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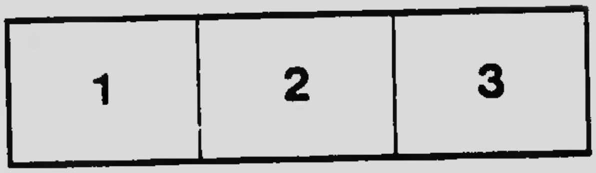
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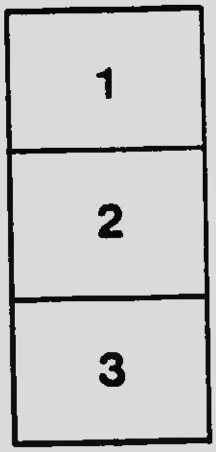
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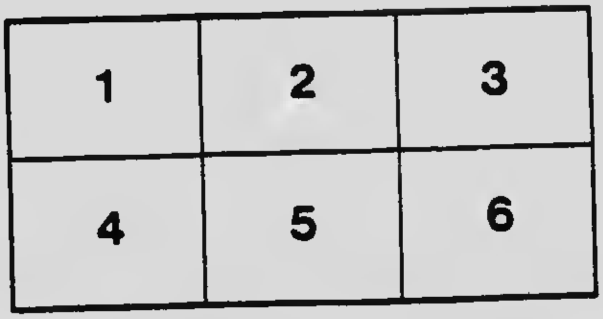
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THE QUEBEC BRIDGE

CARRYING THE
TRANSCONTINENTAL LINE OF THE CANADIAN GOVERNMENT RAILWAYS
OVER
THE ST. LAWRENCE RIVER.
NEAR
THE CITY OF QUEBEC, CANADA.

FOREWORD

THESE views and the text are published with the object of illustrating the construction of the superstructure of the Quebec Bridge. Papers giving a more technical description are being presented to the Engineering Institute of Canada by the constructors of the Bridge and those members of the Engineering Profession who wish to follow the subject further are referred to these papers.

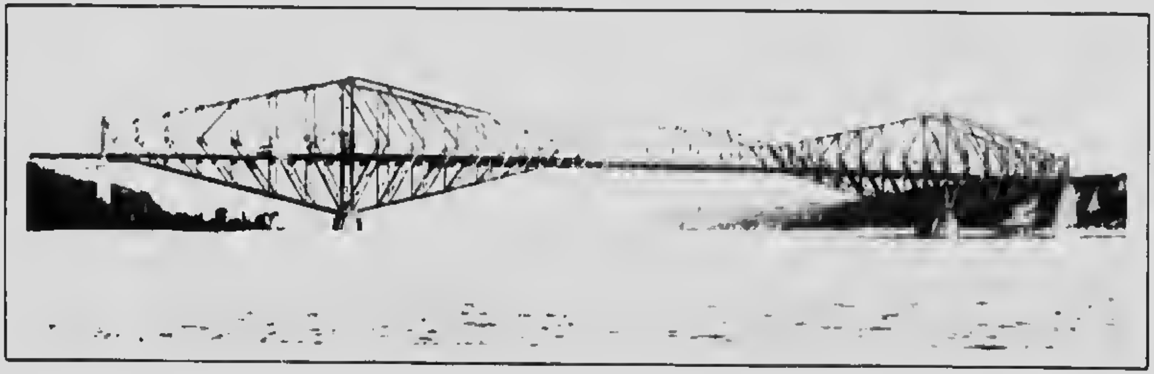
This work has been unavoidably delayed and in the meantime publications have appeared which in large measure take from the St. Lawrence Bridge Company the credit to which it is entitled for the design and the construction of the Bridge.

Before the tenders for the Bridge were opened, the adopted design was prepared in detail by the staff of the St. Lawrence Bridge Company in response to an invitation for competitive designs and was recommended for acceptance by an Advisory Board of Engineers appointed by the Government. At the time of the acceptance the span was increased, necessitating a modification in the number of panels and in the sectional area of the members, but the character of the design was not affected by these changes.

On the 4th of April, 1911, the contract, the general and detail plans and the specifications were signed. Under the terms of this contract the design was fully determined and the Contractors took the entire responsibility for the construction of the Bridge. When the contract was signed the Advisory Engineers and Mr. MacDonald retired, leaving Mr. Ralph Modjeski the only member remaining of the original Board. It was then necessary to re-organize the Board of three engineers provided for by Order-in-Council to carry on the work of checking drawings, inspecting material and workmanship and, generally, to see that the Contractor complied with the terms of the contract and the specification.

A month after the contract was signed, on the 6th of May, 1911, Mr. C. N. Monsarrat was appointed Chairman and Chief Engineer of this Board, and shortly after, Mr. C. C. Schneider was appointed as the third member.

The design of the bridge was settled before Mr. Monsarrat was appointed, the working drawings for the bridge, for the manufacturing plant and for the erection were entirely originated and prepared by the staff of the St. Lawrence Bridge Company, as well as the calculations and the general design. The staff of the St. Lawrence Bridge Company should be given the full credit for the design and for the successful completion of the superstructure of the Bridge.



THE

QUEBEC BRIDGE

CARRYING THE

TRANSCONTINENTAL LINE OF THE CANADIAN GOVERNMENT RAILWAYS

OVER

THE ST. LAWRENCE RIVER

NEAR

THE CITY OF QUEBEC, CANADA

The Bridge was Built for the Department of Railways and Canals

DOMINION OF CANADA

1910 - 1918

Rt. Hon. Sir Wilfrid Laurier, P.C., G.C.M.G.	*Prime Minister*	1906-1911
Rt. Hon. Sir Robert L. Borden, P.C., G.C.M.G.	*Prime Minister*	1911-1918
Hon. Geo. P. Graham	*Minister of Railways and Canals*	1906-1911
Hon. Francis Cochrane	*Minister of Railways and Canals*	1912-1917
Hon. John D. Reid	*Minister of Railways and Canals*	1918

THE SUPERSTRUCTURE WAS DESIGNED, MANUFACTURED AND ERECTED BY THE

ST. LAWRENCE BRIDGE COMPANY, LIMITED

A COMPANY SPECIALLY INCORPORATED IN THE JOINT INTEREST OF THE

DOMINION BRIDGE COMPANY, LIMITED, of Lachine, P.Q. and
THE CANADIAN BRIDGE CO., LIMITED, of Walkerville, Ont.

