1938

Superstructure costs of short span self-anchored suspension bridges

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Superstructure Costs of Short Span
Self-anchored Suspension Bridges

by

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a

Thesis

Submitted to the faculty of the

SCHOOL OF MINES AND METALLURGY OF THE UNIVERSITY OF MISSOURI

in partial fulfillment of the requirements for the

Degree of

CIVIL ENGINEER

Pittsburgh, Pa.

1938

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Approved by ..Joe B. Butler..

Professor of Civil Engineering

Acknowledgment

To Mr. Howard Mullins, for his valuable help and suggestions, the writer owes an expression of appreciation.

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Synopsis

Complete designs and estimates for three self-anchored highway suspension bridges are made in this paper. The span lengths investigated are commonly considered to be shorter than the economic limit for suspension bridges. Simple truss and cantilever bridges are usually considered the most economic types for these span lengths.

In the past twenty years a number of self-anchored suspension bridges have been built. These are of widely varied proportions and carry various kinds of loadings. Most of these bridges are designed to carry street-car loading, and thus have a high ratio of live load to dead load, which is less advantageous in a suspension bridge than in any other type. Consequently the economics of self-anchored suspension bridges for light highway loading are not very well known.

There have been only five self-anchored suspension bridges constructed in the Western Hemisphere. Three of these are almost identical, and carry two lines of street car tracks.

The bridges considered here are designed to meet the specifications of the American Association of State Highway Officials for H-15 loading. As the quantities and costs would vary considerably for different specifications, materials, and unit costs, they are more significant when compared with the quantities and costs of simple truss and cantilever bridges designed for the same conditions. A comparison is here made with published data on more common types. The relative costs of the various types of bridges will remain essentially the same, even though the prices may fluctuate considerably.

As substructure costs depend entirely on local conditions for each crossing, they are not considered here. However, for any particular location, part of the substructure cost will be proportional to the superstructure cost, and part of it will be constant regardless of the superstructure. The pier sizes for suspension bridges can be reduced because the loads are smaller, less bearing area is required, and only one shoe is required for each pier. Consequently, economic comparisons of types based on superstructure estimates only, will remain valid for comparisons of the total cost of the structure.

Introduction

History of Type

The self-anchored suspension bridge was probably originated by Josef Langer, an Austrian Engineer. Langer used this type of structure for his Wrsowic Bridge on the Franz Joseph Railway, built in 1870. This bridge, however, had the cable anchored to the stiffening girder near the center of the main span, as well as at the ends. No other bridge has been constructed in this manner.

Charles Bender, an American engineer, patented the self-anchored suspension bridge in the United States in 1867. Bender's patent drawing shows the cable anchored near the middle of the side spans. No bridge of this type was constructed, however, probably because the theory of the stiffening truss was not very well developed at that time. The stiffening truss of an external anchored suspension bridge is not a major stress carrying member, and many trusses on this type of bridge were first designed by guess and later replaced with heavier trusses when failure occurred. The failure of the stiffening truss of a self-anchored bridge would result in the collapse of the structure, and consequently an accurate method of analysis of the truss was necessary before bridges of this type could be built.

Existing Bridges

The general dimensions of existing self-anchored suspension bridges can be conveniently arranged in tabular form. Table I is a chronological and geographical list of the bridges which have been constructed. Several other self-anchored suspension bridges are proposed or under construction at the present time (1938).

Most of the European bridges listed in Table I carry street cars as well as highway loading. The Sixth, Seventh, and Ninth Street bridges in Pittsburgh are designed for two lanes of 18-ton trucks and two lines of 60-ton street cars.

TABLE I - SELF-ANCHORED SUSPENSION BRIDGES

EUROPEAN BRIDGES

Name and Location	Year Built	River	Length, Ft.		Sag of Suspension Member, Ft.	Suspension Member	Depth of Stiffening Member, Ft.	Stiffening Member	Towers	Side Span Condition	
			Main Span	Side Span							
Muhlenthor, Lubeck, Germany	1899	Elbe-Trave Canal	137.75	64.51	18.79	Riveted	4.30	Continuous Warren Truss	Rocker	Loaded	Zeitschrift des Vereines deutscher Ingenieure, 1900. Eiserne Brucken, 1911.
Napageld, Austria	1910	March	118.11	68.90	13.12	Riveted	5.62	Continuous Truss	Rocker		Eisenbau, 1910.
Köln-Deutz, Köln, Germany	1915	Rhine	605.18	302.59	70.67	Eyeplate	10.50	Continuous Girders	Rocker	Loaded	Zeitschrift des Vereines deutscher Ingenieure, 1920.
Lippstadt, Germany	1917	Lippe	181.07	37.72		Riveted		Three-hinged Truss			Die Bautechnik, 1923.
Admiral Scheer, Berlin Germany	1927	Spree	315.95	121.07	35.11	Eyeplate	7.18	Continuous Girders	Rocker	Loaded	Die Bautechnik, 1932.
Forst, Germany	1927	Neisse	129.89	64.94		Eyeplate		Continuous Truss			
Köln-Mülheim, Köln, Germany	1929	Rhine	1,033.46	298.65	113.19	Prestressed Locked-Wire Strands	19.69	Cantilever Girders	Rocker	Unloaded	Der Bauingenieur, 1929. Mohringer, "Bridges of the Rhine."
King Alexander I, Belgrade, Yugoslavia	1934	Save	856.31	246.07	92.08	Prestressed Locked-Wire Strands	14.04	Cantilever Girders	Rocker	Unloaded	Der Bauingenieur, 1930.
ASIATIC BRIDGES											
Kiyosu, Tokyo, Japan	1928	Sumida	300.00	150.00	42.00	Eyeplate	8.5	Three-hinged Girders	Rocker	Loaded	Engineering News-Record, Oct. 3, 1929. World Engineering Congress, Tokyo, 1929, Vol. X, Part 2, Public Works.
AMERICAN BRIDGES											
Seventh St., Pittsburgh, Pa.	1926	Allegheny	442.08	221.36	54.29	Eyebar	9.21	Continuous Girders	One Fixed One Movable	Loaded	Engineering News-Record, Dec. 18, 1924, Sept. 23, 1926.
Ninth St., Pittsburgh, Pa.	1927	Allegheny	430.00	215.00	52.80	Eyebar	9.04	do	do	Loaded.	
Sixth St., Pittsburgh, Pa.	1928	Allegheny	430.00	215.00	52.80	Eyebar	9.04	do	do	Loaded	
Little Niangua, Macks Creek, Mo.	1933	Little Niangua	225.00	112.50	25.00	Prestressed Wire Strands	2.75	Two-hinged Girders	Fixed	Loaded	Engineering News-Record, Sept. 28, 1933.

* Table compiled by Mr. Howard Mullins

Method of Design

Notation

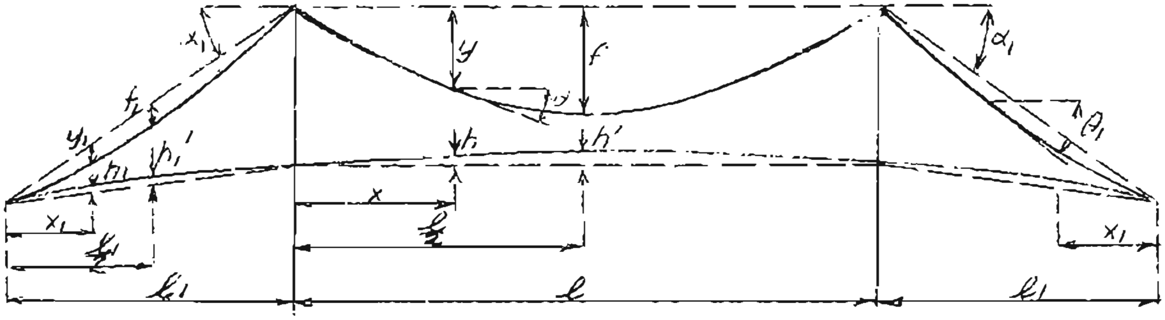

Fig. 1.

H = horizontal component of cable stress due to live load.

H_w = horizontal component of cable stress due to dead load.

w = dead load in pounds per foot per cable.

M' = bending moments (in the stiffening truss) under given loads, for H = 0.

m = bending moments (in the stiffening truss) with zero loading, for H = 1.

u_c = direct stress in cable for H = 1.

u_t = direct stress in truss for H = 1.

E_c = modulus of elasticity of cable material.

E = modulus of elasticity of stiffening truss material.

A_c = area of cross-section of cable.

A = area of cross-section of stiffening truss.

I = moment of inertia of stiffening truss in main span.

I_1 = moment of inertia of stiffening truss in side spans.

θ = angle that the tangent to the cable at any point makes with the horizontal

The notation for the general dimensions of the structure is evident from Fig. 1. Subscripts (l_1, f_1, x_1, h_1 , etc.) denote side span terms. The following notation will also be used for constants which appear frequently in equations:

$$i = \frac{I}{I_1}\ ; \quad r = \frac{l_1}{l}\ ; \quad F = f + h'\ ; \ F_1 = f_1 + h_1'\ ;$$

$$v = \frac{F_1}{F}\ ; \quad y' = y + h = \frac{4Fx}{l^2}(l - x)\ ;$$

$$n = \frac{f}{l}\ ; \quad n_1 = \frac{f_1}{l_1}\ ; \quad y_1' = \frac{4F_1x_1}{l_1^2}(l_1 - x_1)\ ;$$

$$e = \frac{2 + 2irv}{3 + 2ir}$$

Effect of Deflections

Suspension bridges with external anchorages, unlike most engineering structures, deflect enough to appreciably change the moment arms of the forces acting. In an accurate analysis, these deflections are considered, and the analysis is thus made more difficult. Because of this effect of deflections, deformations are not proportional to loads, and the common methods of superposition and influence lines cannot be used.

The deflections of self-anchored suspension bridges are also large. However, if a vertical section is passed through the cable and stiffening truss at any point, the horizontal components of stress in the cable and stiffening truss form a couple, the value of which is not affected by deflections.

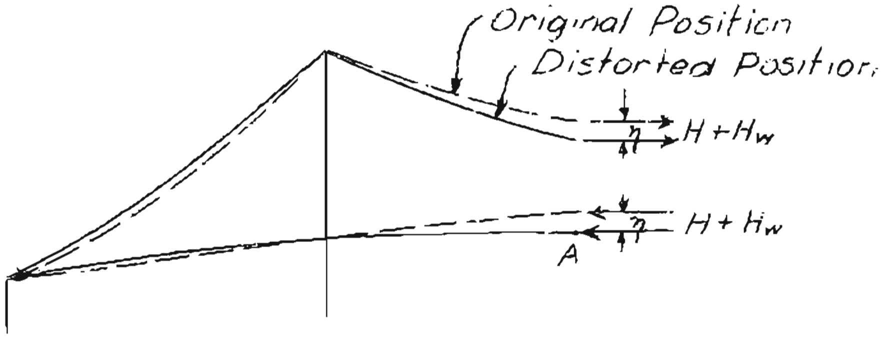

Fig. 2.

In Fig. 2. the bending moment at any point A, will be,

$$M_A = M' + Hm - (H + H_w)\eta + (H + H_w)\eta \qquad (1)$$

or

$$M_A = M' + Hm \qquad (2)$$

The deflection, η , cancels out of the moment equation, as does the dead load cable stress, H_W . Therefore, the changes in moment arms caused by deflections may be disregarded, and the live load stresses may be computed separately and superimposed on the dead load stresses. Influence lines can also be used for self-anchored suspension bridges.

