the concrete section from the center of gravity of the ideal section.

e = distance of the center of gravity of the cables from the geometric center of gravity of the concrete section.

Given:

$$\alpha = n\, A_f \left(\frac{1}{Ai} + \frac{e_v^2}{Ji} \right)$$

(A_f = total area of the cables in the section under consideration). With the hypothesis that the curve $\epsilon_s = f_1(t)$ is analogous to that $\mu_t = f_2(t)$ it is possible to evaluate the loss of tension due to shrinkage along with that due to the plastic flow of the concrete. Finally we obtain the variation ΔX of the force of prestressing:

$$\Delta X = nA_f. \left[\frac{X' \frac{\alpha}{n\, A_f} - \frac{Mg}{J_i} e_v - \frac{Ng}{A_i} + E_c. \frac{\epsilon_s}{\mu_E}(1 - \alpha)}{\frac{1}{\mu} + \frac{\alpha}{2}} \right]$$

The plastic deformation of the steel which produces the total tension losses of 7% takes place during the same period in which the slow deformation of the concrete occurs.

For this reason the average loss will be valued in the measure of 3.5% in the above formula for which: $X'_o = 0.965\, X$ in which X is the force of pre-tensioning at the time $t = 0$.

Mg and Ng are stresses due solely to the permanent loads (exclusive of pre-stressing and live loads).

Isostatic systems: The relation is exact for every section.

Hyperstatic systems: We have a good approximation in the case in which the static system is not modified after prestressing.

In the hyperstatic system we must also consider M and N as coming from the hyperstatic effects of prestressing.

For the 151′ long beam, the total loss of tension due to creep in the steel, and plastic flow and shrinkage of the concrete is 19%.

III)–Determination of the effective forces of prestressing in any section at the time $t = 0$ and $t = \infty$.

Based upon the maximum stress admissible at the anchorage, we proceed to the verification of the stresses at the sections, taking into account that the most unfavorable conditions of stressing are:

$t = 0$: Minimum moment relative to the time of construction when, the force of prestressing X′=X max.

$t = \infty$: Maximum moment that can be realized during the structures lifetime with the force of prestressing X′=X min.

METHODS OF CONSTRUCTION:

Concerning the construction methods, summarized below are the general concepts:

For the sector of the bridge lying towards Punta Jguana, including all the lesser spans whose supports vary in height above the level of the lake, we proceeded by launching (by

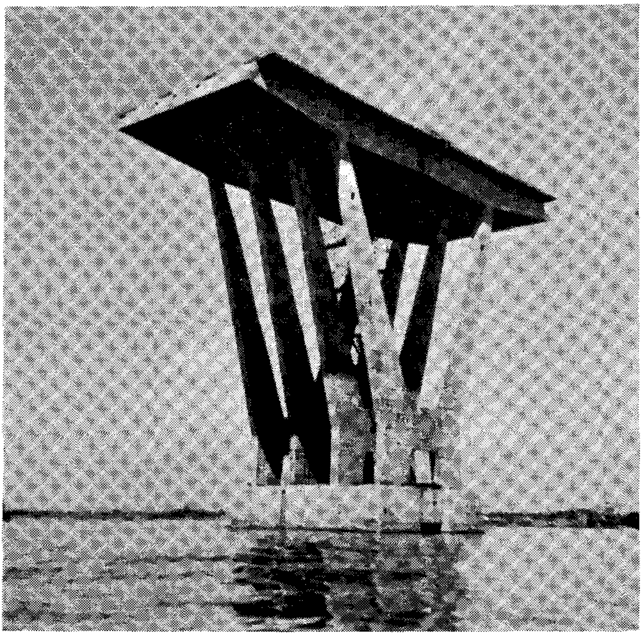

Fig. 15—Pier Construction 279 ft. Spans

Fig. 16—Pier and Beam Construction 279 ft. Span

means of floats) two beams which constituted half of the width of the roadbed structure.

The four beams, separately prefabricated, were brought together two at a time on the vessels which transported them into their position with respect to the piers. The floats were sunk which transferred the support of the beams to the piers.

In this way the only poured in place operation was that of the central portion of the slab after the placing of the transverse prestressing cables in the slab.

A similar method of execution was followed for the 151 feet beams, with the only variation that it was necessary to resort to a system of cranes in order to raise the beams from the level of the floats to the level of the supports.

On the other hand, as far as all the piers and trestles in the form of an "H" and double "X", these are being poured in place with the use of metal forms and centerings in tubular steel. For the pouring of the large beams of the major spans, specially trussed steel centerings will be hung by means of temporary tension rods from the antennae from which the final tension members will hang.

At the present moment, we have already built about 30 spans towards Punta Jguana and 5 spans towards Punta Piedras. The rest of the foundations are presently in construction while all the prefabricated beams are in the last phase of construction.

It is estimated that the bridge will be completed in the first part of 1962.