WITH A VIEW TO COMBINING THE ORGANIZATIONS & RESOURCES OF THE TWO COMPANIES FOR THE EXECUTION OF THE WORK

THE SUBSTRUCTURE FOUNDATIONS AND MASONRY WAS CONSTRUCTED BY

M. P. & J. T. Davis, *Contractors* — S. H. Woodard, *M. Am. Soc. C.E.*, *Engineer*

The Engineers representing the Government were

The Advisory Board of Engineers appointed to recommend a design and specification to the Minister upon which the contract would be awarded.

Ralph Modjeski, *M. Am. Soc. C.E.*	Chicago, Ill.
Chas. MacDonald, *M. Can. Soc. C.E.*	Gananoque, Ont.
M. J. Butler, C.M.G. *M. Can. Soc. C.E.*	Montreal, P.Q.
H. W. Hodge, *M. Am. Soc. C.E.*	New York, N.Y.
H. E. Vautelet, *M. Can. Soc. C.E.*, *Chairman*	Montreal, P.Q.

The Supervising Board of Engineers during the construction of the work

Ralph Modjeski, *M. Am. Soc. C.E.*	Chicago, Ill.
C. C. Schneider, *M. Am. Soc. C.E.*	Philadelphia, Pa.
H. P. Borden, *M. Can. Soc. C.E.*	Montreal, P.Q.
C. N. Monsarrat, *M. Can. Soc. C.E.*, *Chairman*	Montreal, P.Q.

ORGANIZATION OF THE

ST. LAWRENCE BRIDGE COMPANY, LIMITED

INCORPORATED 1910

DIRECTORS

Chas. Cassils, *Vice-Pres.*; B. S. Colburn; G. H. Duggan; Phelps Johnson, *President*; F. C. McMath; Willard Pope; F. L. Wanklyn; J. F. Weber

OFFICERS

Phelps Johnson	*President*	S. P. Mitchell	*Consulting Engineer on Erection*
G. H. Duggan	*Chief Engineer*	W. P. Ladd	*Works Manager*
G. F. Porter	*Engineer of Construction*	W. B. Fortune	*Superintendent of Erection*
F. C. McMath	*Consulting Engineer*	J. F. Weber	*Secretary-Treasurer*

DOMINION BRIDGE COMPANY, LIMITED

INCORPORATED 1883 ORGANIZATION IN 1910

DIRECTORS

R. B. Angus; Chas. Cassils; G. H. Duggan, *2nd Vice-Pres.*; C. B. Gordon; Phelps Johnson, *1st Vice-Pres.*; J. M. McIntyre; Jas. Ross, *President*; F. L. Wanklyn, *3rd Vice-President*

OFFICERS

Phelps Johnson, *Manager* G. H. Duggan, *Chief Engineer* R. M. D *Secretary-Treasurer*

THE CANADIAN BRIDGE COMPANY, LIMITED

INCORPORATED 1900 ORGANIZATION IN 1910

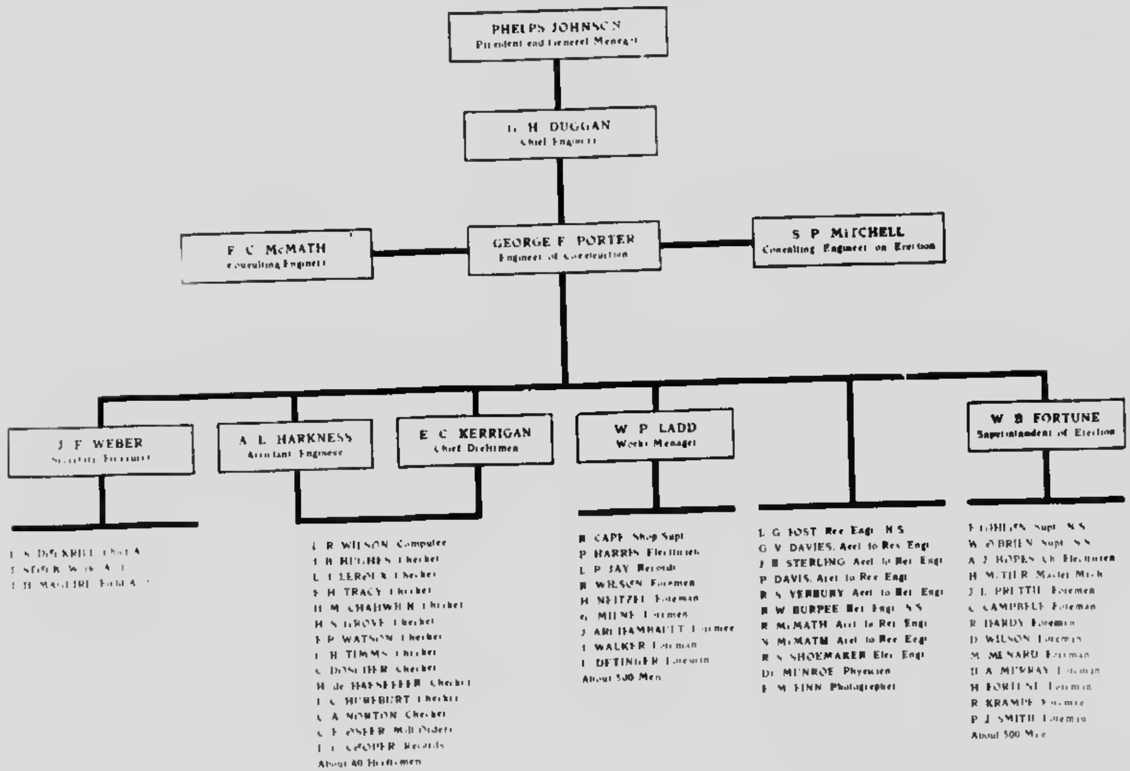
DIRECTORS

Burnham S. Colburn; A. L. Colby; Joshua Hatfield; Francis C. McMath; Willard Pope; Frank B. Thompson; August Zeising