Equation (1) has another significance. The stiffening girder functions as a long column carrying a compression of $H+H_w$. If it were not attached to the cable, it would tend to buckle vertically from the moment $(H+H_w)\eta$, the last term in Equation (1). This tendency to buckle vertically is counteracted by the cable, as shown by the fact that this term vanishes from Equation (1).

The bending moment at any point in the stiffening truss of an external-anchored suspension bridge would be represented by the Equation,

$$M_A = M' + Hm - (H+H_w)\eta. \tag{3}$$

The last term of Equation (3) represents the effect of deflections in reducing bending moments. Since this term does not appear in Equation (2) for a self-anchored suspension bridge, the bending moments will be larger than for a similar external-anchored suspension bridge. This disadvantage in the self-anchored type is partially offset by cambering the stiffening girder, and thus reducing the bending moments.

<u>Design Equations</u>

The self-anchored suspension bridge with continuous stiffening truss is statically indeterminate to the third degree. If the cable is removed, the resulting

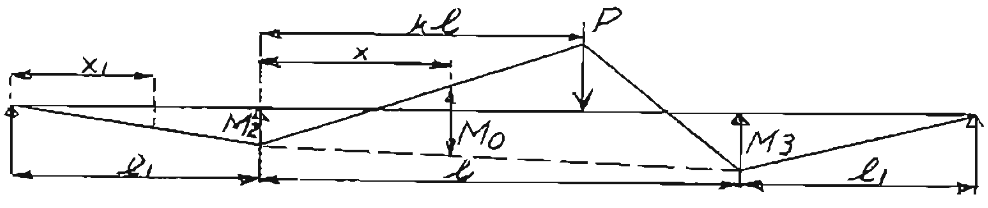

Fig. 3.

structure is a continuous girder over three spans. If M_0

is the bending moment in a beam simply supported at the towers, and M_2 and M_3 are the bending moments in the girder at the towers, it is seen from Fig. 3 that the bending moment at any point a distance x from the end of the main span is found from the equation,

$$M' = M_0 + M_2 + \frac{x}{l}(M_3 - M_2) \tag{4}$$

In the left side span the equation becomes,

$$M_1' = M_0 + \frac{x_1}{l_1} M_2 \tag{5}$$

For the right side span the equation is,

$$M_1' = M_0 + \frac{x_1}{l_1} M_3 \tag{6}$$

The values of M_2 and M_3 as determined by using the three-moment equation are substituted in Equations (4), (5), and (6).

The bending moment, m, in the stiffening girder developed by a unit H, is made up of a uniform suspender pull in each span and of the bending moment caused by the parabolic camber. These loads are shown in Fig. 4, and the corresponding bending moment diagram is shown in Fig. 5.

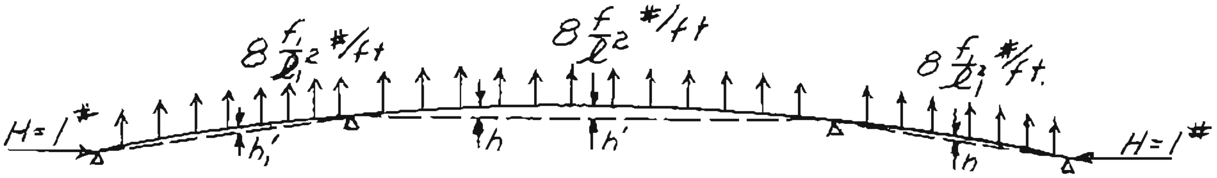

Fig. 4.

From Fig. 5, the bending moment at any point a distance x

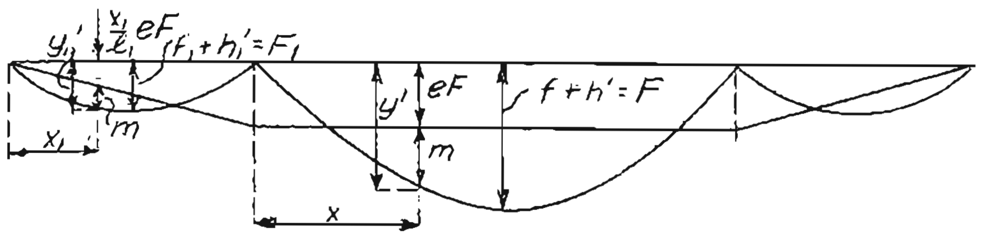

Fig. 5.

from the end of the main span is,

$$m = -y' + eF \tag{7}$$

At any point a distance x_1 from the end of the side span, the bending moment is

$$m_1 = -y_1' + \frac{x_1}{\ell_1} eF \tag{8}$$

The horizontal component of the cable stress, H, for any loading, will be found from the equation,

$$H = -\frac{\int \frac{M'm}{EI}\,dx}{\int \frac{m^2}{EI}\,dx + \int \frac{u_c^2}{A_c E_c}\,ds + \int \frac{u_t^2}{AE}\,dx} \tag{9}$$

in which the limits of the integrations are taken over the entire structure. Substituting values from Equations (4) to (8), and evaluating the integrals, the following equation is obtained.

$$H = \frac{\frac{3}{F^2\ell}\left[\int_0^{\ell} M'(y'-eF)\,dx + i\sum\int_0^{\ell_1} M_1'\left(y_1'-\frac{x_1}{\ell_1}eF\right)dx_1\right]}{\frac{8}{5}-4e+3e^2+2ir\left(\frac{8}{5}v^2+e^2-2ev\right)+\frac{E}{E_c}\frac{3I}{A_cF^2}(1+8n^2)+\frac{E}{E_c}\frac{6I}{A_cF^2}\frac{\ell_1}{\ell}\sec^3\alpha_1(1+8n_1^2)+\frac{3I}{F^2\ell}\left(\frac{\ell}{A}+\frac{2\ell_1}{A_1}\right)} \tag{10}$$

The denominator of Equation (10) is constant for any structure, being independent of the loading conditions. It is also a dimensionless number, containing only ratios. If this denominator is called N, and the numerator is evaluated for the case of a load P in the main span at a distance $k\ell$ from the left tower, Equation (10) becomes,

$$H = \frac{P\ell}{NF}\left[k(k^3 - 2k^2 + 1) - \frac{3}{2}e(k - k^2)\right] \qquad (11)$$

For a load P_1 at a distance $k_1\ell_1$ from the outer end of the side span, Equation (10) becomes,

$$H = \frac{P_1 \ell i r^2}{NF}\left[v k_1(k_1^3 - 2k_1^2 + 1) - \frac{e}{2}(k_1 - k_1^3)\right] \qquad (12)$$

In analyzing a self-anchored suspension bridge, influence lines for H may be constructed from Equations (10), (11), and (12). Influence lines for bending moments at any point may be constructed from Equations (2), (4), (5), (6), (7), and (8).

Cable Anchored to Chord of Truss

The self-anchored suspension bridge with a stiffening truss will be analyzed by the preceding equations if the cable is anchored to the truss at the center of gravity of the truss section. Usually, however, it will be more convenient to anchor the cable to the lower chord of the stiffening truss. This will include an end moment of $-HCF$ in the above equations, where CF is the distance from the center of gravity of the truss to the point where the cable is anchored (Fig. 6).

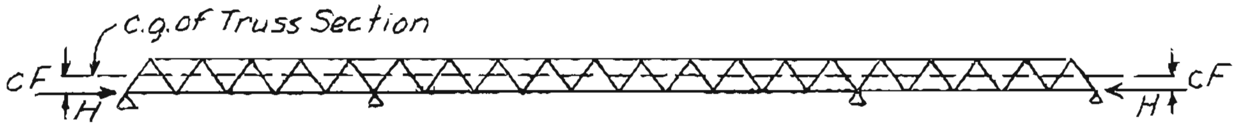

Fig. 6.

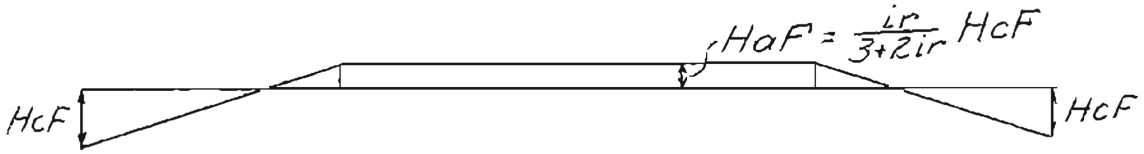

Fig. 7.

Equation (7) will be changed by the bending moments shown in Fig. 7. The bending moment, m, for a unit H, will be

$$m = -y' + (e+a)F \tag{13}$$

Equation (8) will be replaced by the equation

$$m_1 = -y_1' + \frac{x_1}{l_1}(e+a+c)F - cF \tag{14}$$

If the values from Equations (13) and (14) are substituted in Equation (9), the value of H for a load P in the main span at a distance kl from the left tower is obtained.

$$H = \frac{\frac{Pl}{F}\left[k(k^3 - 2k^2 + 1) - \frac{3}{2}(e+a)(k-k^2)\right]}{\frac{8}{5} - 4(e+a) + 3(e+a)^2 + 2ir\left[\frac{8}{5}v^2 + (e+a)^2 - 2(e+a)v + c^2 - c(e+a) + 2vc\right] + \frac{E}{E_c}\frac{3I}{A_cF^2}(1+8n^2) + \frac{E}{E_c}\frac{6Il_1}{A_cF^2l}\sec^3\alpha_1(1+8n_1^2) + \frac{3I}{F^2l}\left(\frac{l}{A} + \frac{2l_1}{A_1}\right)} \tag{15}$$

In designing the stiffening truss it will be more convenient to compute the direct stress in the lower chord, and the bending moment about the lower chord, than to use the above forms for the bending moment about the center of gravity of the truss section.

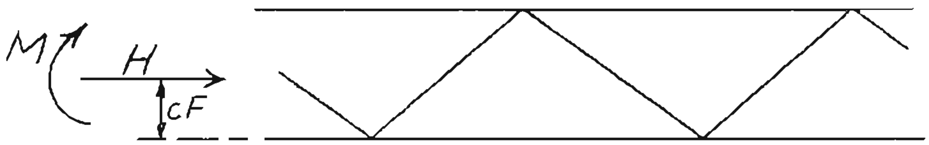

Fig. 8.

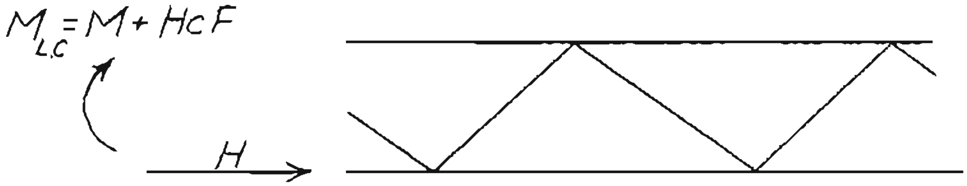

Fig. 9.

The bending moment shown in Fig. 8, in which H acts at the center of gravity of the truss section must be increased by the moment HcF, as shown in Fig. 8. The bending moment at any point in the main span will then be

$$M_{L.C.} = M' - H[y' - (e+a+c)F]. \tag{16}$$

For any point in the side span, the bending moment will be

$$M_{L.C.} = M' - H\left[y' - \frac{x_1}{\mathcal{L}_1}(e+a+c)F\right] \tag{17}$$

Designs and Estimates

Design Specifications

The self-anchored suspension bridges are designed according to "Standard Specifications for Highway Bridges," adopted by the American Association of State Highway Officials (A.A.S.H.O.), and published by the Association in 1935. The loading used is H-15 loading, consisting of a 15-ton truck preceded and followed by $11\frac{1}{2}$-ton trucks on each traffic lane. For loaded lengths of 60 feet or greater, an equivalent loading is used, as given in the specifications.

The costs of simple span and cantilever bridges are computed from quantities published by Dr. J. A. L. Waddell[1]. These quantity curves have been plotted from actual weights of hundreds of structures, and are probably the most reliable data of their kind available. The structures are designed for Dr. Waddell's specifications, which differ from the A.A.S.H.O. specifications in many respects. Dr. Waddell gives formulas for finding quantities in structures designed for other specifications.

The simple truss and cantilever spans were designed for a standard 8-inch reinforced concrete floor with 1-inch wearing surface, which weighs 110 lb. per sq. ft. and is estimated to cost $0.80 per sq. ft. The suspension bridges are designed for a 3-inch steel-concrete floor which weighs 47 lb. and is estimated to cost $1.25

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[1] Waddell, J.A.L., "Weights of Metal in Steel Trusses," <u>Transactions</u>, Am. Soc. C. E., 1936, pp. 1 - 34.

per sq. ft. Studies made by Dr. Waddell show that for the span lengths considered here, the costs of simple truss and cantilever bridges will be approximately the same for the lighter, more expensive floor as for the heavier, cheaper floor.[1]

The estimates for simple trusses and cantilevers are made for 20-foot roadways and for steel with a working stress of 16,000 lb. per sq. in. The estimates for the self-anchored suspension bridges are made for 22-foot roadways and for a working stress of 18,000 lb. per sq. in. Waddell gives the formula,[2]

$$w' = w\left(0.3 + 0.7\frac{16,000}{18,000}\right) = 0.922\ w \qquad (18)$$

for converting the weight, w, based on a working stress of 16,000 lb. per sq. in. to the weight, w', obtained with a working stress of 18,000 lb. per sq. in. If the weight for a wider structure is proportional to the width of roadway, the weight of steel, w", for a 22-foot roadway would be

$$w'' = 0.922\ w \times \frac{22}{20} = 1.014\ w \qquad (19)$$

Equation (19) shows that the effect of the wider roadway compensates for the effect of the higher working stress within an accuracy of 1.4%. As this error is within the limits of the accuracy of the estimates, it

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[1] Waddell, J.A.L., "Economics of Highway-Bridge Floorings of Various Unit Weights," Transactions, Am.Soc.C.E.,1938.

[2] Waddell, J.A.L., op, cit., p.9.

will be disregarded, and the designs compared as if they were based on the same specifications.

The most important difference in the specifications by which the bridges were designed, is the magnitude of the live load. The H-15 loading is represented by an equivalent uniformly distributed load and a concentrated load. The uniformly distributed load is the same for all span lengths. Waddell's Class "A" loading is represented by an equivalent uniformly distributed loading, without a concentrated load.[1] The distributed load is greater for shorter span lengths and decreases for longer spans. Waddell's Class "A" loading probably gives higher stresses than H-15 loading for shorter span lengths, and approximately equal stresses for the longer spans considered here.

The working stress for prestressed wire strand cables is not given in the A.A.S.H.O. specifications. In the suspension bridge designs a working stress of 65,000 lb. per sq. in. is used. This is a conservative value for the working stress in this type of cable.

Bridges with 240-foot Main Span

The stress sheet for a self-anchored suspension bridge with a main span of 240 feet and side spans of 100 feet is shown in Fig. 10. These stresses are computed by Equations (4) to (12). The main cables are each composed of four $1\frac{3}{4}$-inch galvanized bridge strands.

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[1] Waddell, J.A.L., "Bridge Engineering."

These strands are prestressed to increase the modulus of elasticity to 24,000,000 lb.per sq.in., and to eliminate inelastic action under load. The lengths of the strands for cables and suspenders are measured after prestressing, and while the strands are carrying their dead-load tension. The cables and suspenders are socketed in the shop, with no provision for adjusting the lengths in the field, except by shims between the sockets and bearing blocks of the main cable strands. The strands of the main cables are spaced in an open arrangement for convenience in inspecting and painting.

The stiffening girders are composed of 36-inch wide flange rolled sections, with cover plates where required. These girders are field spliced at several points. Structural plates are riveted to the girder webs and pass through slots in the upper flange to attach to the suspender sockets. The cable attaches to the stiffening girder at the end, through cast steel bearing blocks which bear on a 7½-inch pin through the girder web. The girder web is reinforced by bearing plates.

The roadway surface is composed of a 3-inch steel and concrete floor weighing 47 lb.per sq.ft. The stringers are spaced at 5'-0" centers, and the floorbeams are spaced at 20'-0" centers. As the economic panel length is determined by the floor and live load, it will be approximately the same for bridges of any span length. The floor systems are the same for all three suspension bridges designed in this paper. Additional details of the stiffening girders and floor system are shown in Fig. 11.

The main tower columns are made up of rolled steel sections as shown in Fig. 12. The towers are of the rocker type, so that temperature stresses are eliminated. The reactions at the tower base are distributed to the pier masonry by rolled steel slabs. The rocker plates are also made of rolled slabs, which are machined to a cylindrical surface. The cable reaction is distributed to the top of the tower columns by cast-steel saddles.

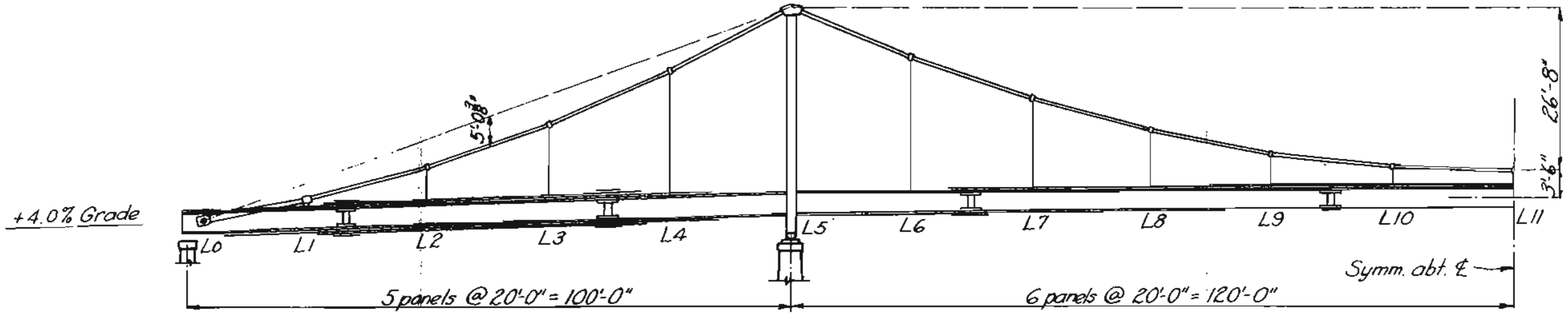
The superstructure quantities and costs for the suspension bridge with 240-foot main span, as computed from the designs of Figs. 11 and 12, are as follows:

Structural Steel				
Towers	30,860	lb.		
Main Girders	219,460	lb.		
Laterals	15,940	lb.		
Floor System	154,500	lb.		
Curb, rail	59,720	lb.		
	460,480	lb.	@ $0.06=	$27,700
Cast Steel-- Saddles	3,750	lb.	@ $0.18=	680
Pins and Nuts	1,100	lb.	@ $0.10=	110
$1\frac{3}{4}$-in. Prestressed Strands	23,500	lb.	@ $0.20=	4,700
1-in. Prestressed Strands	650	lb.	@ $0.20=	130
1-1/8 in. Open Sockets	28		@ $6.00=	170
Special Open Sockets	28		@ $10.00=	280
Sockets for Main Strands	16		@ $ 6.25=	100
Cable Clamps	38		@ $12.00=	460
Strand Spreader Clamps	4		@ $50.00=	200
Strand Bearing Blocks	8		@ $50.00=	400
Floor-3" Steel-Concrete	9680	sq.ft.	@ $1.25=	12,100
Total Superstructure Cost				$47,030

FIG 10

Cable: 4 - $1\frac{3}{4}$" Galvanized prestressed strands
Hangers: 1 - 1" Galvanized prestressed strands

Maximum Cable Stress
D.L. 860
L.L. 310
Total 1170



ELEVATION OF SUPERSTRUCTURE

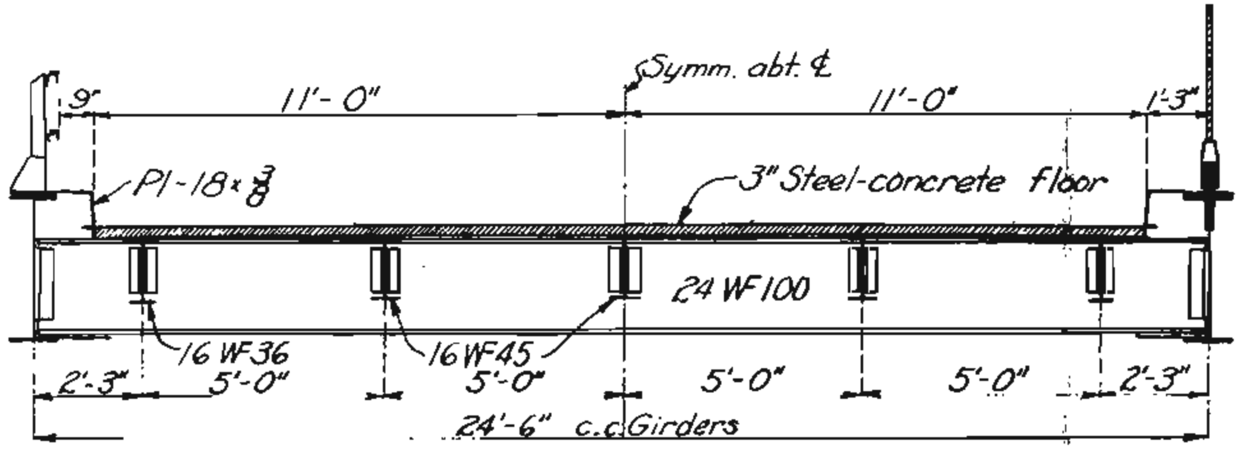
BENDING MOMENTS IN STIFFENING GIRDER

Panel Point		L0	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11
Dead Load	H	270	270	270	270	270	270	270	270	270	270	270	270
	M	0	+3	+24	+65	+124	+203	+95	+5	-62	-110	-141	-151
Maximum Pos. Moment	H	415	260	260	260	260	357	295	304	334	372	395	415
	M	0	+663	+990	+965	+634	+453	+495	+710	+839	+910	+904	+925
Maximum Neg. Moment	H	415	401	401	401	400	327	370	363	355	320	295	261
	M	0	-562	-853	-840	-676	-637	-405	-385	-394	-332	-271	-222