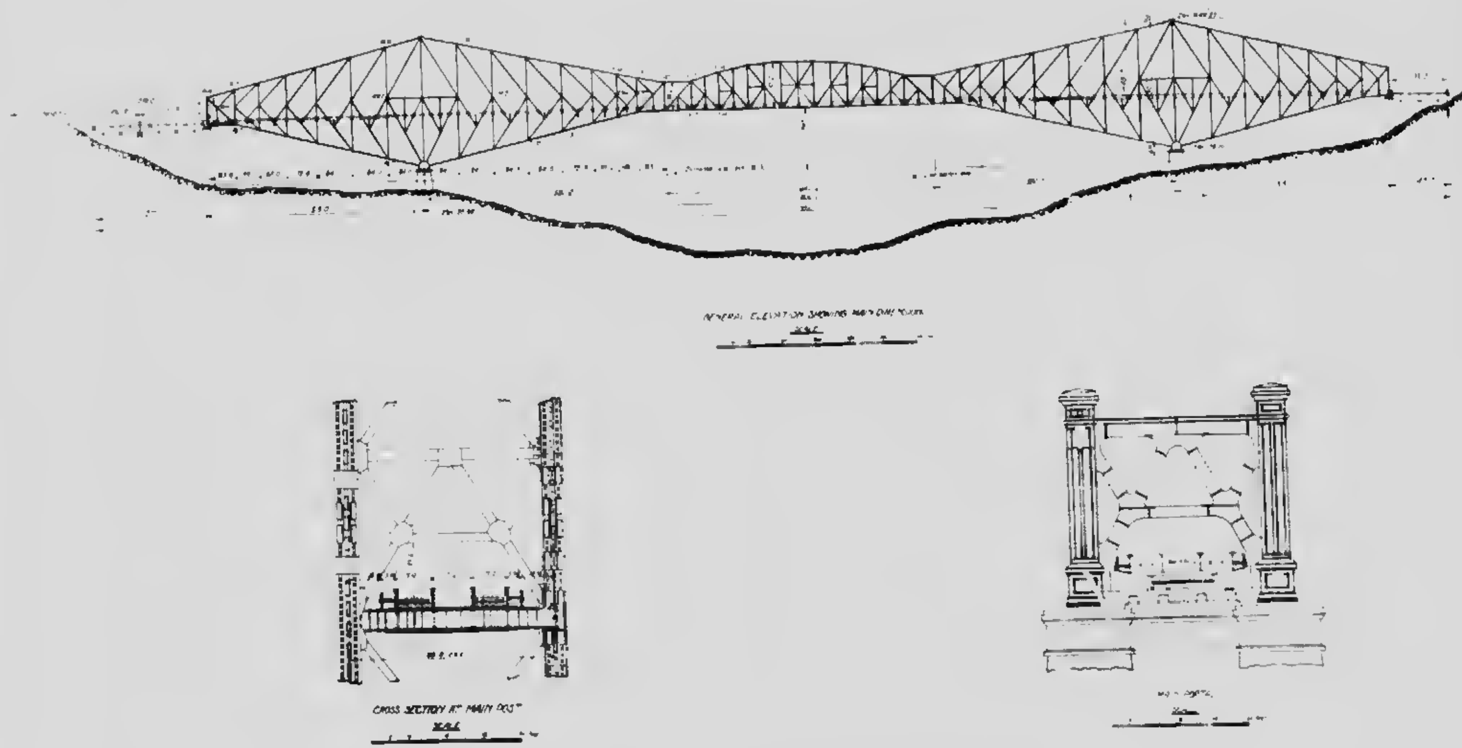
OFFICERS

Francis C. McMath	*President*	Burnham S. Colburn	*Treasurer*
Willard Pope	*Vice-President*	Charles T. Miller	*Secretary*

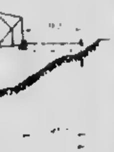
ORGANIZATION OF ST. LAWRENCE BRIDGE CO., LIMITED



1 Chart of site showing also the positions of the storage yards camp, and Sillery Cove, as well as the railways and highways in the vicinity



2 Diagram showing principal dimensions of giant cantilever bridges. Special elevation of the design under construction by the Phoenix Bridge Company.



THE Bridge is notable not only as having the longest and by far the heaviest single span yet built, but for the use, the first time in an important structure, of what has become known as the "K" system of web bracing, which is believed to have important advantages over the Pratt or the Warren web system generally used in cantilevers.

It is statically determinate as regards stresses.

The deflection is uniform, without local irregularities, and secondary strains are negligible.

Each web member carries only about one-half of the total shear.

Diagonal web members have economical inclination.

Main panels are short, resulting in more numerous and smaller increments of chord stress than in trusses with long panels.

All web members of the trusses transmit live as well as dead load stresses.

The support for an intermediate floor beam in each main panel is readily provided without injurious bending of any main member.

The truss members at their connections meet at favorable angles and simple and satisfactory connecting details are easily arranged.

The assembly in erection is the adding of simple unsubdivided triangles one to another, each self-supporting as completed and requiring but a minimum of temporary supporting members.

The use of the "K" web system was conceived and proposed by PHELPS JOHNSON. The design was developed by G. HERRICK DUGGAN. The detailing and erection was under the direction of GEORGE F. PORTER.

Before the final decision to adopt the "K" system of bracing was reached, practically all other web systems were studied. The decision to use the "K" bracing was largely influenced by considerations connected with the erection of the structure and, particularly by the conclusion that there would be no necessity for leaving any compression joints partly open and unrivetted, until the deformation of the truss, due to the addition of dead load as the erection progressed, was sufficient to close the joints.

This conclusion was found to be fully warranted and in erection the abutting faced ends of all compression joints were easily brought to a full bearing and rivetted before succeeding material was placed.

The engineers of the Company had long been convinced that the initial cause of failure of the Phoenix Company's Bridge was the high intensity of pressure and consequent distortion and displacement of material at the bearing edges of the lower chord sections of the anchor arm. These chords had been assembled with partly open joints, which were expected to gradually close as the cantilever arm and the suspended span were built out, and the consequent increased stresses and changes in the lengths of the truss members brought the chord sections to full bearing. Before the closing of the joints was complete the chords must have been subject to practically the full stress intended to be borne by their full section, resulting in a very great intensity of pressure upon the limited areas actually in contact.

CAPACITY

The Bridge was designed to carry two railway tracks spaced 32 feet 6 inches centre to centre and on the outside of each of these tracks was provided a 5-foot concrete sidewalk.

RAILWAY LIVE LOAD:

2 Coopers' Class E60 locomotives, followed by 5,000 lbs. per lineal foot on each track.

SIDEWALK LIVE LOAD:

500 lbs. per lineal foot for each walk.
500 lbs. per lineal foot of snow on bridge.

WIND LOAD:

30 lbs. per square foot of the exposed surface of two trusses and $1\frac{1}{2}$ times the elevation of the floor; plus a moving load of 300 lbs. per lineal foot applied 9 feet above the rail.

IMPACT:

Trusses, 20 per cent of Ry. Load.
Floor Beams, 75 per cent of Ry. Load.
Stringers, 100 per cent of Ry. Load.

UNIT STRESSES:

Tension:	Lbs. per sq. in.
Eyebars	20,000
Rivetted Members . . .	18,000
Including Secondary Stresses .	24,000
Compression:	
Short Members with l/r 50 and under	14,000
Long Members with l/r over 50	17,500-70 l/r
Including Secondary Stresses	18,000

The above unit stresses are for carbon steel. For nickel steel increase by 40 per cent.

Quality of Steel:	Carbon Steel lbs. per sq. in.	Nickel Steel lbs. per sq. in.
Ultimate Strength .	62,000-70,000	85,000-100,000
Minimum Yield Point .	35,000	50,000
Elongation in 8 In. .	1,[illegible],000 / Ultimate	1,600,000 / Ultimate
Minimum reduction of area	44%	40%

Each track is carried on through plate girder spans with wooden ties resting on 24" I-Beam stringers spaced 7 feet centres. The upper flanges of the girders are reinforced with heavy 15-inch channels for protection in case of derailment.

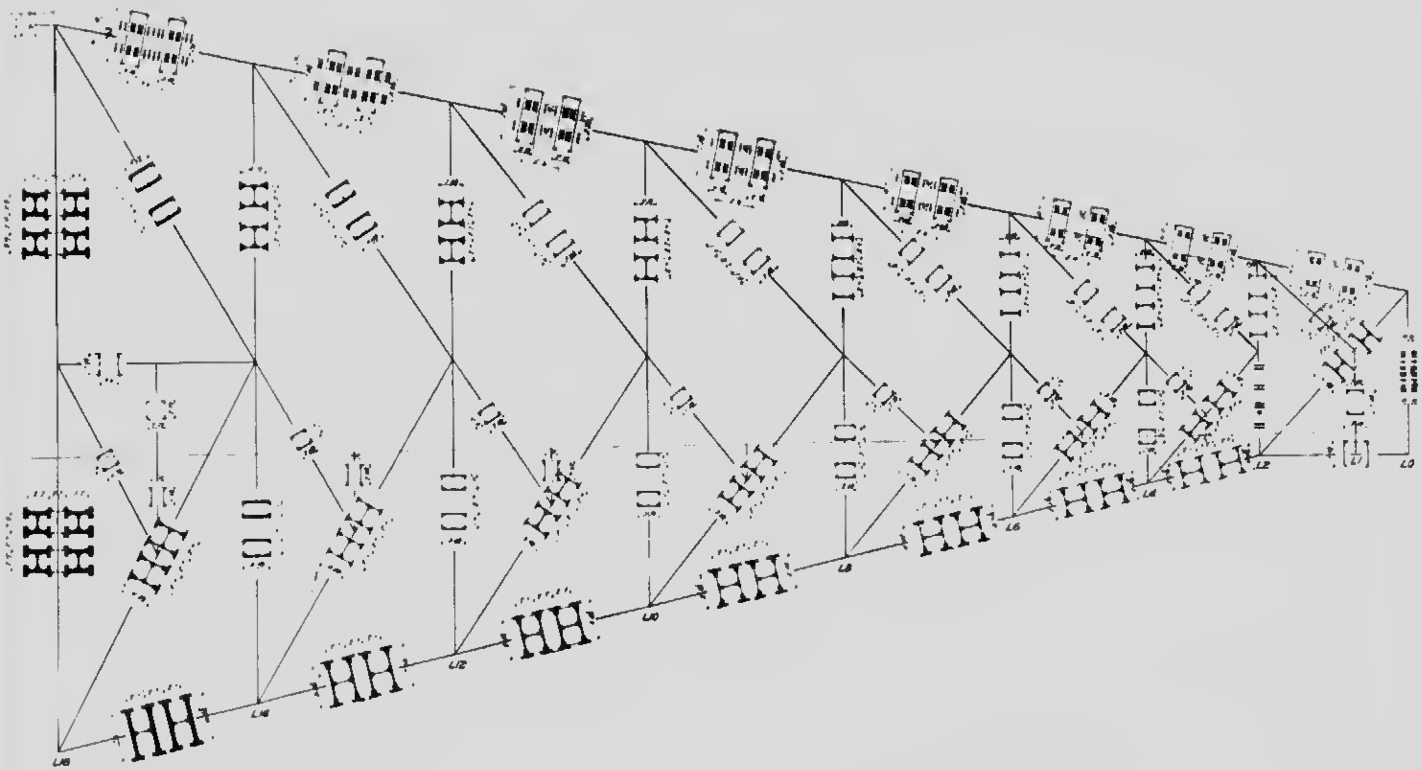
The floor beams, with the exception of those of the suspended span and at the L^1 and L^2 panel points of the cantilever and anchor arms, are hung on pins on the centre line of the trusses, the pin holes in the floor beams being bushed to give large bearing surfaces and to prevent cutting friction, this construction being adopted for the purpose of equally loading the truss members and to prevent the deflection of the long floor beams bending the members. See Plates 18 and 26.