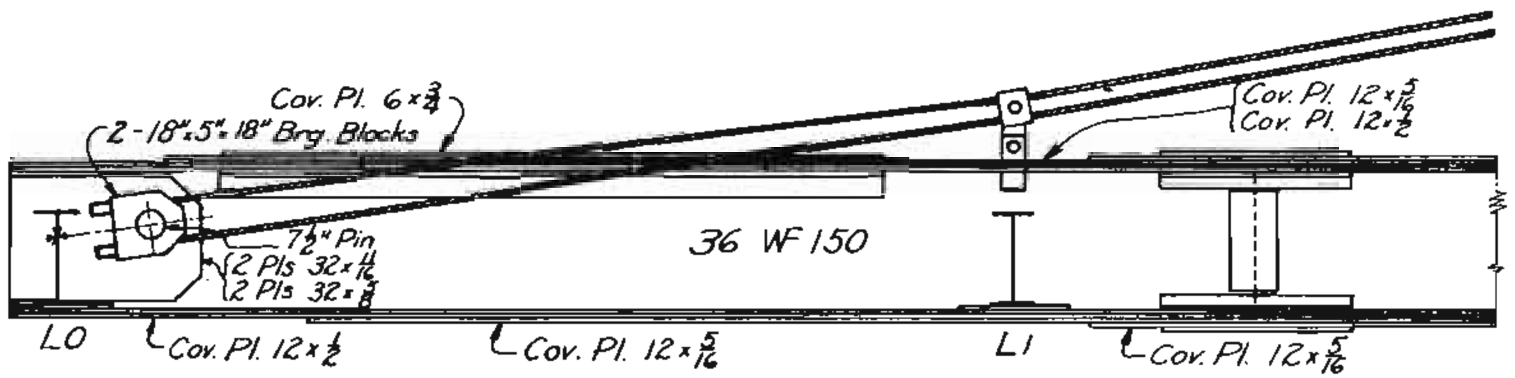
Note: Stresses are in kips
Bending moments are in ft.-kips

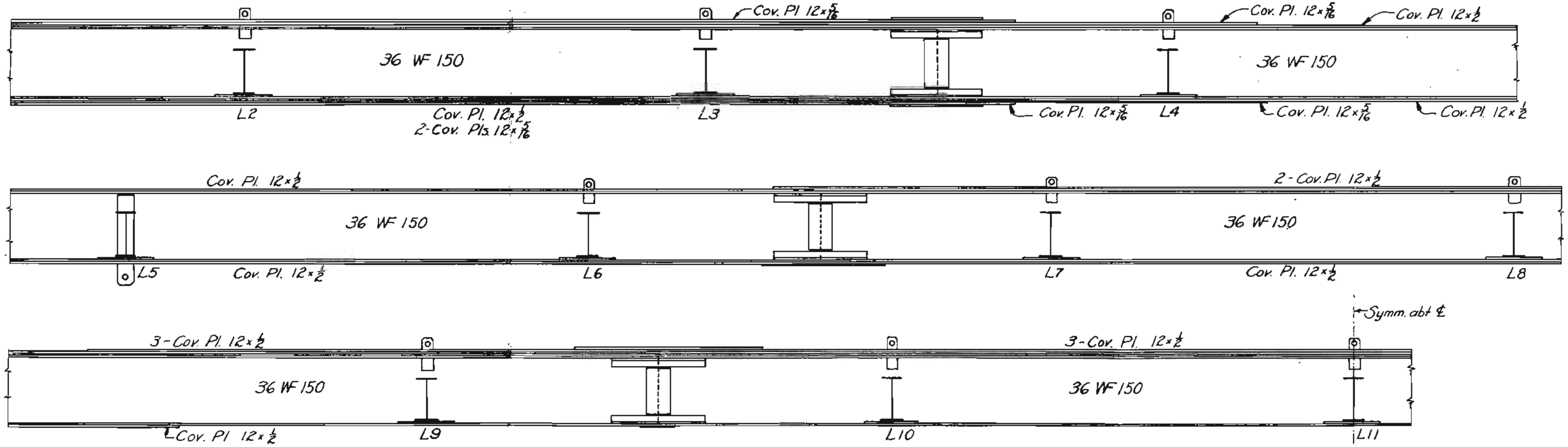
SELF-ANCHORED SUSPENSION BRIDGE
SPANS 100'-240'-100' LOADING H-15
DESIGNED BY D.J. PEERY
PITTSBURGH, PA. 1938

FIG. 11



SECTION THROUGH ROADWAY





STIFFENING GIRDER DETAILS

SELF-ANCHORED SUSPENSION BRIDGE
SPANS 100'-240'-100' - LOADING H-15
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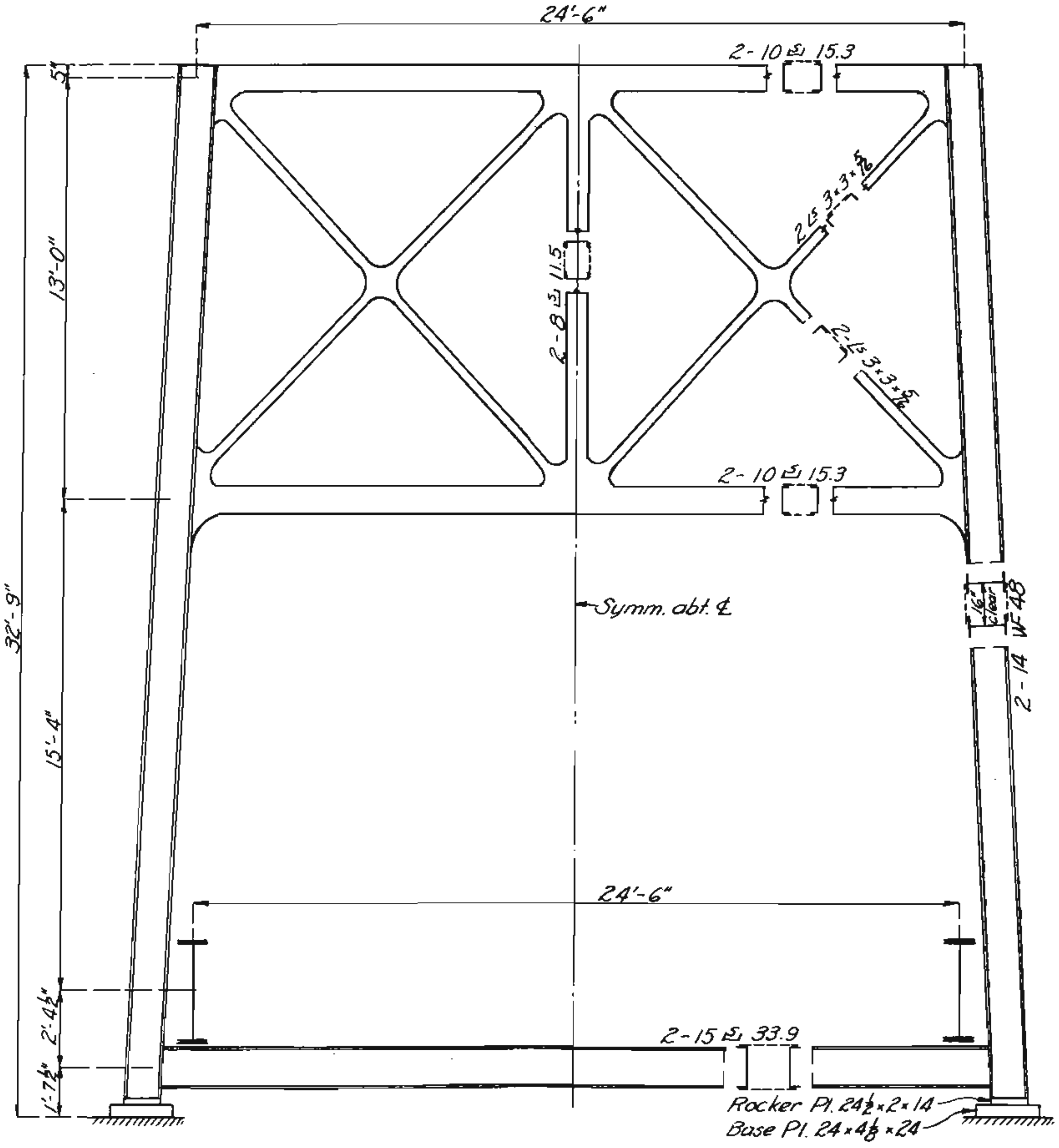
FIG. 12



TOWER DETAILS

SELF-ANCHORED
SUSPENSION BRIDGE
SPANS 100'-240'-100'
LOADING H-15
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This estimated cost will have more significance when compared with superstructure costs of simple span bridges designed for the same lengths and with the same unit prices. This span length is too short for a cantilever bridge to be economical. There are two simple span layouts which might be used, the choice being determined by local conditions. If piers can be placed at any point in the stream, three equal spans of 146'-8" might be used, as shown in Fig. 13. With this layout, the weight of steel per foot of bridge will be 1970 lb. The total quantities and costs will be as follows:

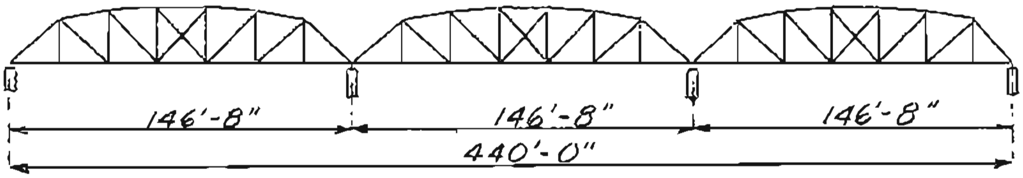


Fig. 13.

Structural Steel--	866,000 lb.	@ $0.06 =	$52,000
9" Concrete Floor--	9680 sq.ft.	@ $0.80 =	7,740
Curbs	440 ft.	@ $3.60 =	1,590
Total Superstructure Cost			$61,330

For locations where it is important that the main span be long enough to give satisfactory foundations or clearance, the simple span arrangement would be as shown in Fig. 14. This arrangement of spans should be compared with the suspension bridge, as all the spans are the same lengths as the spans of the suspension bridge.

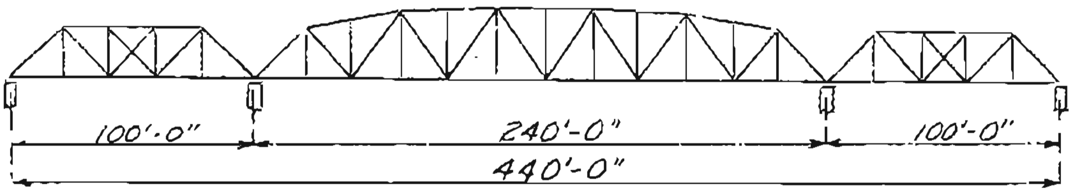


Fig. 14.

The quantities and costs of this bridge will be as follows:

Structural Steel	-- 936,000 lb.	@ $0.06 =	$56,200
9" Concrete Floor	-- 9680 sq.ft.	@ $0.80 =	7,740
Curbs	-- 440 ft.	@ $3.60 =	1,590
Total Superstructure Cost			$65,530

Bridges With 340-Foot Main Span

The stress sheets for a self-anchored suspension bridge with a main span of 340 feet and side spans of 140 feet are shown in Figs. 15 and 16. These stresses are computed from Equations (13) to (17). The bending moments tabulated in Fig. 15 are about the lower chord, as computed from Equations (16) and (17). In Figure 16, the maximum positive and negative stresses for each member of the stiffening truss are given, and the sections designed to resist these stresses are shown.

The main cables are each composed of nine 1½-inch prestressed strands. The strands have a similar open arrangement to that used for the bridge with a 240-foot main span.

The bridge is stiffened by a truss having a depth of 6'-8" between centers of chords. The cable is anchored to the lower chord of the stiffening truss, since this chord is braced laterally, and is better able to resist compressive stress. However, part of this compressive stress is carried by the upper chord, as is evident from Figs. 6 and 7. The design equations for a bridge having the cable anchored to the lower chord of the stiffening truss will not be the same as for a bridge in which the cable is anchored at the center of gravity of the truss section.

The towers are similar in design to the towers for the bridge with 240-foot main span. Tower details are shown in Fig. 17. Details of the stiffening truss and suspender connections are shown in Fig. 18.

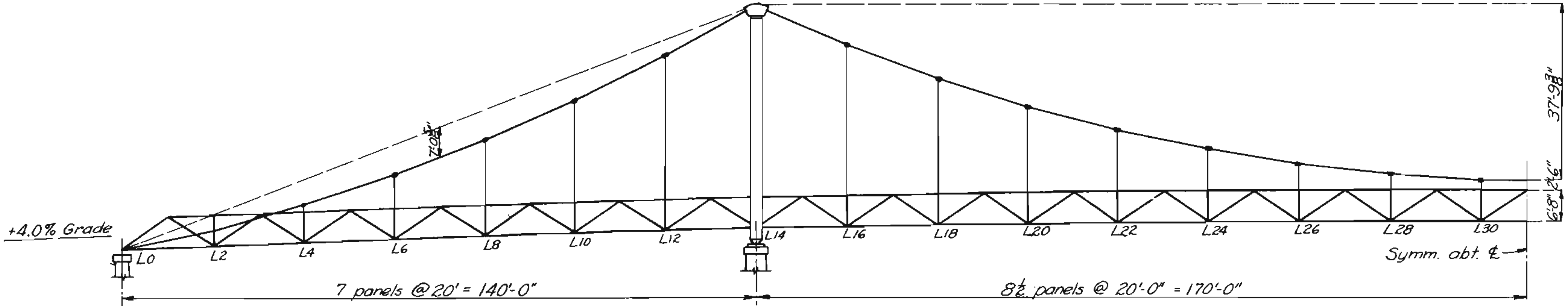
The superstructure quantities and costs for the 340-foot span suspension bridge are as follows:

Structural Steel			
Towers	71,600 lb.		
Trusses	398,880 lb.		
Laterals	35,010 lb.		
Floor System, Curb & Rail	250,000 lb.		
	755,490 lb.	@ $0.06 =	$45,300
Cast Steel--Saddles	5,770 lb.	@ $0.18 =	1,030
$1\frac{1}{2}$-in. Prestressed Strands	55,100 lb.	@ $0.20 =	11,020
Pins and Nuts	2,500 lb.	@ $0.10 =	250
1-in. Prestressed Strands	1,440 lb.	@ $0.20 =	290
Open Sockets (attached)	88	@ $7.00 =	620
Sockets for Main Strands	36	@ $7.00 =	250
Cable Clamps	52	@ $15.00 =	780
Floor--3" Steel-Concrete	13,640 sq.ft.	@ $1.25 =	17,060
Total Superstructure Cost			$76,600

FIG. 15

Cable: 9-1½" Galvanized
prestressed strands
Hangers: 1-1" Galvanized
prestressed strand

Maximum Cable Stress
D.L. 499
L.L. 245
Total 744



ELEVATION OF SUPERSTRUCTURE

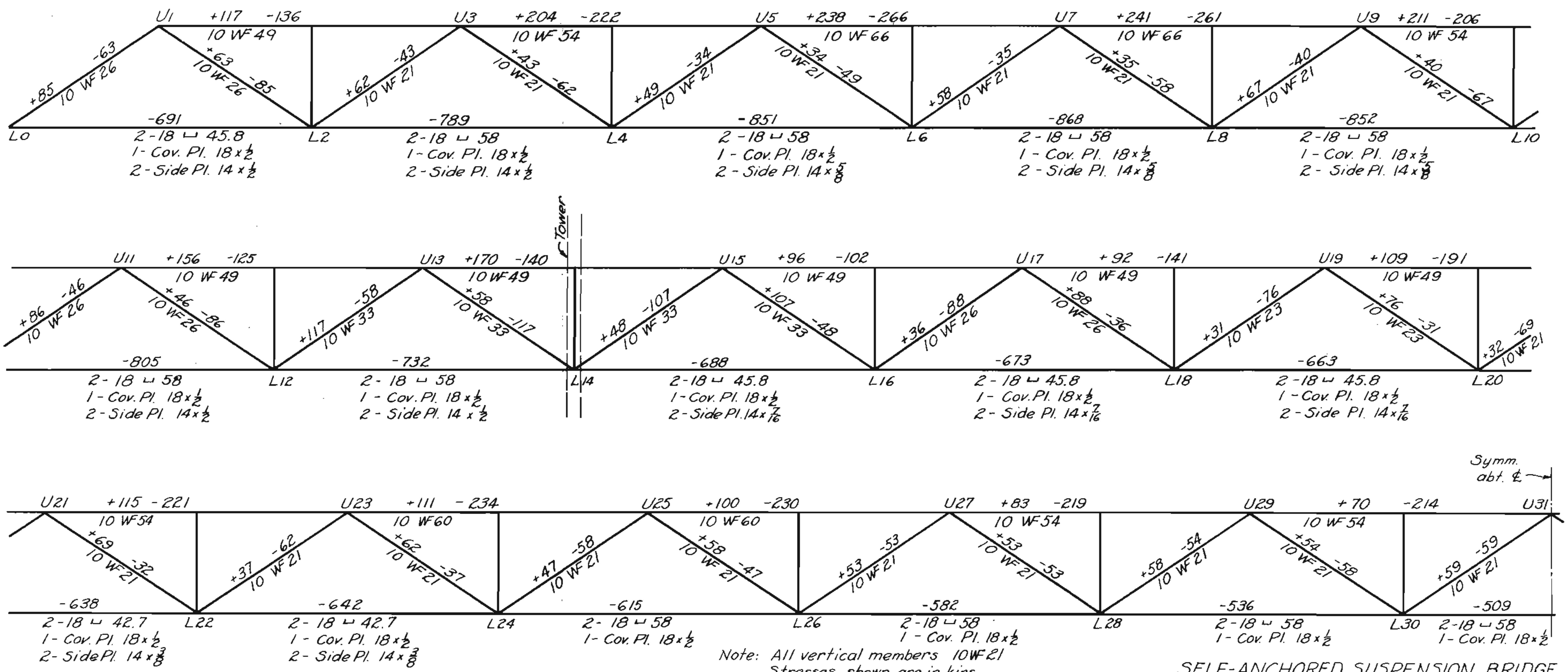
BENDING MOMENTS AND SHEARS IN STIFFENING TRUSS

Panel Point		L0	L2	L4	L6	L8	L10	L12	L14	L16	L18	L20	L22	L24	L26	L28	L31
Dead Load	H	439	439	439	439	439	439	439	439	439	439	439	439	439	439	439	439
	M	0	0	+17	+66	+132	+220	+334	+466	+286	+128	-9	-123	-211	-281	-325	-347
Maximum Pos. Moment	H	654	426	425	425	425	425	426	539	469	402	506	533	553	573	497	621
	M	0	+900	+1480	+1770	+1730	+1370	+830	+930	+680	+940	+1270	+1470	+1560	+1540	+1470	+1430
Maximum Neg. Moment	H	654	632	631	629	627	625	619	526	579	569	554	537	519	499	479	439
	M	0	-780	-1360	-1590	-1610	-1410	-1040	-1140	-630	-620	-730	-760	-740	-670	-560	-470
Maximum Pos. Shear		+35	+24	+19	+19	+22	+25	+32	+59	+49	+42	+38	+34	+32	+30	+30	+33
Maximum Neg. Shear		-47	-35	-28	-28	-37	-47	-65	-27	-20	-17	-18	-21	-26	-30	-32	-33

Note: Stresses are in kips
Bending moments are in ft.-kips

SELF-ANCHORED SUSPENSION BRIDGE
SPANS 140'-340'-140' - LOADING H-15
DESIGNED BY D.J. Peery
PITTSBURGH, PA. 1938

FIG 16



Note: All vertical members 10WF21
Stresses shown are in kips
Tension (+); Compression (-).

SELF-ANCHORED SUSPENSION BRIDGE
SPANS 140'-340'-140' - LOADING H-15
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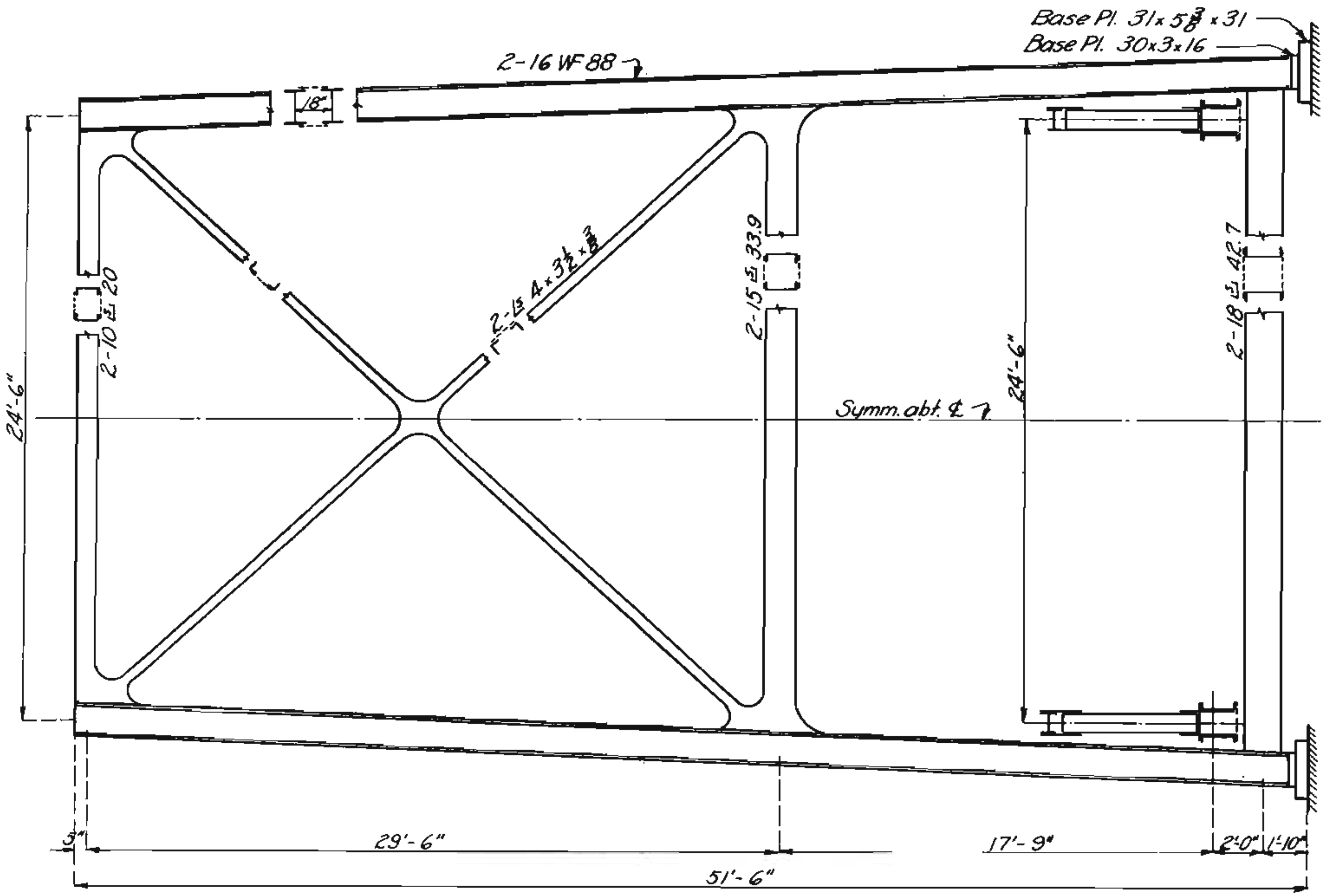
FIG. 17