The main truss members of the cantilever structure are made of four ribs consisting of symmetrical I sections for compression members, and channel sections for tension members, built up of plates and angles. The compression ribs are connected in pairs by longitudinal diaphragms on the centre lines and lattice and tie plates connecting the flanges thus forming two H sections, which were again connected in the field by tie plates on centre lines and flanges.

The tension ribs were assembled in pairs with flanges turned in and connected by lattice and tie plates on the flanges only.

Each member was, however, completely assembled in the shop, for the purpose of finishing the ends, boring pin holes and drilling splicing material. Most of the pins connecting the web system were in two lengths. This construction practically divided each main truss into two complete trusses placed side by side and field connected together which facilitated the transportation and erection of the large members.

All the webs were parallel through the trusses, but the lower chords were tapered in elevation from a depth



3—Cross sections of important members of the cantilever arms
NOTE: The cross sections of the members of the anchor arms are similar

of 84 inches at the shoe to a depth of 45 inches at their outer ends. This added appreciably to the difficulty of manufacture but permitted a very satisfactory arrangement of material as the increase in section required towards the shoes was to some extent provided for by the increased depth and the thickness of the material was kept within desirable limits. All butt joints in compression chords and diagonals were fully spliced by material and rivets, no reliance being placed on the bearing of faced ends, although these were found in all cases to be in perfect contact.

The upper chord panels were too long for single length eyebars which were therefore made in two lengths connected by pins in the centre of the panels. They were packed in two tiers to reduce the length of pins and to ensure an equal distribution of stress throughout all the bars. To prevent deflection of the bars where they were joined at the centre, the connecting pins were carried by trusses spanning the length of a panel. The trusses with their lateral bracing formed a box frame in which the bars were packed before erection: this arrangement greatly simplified the erection and held the eyebars in place until the end pins could be driven.

The general make-up of the members is shown on Plate 3 and the form of the details is indicated by the photographs.

The suspended span, while 640 feet long and ranking among exceptionally long span bridges, did not require such heavy sections, and it was found more economical to make the chords and end posts of three webs 45 inches deep, connected on the top by cover plates 64 inches wide, also connected by diaphragms and the usual tie plates and lattice bars on the bottom. The top chords were shipped and erected in half panel lengths but spliced with material and rivets to take up the full stress after being erected. The connections at the main panel points were made on pins which also served for the upper connection of the main web members. The end tension diagonals were eyebars connected on pins, but all other web members consisted of two built-up channels all having their webs in the same plane parallel to the centre line of the trusses in order that they could be connected at the ends by rivetting to connection plates through which the chord pins passed. The lower chords were nickel steel eyebars throughout packed parallel in one tier. The floor beams were passed through and were connected to the inside channel of the vertical members as well as being connected to the outside channel, thus distributing the load on both sides of the verticals and due allowance was made for the bending stresses in the verticals caused by the deflection of the long floor beams. The bottom flanges of the floor beams were placed below the eyebar heads in order that the bottom lateral connection plate might be rivetted both to the floor beam and to the bottom of the vertical post.

Some of the larger and more important dimensions and weights are given below:

Shoes: The total vertical load on one shoe was estimated at 27,600 tons, and the bearing area on the masonry is 550 square feet.

Each shoe rests on a cast steel grillage made of four box sections 6 feet 7 inches by 4 feet deep by 20 feet 10 inches long, each weighing about 40 tons before machining.

The total weight of the ·illage at one corner is 146 tons; of the shoe 262 tons, and of the completed bearing, grillage, shoe sleeves and pins 507 tons.

The thrust of the lower chord is carried by 30 inch pins, each in two lengths, 5 feet 2 inches long, weighing 12,300 lbs. These pins are surrounded by sleeves in halves, 45 inches outside diameter, each 4 feet 10 inches long, weighing 13,750 lbs. The sleeves were adopted to reduce the bearing on the surface of the pin to about 7,000 lbs. per square inch, as it was desired to eliminate the bending stresses in the end lower chord that would occur during erection if the chord could not deflect without too great restraint at its junction with the shoe. The bearing of sleeves on pins was lubricated with paraffin, which special experiments had shown to give a very low coefficient of friction under this pressure.