TOWER DETAILS

SELF-ANCHORED
SUSPENSION BRIDGE

SPANS 140'-340'-140'

LOADING H-15

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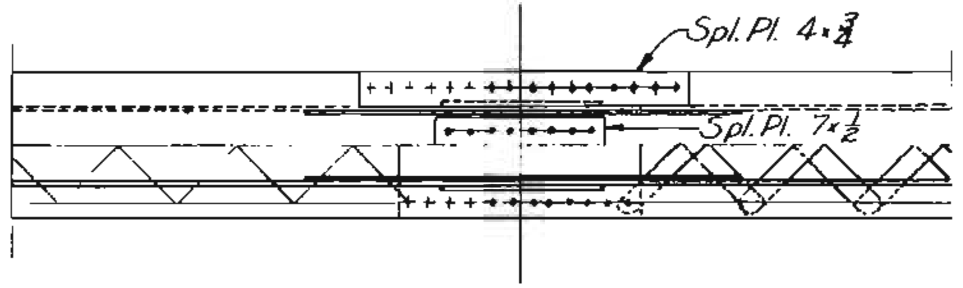
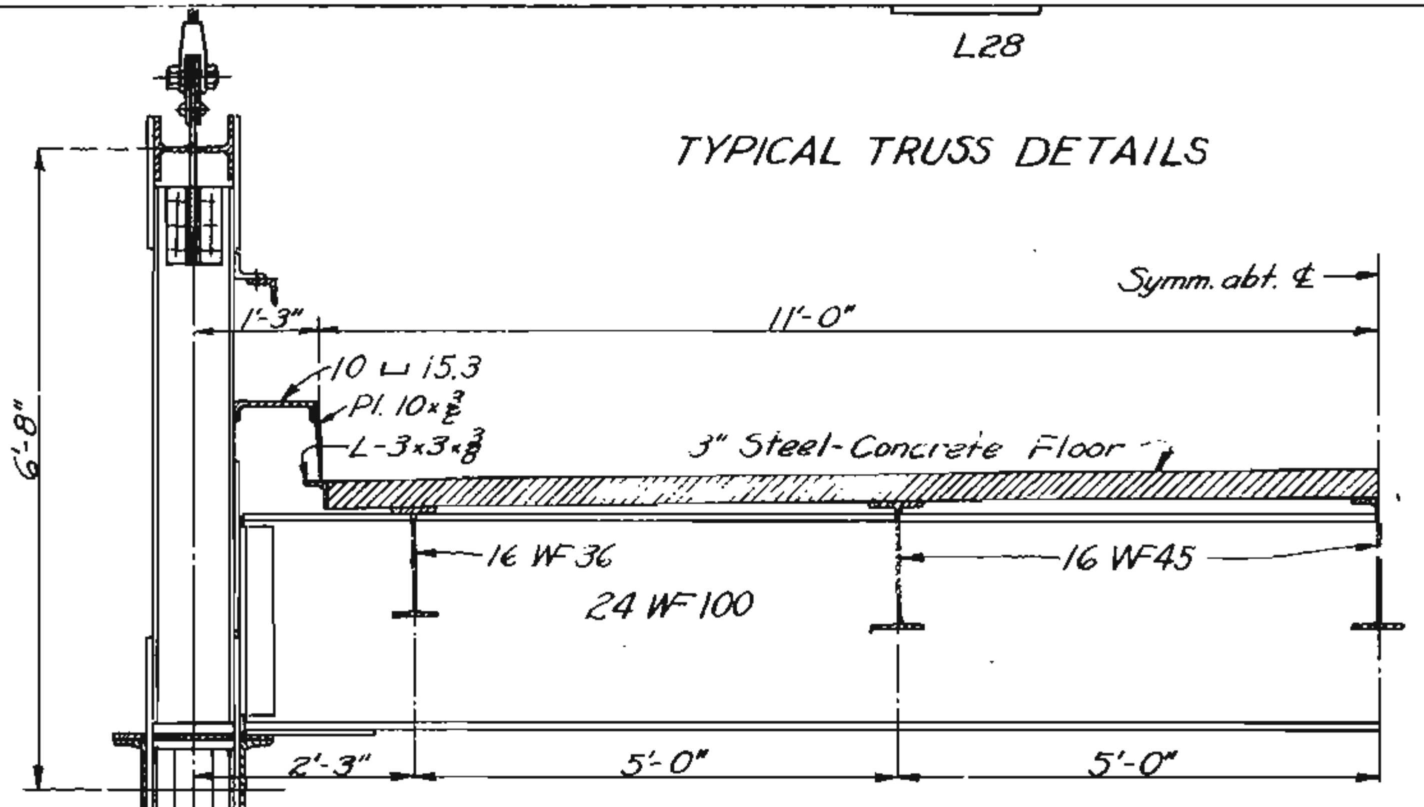
PITTSBURGH, PA. 1938

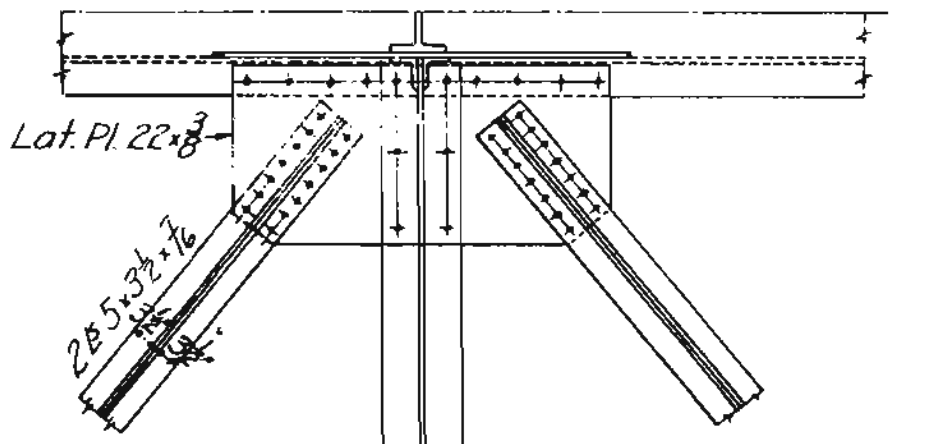
FIG. 18

TYPICAL TRUSS DETAILS





SECTION THROUGH ROADWAY



SELF-ANCHORED SUSPENSION BRIDGE

SPANS 140'-340'-140' LOADING H-15

DESIGNED BY D.J. PEERY

PITTSBURGH, PA. 1938

The cost of a cantilever bridge for the same span lengths will be computed. For a cantilever structure, silicon steel will be more economical than carbon steel. It is possible that some saving could also have been made in the cost of the suspension bridge by the use of silicon steel.

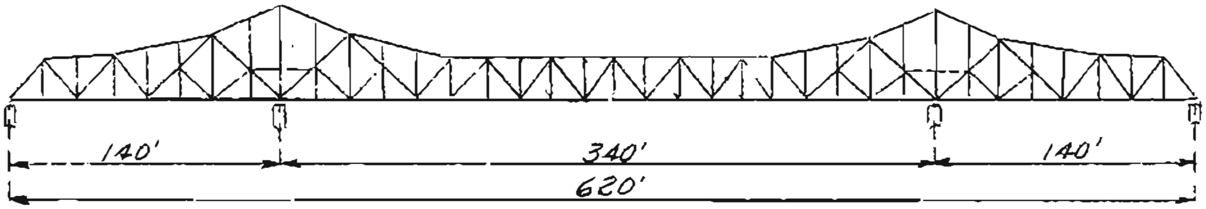


Fig. 19.

The quantities and costs for the cantilever shown in Fig. 19 will be as follows:

Silicon Steel	712,000 lb.	@ $0.075 =	$53,400
Carbon Steel	475,000 lb.	@ $0.06 =	28,500
9" Concrete Floor	13,640 sq.ft.	@ $0.80=	10,920
Curbs	620 ft.	@ $3.60 =	2,230
Total Superstructure Cost			$95,050

The cost of a simple span layout with the same span lengths will be estimated. The side spans will be

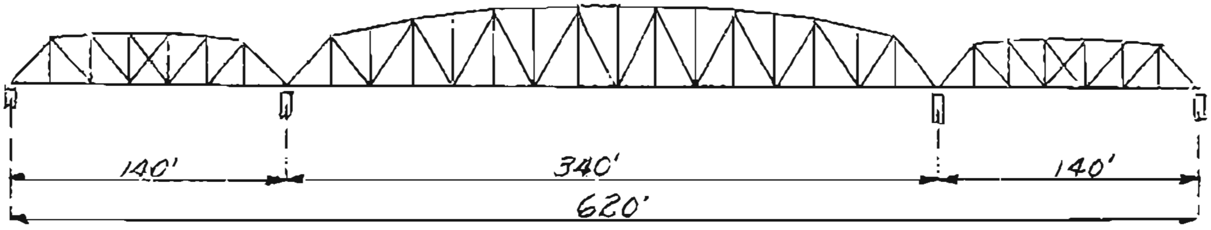


Fig. 20.

shorter than the economic limit for silicon steel and the cost of the main span will be approximately the same for carbon steel as for silicon steel. The estimate will therefore be made for carbon steel in the entire structure.

The quantities and costs for the bridge shown in Fig. 20 will be as follows:

Structural Steel--	1,536,000 lb. @ $0.06 =	$92,200
9" Concrete Floor		10,920
Curbs		2,230
Total Superstructure Cost		$105,350

The layout for three equal simple spans of the same total length as the above structure is shown in Fig.21.

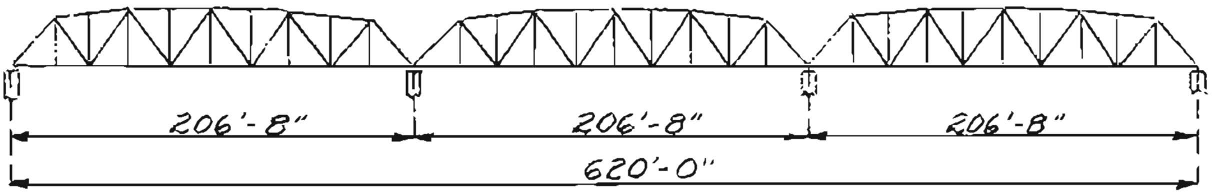


Fig. 21.