TABLE SHOWING DIMENSIONS AND WEIGHTS OF SOME OF THE PRINCIPAL MEMBERS

Member	Mark	Area Sq. Ins.	One Panel One Truss: Dimens., Feet	One Panel One Truss: Lin. Ft.	Total Wt., Tons	Largest Piece Shipped: Dimens., Feet	Largest Piece Shipped: Lin. Ft.	Largest Piece Shipped: Wt. Tons	Largest Piece Erected: Dimens., Feet	Largest Piece Erected: Lin. Ft.	Largest Piece Erected: Wt. Tons
Comp. Diag.	$AU^{1}L^{2}$	563	4 x 8 8	95 5	150	4 x8 8	65 5	92	4 x8 8	65.5	92
Upper Chord	AU^{12-14}	1120	7.5x 8 5	86 6	224	7 5x2 6	86	10	7.5x2 8	86 0	56
Lower Chord	AL^{12-14}	1902	7 x10.1	86 5	416	7 x4 7	47 4	93	7 x4.7	47 4	93
Ten. Diag.	$AM^{13}U^{11}$	392	4 x 7 4	168 2	154	4 x2	103	53	4 x2	152	77
Comp. Diag.	$AM^{10}L^{11}$	623	4.5x10 1	184 3	280	4.5x1 5	88 7	72	4 5x4.5	88 7	72
Upper Chord	CU^{14-16}	1088	7.5x 8 5	85 7	218	7 5x2.8	85	11	7.5x2.8	85	55
Lower Chord	CL^{14-16}	1631	7.0x10 1	86.3	340	7 0x4 8	49 3	88	7 0x4.8	49.3	88
Com. Vert.	$CM^{11}U^{11}$	428	4 0x 9 6	127	130	4 x4	69 5	54	4 x4	69 5	54
Tens. Vert.	$CL^{14}M^{11}$	296	3 8x 7.4	146	90	3 8x1 8	134	44	3.8x1.8	134	44
Tens. Diag.	$CM^{13}U^{16}$	377	4 x 7 4	167	147	4 x2	102 3	50	4 x2	146.8	73
Comp. Diag.	$CM^{11}L^{16}$	619	4.5x10 1	185 8	283	4.5x4.5	90	73	4 5x4 5	90	73
Main Vert. Post	$AL^{11}U^{11}$	1903	9 x10	310	1207	3 x4 3	57 7	52	3 x4.3	57	52
						9 x4 3	25	48	9 x4.3	2	48
Main Floor Beam	$C.F.^{11}$		10 x1 8	90 3	62	10 x1 8	90 3	62	10 x1 8	9 ,	62

	Tons
Total steel in one Anchor Pier, including Anchor Bars	740
Total steel in one Anchor Arm, exclusive of Floor	14,900
Total steel in one Cantilever Arm " " "	10,430
Total steel in Track Girders	2 400
Total steel in Floor Beams	4,330
Total steel in Floor System complete, including Floor of Suspended Span	8,730
Total steel in Suspended Span, including Floor System	5,510
Total steel in Eyebars, including Anchor Eyebars	7,770
Total steel in Pins	1,700
Total steel in Structure, including Approaches	66,480

Nickel steel was used in the trusses of the suspended span and the cantilever arms except carbon steel in eyebars of upper chord and in the first compression diagonals and all the vertical compression memhers of the cantilever arms. All pins in the suspended span and about one-half those in the other parts of the structure are nickel steel.

The proportion of nickel steel in the structure is 27 per cent.

The rivets in heavy members were 1¼ inches diameter.

With the exception of locomotives and locomotive cranes, electric power was used throughout for erection purposes. Power houses were established on both sides of the River. On the North side were installed four electrically driven air compressors each of 530 cubic feet capacity and two motor generator sets of 250 K.W. to transform A.C. to D.C. current for operating the travellers. A similar transformer set was installed on the South side, but only three 530 cubic feet air compressors. Current was carried to the traveller by heavily insulated cables wound on drums and connected to a switchboard situated in a house supported on the inner track girders at the rear of the traveller and which moved with the traveller. The current was distributed to the motors from this switchboard. The upper hoists on the travellers were magnetically controlled from a working platform on the traveller.

SUMMARY OF PROGRESS DATES

Contract for Substructure awarded to M. P. & J. T. Davis	10 Jan. 1910
Contract for Superstructure let to St. Lawrence Bridge Co.	4 Apr. 1911
North Abutment completed	24 Oct. 1913
North Anchor Pier completed	14 Nov. 1913
North Main Pier completed	7 May 1914
North Approach Spans erected	11 Nov. 1913
North Anchor Arm erected, except Pier Post and First North Vertical Post	4 Dec. 1914
North Anchor Arm completed	8 June 1915
North Cantilever Arm erected	13 Nov. 1915
South Abutment completed	28 Nov. 1913
South Anchor Pier completed	28 Nov. 1913
South Approach Span erected	30 July 1914
South Main Pier completed	1 July 1914
South Anchor Arm erected	8 Nov. 1915
South Cantilever Arm erected	Sept. 1916
Suspended Span swung on supports at Sillery	20 July 1916
Suspended Span lost while being hoisted to position	11 Sept. 1916
Suspended Span (new) floated from Sillery to Site	17 Sept. 1917
Suspended Span connected in final position	21 Sept. 1917
First Train over the Bridge	17 Oct. 1917
Bridge open for regular Train Service	3 Dec. 1917

ERECTION PROGRESS

The following table shows the quantity of steel erected in each of the seasons of 1914, 1915, 1916, together with the average and best rates made:

	Tons Erected	Number Weeks To Erect	Average Tons Erected Per Week	Largest Number Tons Erected In one Week	Largest Number Tons Erected In one Day	Largest Number Tons Erected Date
SEASON 1914:						
North Anchor Arm	13,636	29	470	1039	411	Nov. 22, '14
SEASON 1915:						
South Anchor Arm	19,165	30	638	1823	670	Oct. 6, '15
North Anchor Arm	5,038	10	504	1140	340	May 13, '15
North Cantilever Arm	12,542	25	502	1025	387	June 10, '15
For Season	36,745	35	1049	..	..	..
SEASON 1916:						
South Cantilever Arm	12,642	26	486	1101	499	May 26, '16
Suspended Span	4,701	9	522	898	219	July 12, '16
For Season	17,343	26	667	..	.	