The quantities and costs are as follows:

Structural Steel --	1,366,000 lb. @ $0.06 =	$81,900
9" Concrete Floor		10,920
Curbs		2,230
Total Superstructure Cost		$95,050

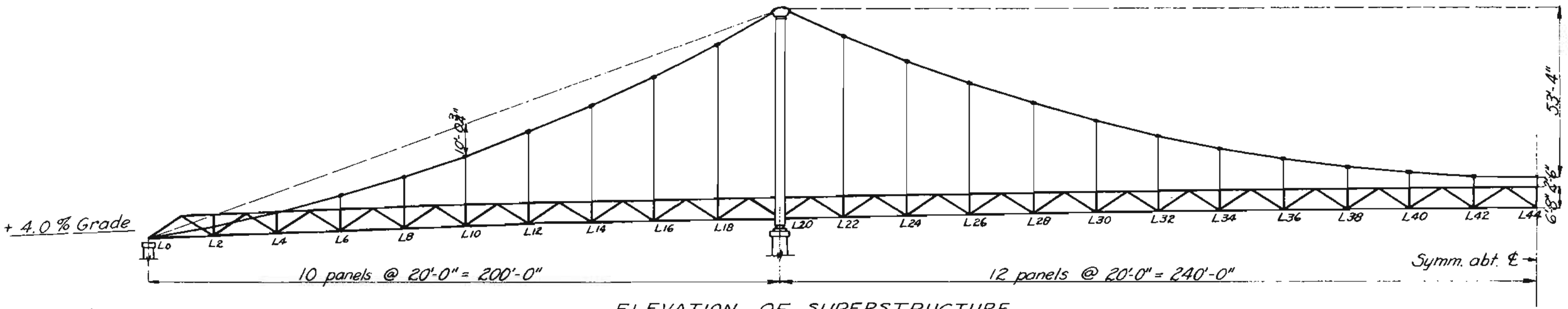
Bridges with 480-foot Main Span

The design of a self-anchored suspension bridge with a main span of 480 feet and side spans of 200 feet is shown in Figs. 22, 23, and 24. This structure is similar to the suspension bridge with a 340-foot main

FIG 22

Cable: - 12-$1\frac{5}{8}$" Galvanized
prestressed strands
Hangers: - 1-$1\frac{1}{8}$" Galvanized
prestressed strand

Maximum Cable Stress
D.L. 860
L.L. 310
Total 1170



ELEVATION OF SUPERSTRUCTURE

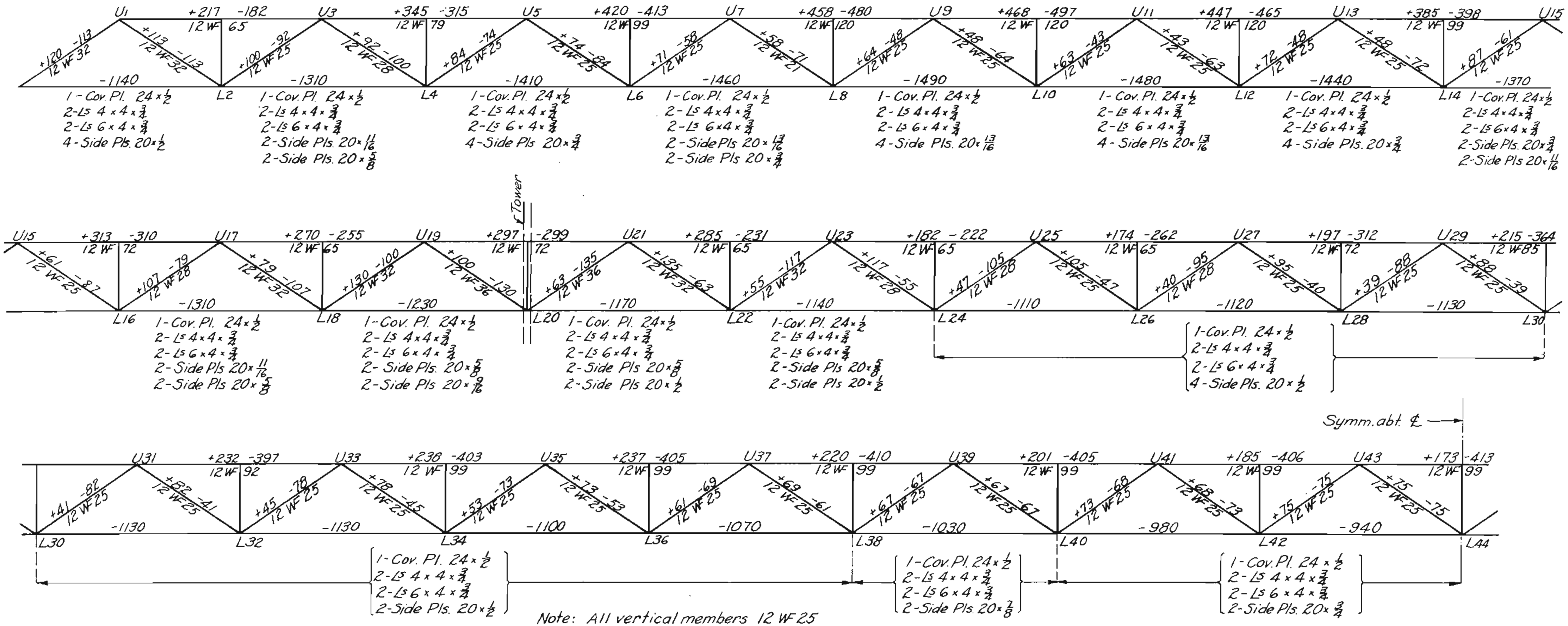
BENDING MOMENTS AND SHEARS IN STIFFENING TRUSS

Panel Point		L0	L2	L4	L6	L8	L10	L12	L14	L16	L18	L20	L22	L24	L26	L28	L30	L32	L34	L36	L38	L40	L42	L44
Dead Load	H	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760	760
	M	0	-8	+8	+50	+130	+230	+360	+510	+690	+900	+1140	+820	+530	+270	+30	-170	-360	-510	-630	-730	-800	-840	-850
Maximum Pos. Moment	H	1030	740	740	740	740	740	740	740	740	740	900	820	810	820	850	870	900	920	940	950	980	1000	1030
	M	0	+1210	+2100	+2750	+3200	+3320	+3100	+2650	+2070	+1700	+1990	+1540	+1480	+1750	+2080	+2430	+2650	+2690	+2700	+2730	+2700	+2710	+2750
Maximum Neg. Moment	H	1030	1030	1030	1020	1020	1020	1020	1020	1020	1020	870	890	920	940	930	920	900	880	850	830	800	770	740
	M	0	-1450	-2300	-2800	-3050	-3120	-2980	-2570	-2090	-1800	-1890	-1900	-1210	-1160	-1310	-1430	-1550	-1590	-1580	-1470	-1340	-1230	-1150
Maximum Pos. Shear		+63	+51	+41	+32	+27	+24	+27	+34	+44	+55	+ 75	+65	+58	+53	+49	+46	+43	+40	+38	+37	+38	+41	
Maximum Neg. Shear		-67	-55	-47	-39	-35	-35	-40	-48	-60	-72	- 35	-31	-26	-22	-22	-23	-25	-29	-34	-37	-40	-41	

Note: Stresses are in kips
Bending moments are in ft.-kips

SELF-ANCHORED SUSPENSION BRIDGE
SPANS 200'-480'-200' - LOADING H-15
DESIGNED BY D.J. PEERY
PITTSBURGH, PA. 1938

FIG. 23



Note: All vertical members 12 WF 25
Stresses shown are in kips
Tension (+) ; Compression (-).

SELF-ANCHORED SUSPENSION BRIDGE

SPANS 200'-480'-200' LOADING H-15

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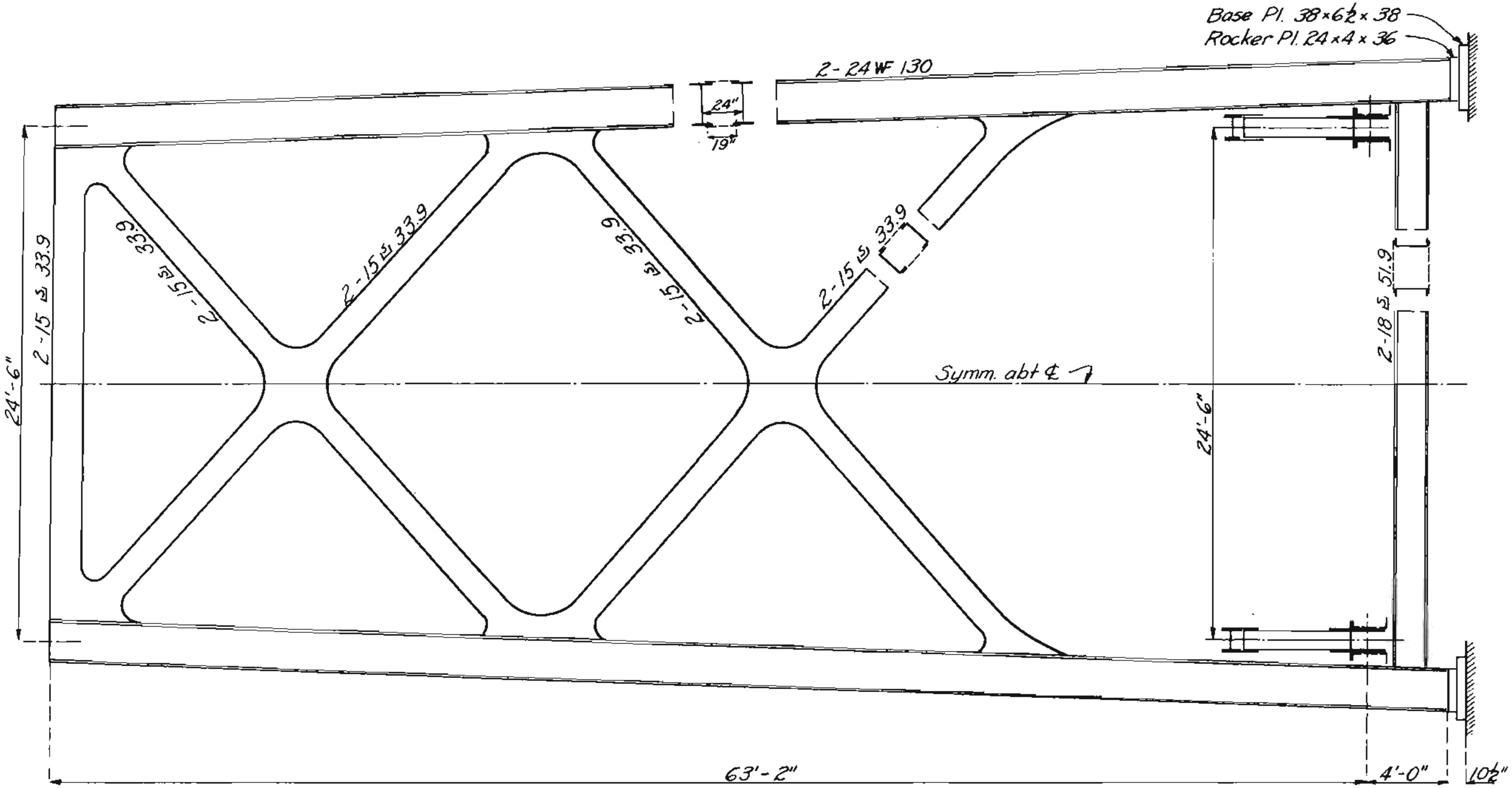
FIG. 24



TOWER DETAILS

SELF-ANCHORED
SUSPENSION BRIDGE
SPANS 200'-480'-200'
LOADING H-15
DESIGNED BY D.J. PEERY
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span. The truss depth for the 480-foot main span is also 6'-8". This is sufficiently deep for this span length. For the 340-foot span a shallower truss would have been desirable, but this would have made it necessary to shorten the panel lengths or use an uneconomical slope for the diagonals. The main cables for the 480-foot span are each composed of twelve 1-5/8 inch prestressed strands.