THE STORY

THE story of the Bridge is briefly told in the following editorial which appeared in the Engineering News - Record of New York under date of September 27th, 1917:

" In the engineering world the name Quebec has for " half a generation been associated with a great prospective " engineering triumph. Twice the hopes of success have " been dashed, but never in the heart of the true engineer " was there doubt that the enterprise would be brought to a " successful completion.

" Now the great hopes are realized. The greatest of " cantilevers stands closed across the St. Lawrence.

" Just ten years ago the south half of the first bridge " crumpled under its own weight, dragging a hundred men " to their death. The investigations and discussions that " followed destroyed that first project to its very roots. " But new leaders were found, new ideas developed. On " the wreckage of the old there arose the finest creation " of bridge-building that any generation has seen.

" What courage was required to attack the work anew " can be realized only when one recalls the extent of the " defects revealed in the old design. True, these dis- " coveries were warnings for the succeeding designers, " but impressed with the terribleness of the first ex- " perience their work could not but be haunted by visions " of what had happened in that dark August of 1907. The " new structure from the start gave evidence of the masterly " hands responsible for it. A new truss design was de- " veloped, the shopwork was of marvelous precision and " finish, the erection novel and courageous.

" Yet, despite the most careful study and precautions, " a second accident marred the record of the structure, " when last year the suspended span, while being hoisted, " fell into the river. One might think that in the face of " this second discouragement the engineers and contractors " responsible might have wavered in their determination " to proceed. But he who thought so failed to reckon with " the mettle of the men in charge. The wires had not " finished sending the story of the lost span to the world " when announcement was made that it would be rebuilt " and erected by the very method employed last year. " The promise of that announcement has now been ful- " filled. What changes there have been from the previous " erection plan are only in details. They are described " elsewhere in this issue.

" Before closing the final chapter in the design and " erection of this remarkable structure, it is proper to " record the debt that bridge-builders owe to the work at " Quebec. It ' as advanced greatly our knowledge of the " problems o. ırge compression members and of tension " bars. The effects of distortion in trusses were explored " farther than before and means devised for dealing with " such effects. Much knowledge has been added to our " store of experience on the assembly of heavy members, " while new standards were set as to degree of precision " and finish in shopwork. Then there is, beyond all this, " a great gain in our general grasp of the problem of very " large bridges as to practicability and cost.

" But these are the gains of the profession as a whole. " To the individual engineer the great value of the achieve- " ment lies in the inspiration emanating from the courage " of the men who have erected on the failure of 1907 and " the loss of 1916 this greatest of bridges and in so doing " not only have erected a monument to themselves and " their courage and ability, but have vindicated the pro- " fession before a doubting world."

PLATE 4 shows, to the same scale, the elevation of the Quebec Bridge and all the great cantilever bridges heretofore constructed. It will be seen that the Quebec Bridge with its span of 1,800 feet exceeds the span of the Forth Bridge by 100 feet, and that these two are in a class by themselves the next longest, the Blackwell's Island Bridge, being less than two-thirds the span of the Quebec Bridge.

Although the difference in span between the Quebec and Forth Bridges is not great, the Forth Bridge was far from being a precedent for the structure at Quebec. The weights of locomotives and all railway loads had increased so much since the earlier Bridge was built it was necessary to proportion the Quebec Bridge for about 2½ times the live load provided for in the Forth Bridge. Again, it was not practicable to adopt many of the unique and excellent features of the Forth Bridge or the method of its construction.

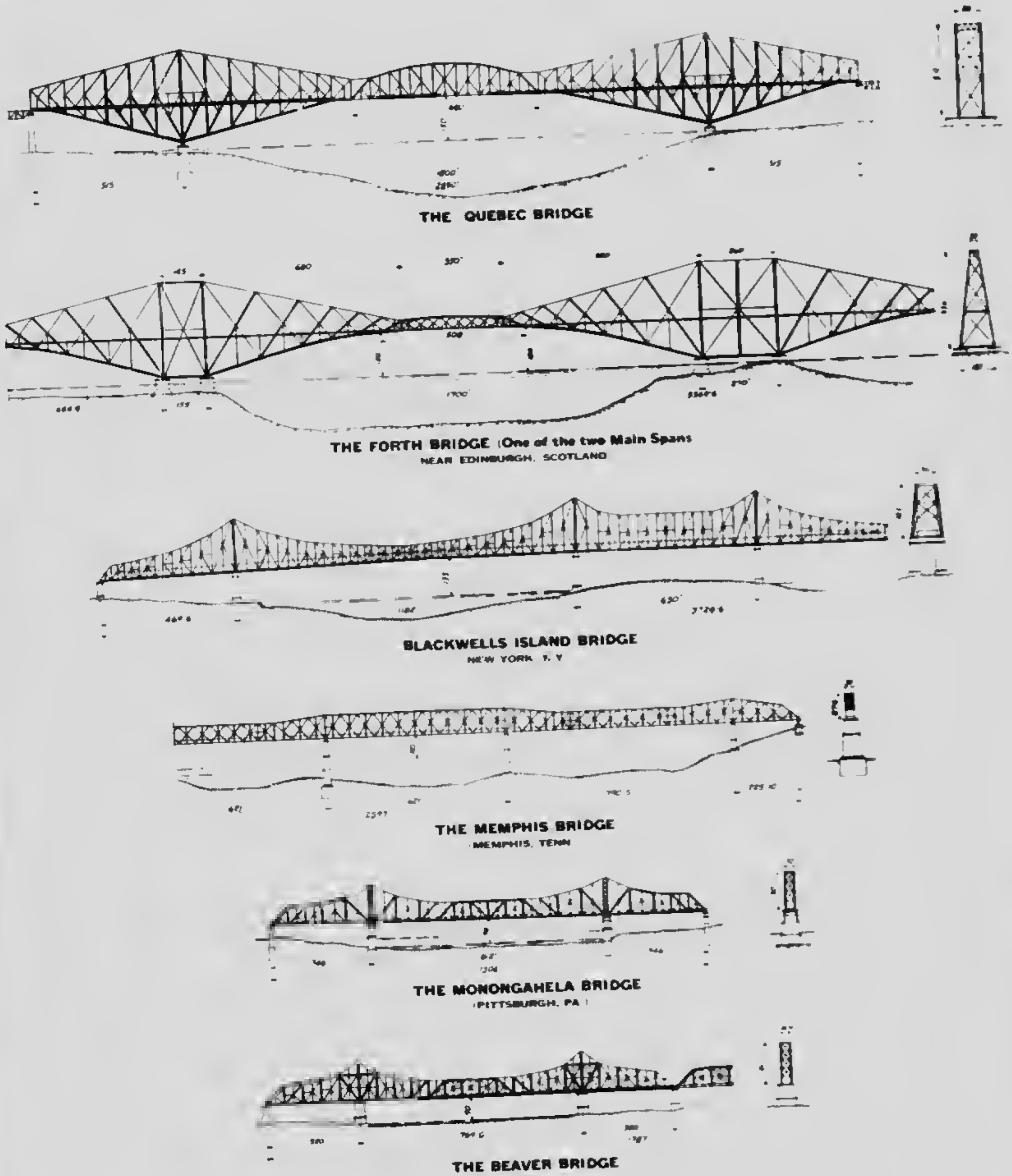
The rolled material for the Forth Bridge was fabricated at the site and fitted to the bridge piece by piece in a manner analogous to steel shipbuilding and thus did not require especially heavy machinery or lifting appliances for placing the material in its final position in the bridge.