The superstructure quantities and costs for the 480-foot span suspension bridge are as follows:

Structural Steel			
Towers	123,860 lb.		
Trusses	849,280 lb.		
Laterals	68,000 lb.		
Floor System	303,000 lb.		
Curb and Rail	62,500 lb.		
	1,406,640 lb.	@ $0.06=	$84,400
Cast Steel--Saddles	8,990 lb.	@ $0.18=	1,600
Pins and Nuts	5,500 lb.	@ $0.10=	550
1-5/8 in. Prestressed Strands	121,200 lb.	@ $0.20=	24,240
1-1/8 in. Prestressed Strands	4,470 lb.	@ $0.20=	890
Open Sockets (attached)	136	@ $8.00=	1,090
Cable Clamps	74	@ $18.00=	1,330
Floor--3" Steel-Concrete	19,400 sq.ft.	@ $1.25=	24,250
Total Superstructure Cost			$138,350

A cantilever bridge with the same span lengths will be more economical if built of silicon steel than if

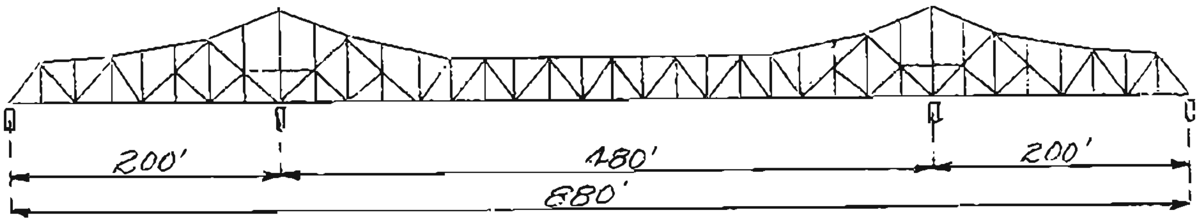

Fig. 25.

built of carbon steel. The quantities and costs of a cantilever bridge layout as shown in Fig. 25 are as follows:

Silicon Steel --	1,430,000 lb.	@ $0.075	=	$107,200
Carbon Steel --	877,000 lb.	@ $0.06	=	52,600
9" Concrete Floor-	19,400 sq.ft.	@ $0.80	=	15,520
Curbs	880 ft.	@ $3.60	=	3,170
Total Superstructure Cost				$178,490

The simple span layout with the spans the same lengths as in the suspension bridge, is shown in Fig. 26.

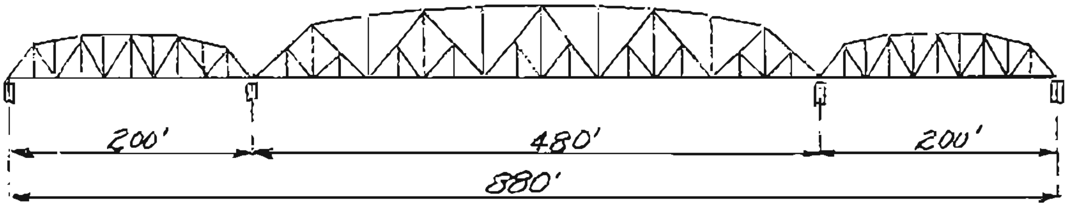

Fig. 26.

The quantities and costs will be as follows:

Silicon Steel --	1,470,000 lb.	@ $0.075	=	$110,000
Carbon Steel	900,000 lb.	@ $0.06	=	54,000
9" Concrete Floor				15,520
Curbs				3,170
Total Superstructure Cost				$182,690

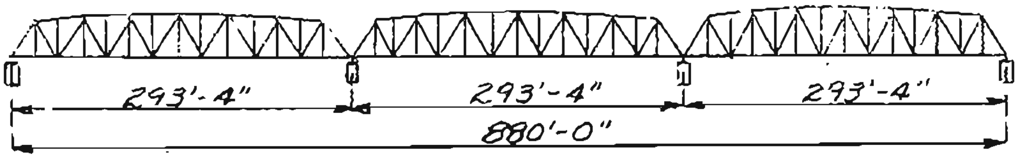

Fig. 27.

The quantities and costs of the simple span layout shown in Fig. 27, which consists of three equal spans of the same total length as the suspension bridge, will be as follows:

Silicon Steel--1,230,000 lb.	@ $0.075 =	$92,200
Carbon Steel -- 753,000 lb.	@ $0.06 =	45,200
9" Concrete Floor		15,520
Curbs		3,170
Total Superstructure Cost		$156,090

Summary and Conclusions

The costs of the structures which have been estimated are tabulated in Table II. The costs are

Table II

Type	Spans (feet)	Superstr. Cost	Difference in Cost of Trusses and Suspension Bridges Diff.	%
Self-anchored Suspension	100-240-100	$47,030	--	--
Simple Spans	100-240-100	$65,530	$18,500	28.3%
Simple Spans	3 @ 146'-8"	$61,330	$14,300	23.3%
Self-anchored Suspension	140-340-140	$76,600	--	--
Cantilever	140-340-140	$95,050	$18,450	19.4%
Simple Spans	140-340-140	$105,350	$28,750	27.3%
Simple Spans	3 @ 206'-8"	$95,050	$18,450	19.4%
Self-anchored Suspension	200-480-200	$138,350	--	--
Cantilever	200-480-200	$178,490	$40,140	22.4%
Simple Spans	200-480-200	$182,690	$44,340	24.2%
Simple Spans	3 @ 293'-4"	$156,090	$17,740	11.2%

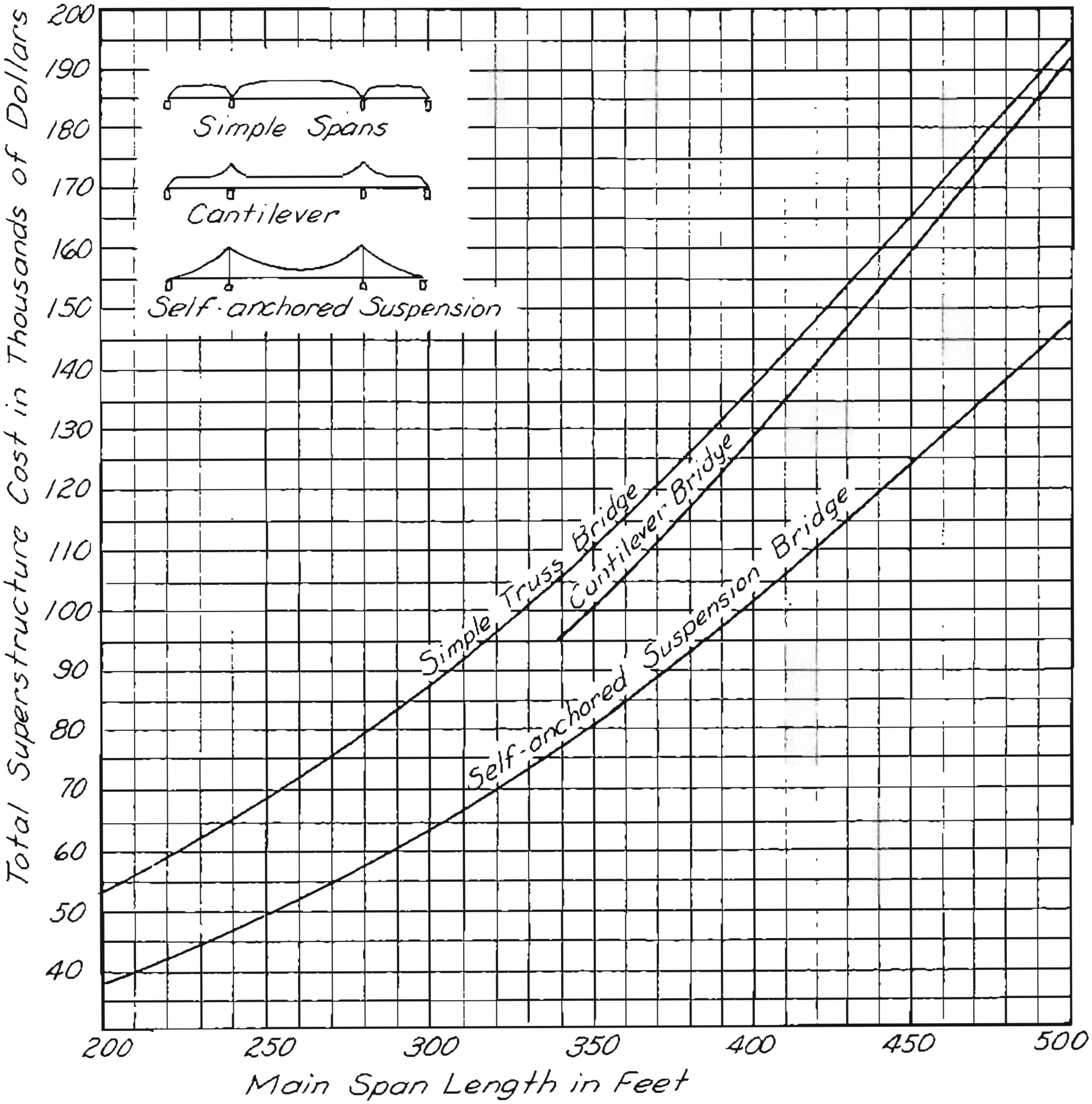

FIG. 28. - SUPERSTRUCTURE COSTS OF HIGHWAY BRIDGES

plotted for the various types and span lengths in Fig. 28. From the cost curves it is possible to determine the superstructure costs of bridges of other span lengths. For unit prices other than those used in this investigation, the curves may be adjusted by multiplying by the ratio of the unit prices.

The above investigation shows self-anchored suspension bridges to have an economy of from 19.4% to 28.3% over cantilevers and simple trusses of the same span lengths. However, the validity of the cost estimates will depend somewhat on the location for which the bridge is designed. For locations where it is difficult to use falsework or a temporary anchorage for erection, a cantilever bridge might be more easily erected and hence the unit prices would be lower for the cantilever.

The quantities for the suspension bridges are believed to be correct within an accuracy of 3%. The greater accuracy obtained by completely detailing the structures would not be justified, as the variation in practice of different designers would introduce differences as great as this error. The economic proportions of self-anchored suspension bridges have not been thoroughly studied. It is possible that by varying the ratios of cable sag to span length, side span to main span, truss depth to span, or panel length to width, an additional economy may be obtained from self-anchored suspension bridges.

The recent use of self-anchored suspension bridges carrying light live loads shows economy which has not long been appreciated. The aesthetic advantages of suspension bridges have always been recognized, and have been responsible for the construction of several of the existing self-anchored bridges. The economic and aesthetic advantages of self-anchored suspension bridges should make this type of structure very popular in the future.

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