This method of manufacture and erection permitted the use of large open panels with diagonals at an economical inclination, the use of battered and horizontally tapering trusses, and of circular compression members, all tending towards economy of material. Conditions in Canada did not permit manufacture at the site or placing the material in position in the manner used at the Forth Bridge and all the cantilever designs submitted for the Quebec Bridge were based on assembling the rolled material into members of as large dimensions as could be transported from the shops and erected in the bridge.

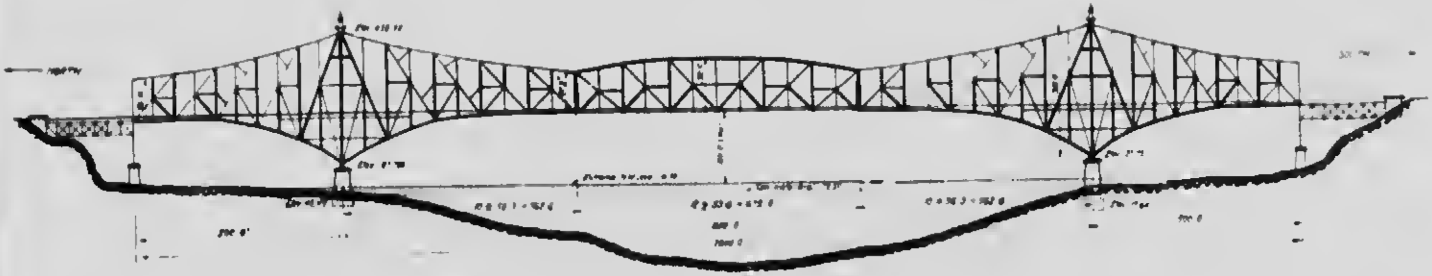
It was natural that the project of building a bridge across the St. Lawrence River at Quebec should have been of great interest to many bridge engineers, it being foreseen that it would be a longer and heavier span than any hitherto built and that the increase in span and capacity to very near the limiting length of the cantilever type of bridge would bring with it new and important problems to be solved. When tenders were first called for its construction by the Quebec Bridge & Railway Company in 1899 most of the prominent bridge engineers of America were in some measure connected with the competition.

A contract for the foundations and masonry was let to Messrs. William Davis & Sons and a contract was made with the Phoenix Bridge Company of Phoenixville, Pa., for the construction of the superstructure on a design prepared by the Phoenix Company.

The masonry was satisfactorily completed and work on the superstructure proceeded until the South anchor arm, cantilever arm and nearly half of the suspended span were erected when on the 29th August, 1907, all of this portion of the superstructure suddenly collapsed.



4 Elevations, to the same scale, of the Quebec and other great cantilever bridges



GENERAL ELEVATION OF THE DESIGN PROJECTED BY THE PHOENIX BRIDGE COMPANY

SCALE

The cut above is an elevation of the Quebec Bridge as projected by the Phoenix Bridge Co.

Plate 5 is a photograph taken of the bridge on the 27th August, 1907, two days before it collapsed. Plates 6 and 7 show views of the wreck after the accident. The disaster was accompanied with heavy loss of life. The accident made a profound impression upon the Engineering World and indeed, upon the general public both in Canada and in other countries. The Government at once appointed a Royal Commission consisting of Professor John Galbraith, J. G. Kerry and Henry Holgate, Chairman, to investigate and report upon the accident. An independent report was also asked from Mr. C. C. Schneider which was incorporated in the Blue Book on the inquiry. The Blue Book was very complete, the Commission having assembled most of the available data on other long span bridges, illustrated their important features, recorded the tests on large size compression members that had previously been made together with a number of tests made by the Commission on the behavior of such members under stress.

After receiving the report of the Royal Commission the Minister of Railways & Canals appointed a Board of Engineers to prepare plans and specifications for a new bridge. The Board, which was appointed on the 17th August, 1908, consisted of Messrs. Maurice FitzMaurice, M.I.C.E., of London, England; Ralph Modjeski, M.A.S.C.E., Chicago, and H. E. Vautelet, M.C.S.C.E., of Montreal, Chairman and Chief Engineer.

Mr. Vautelet prepared plans and specifications which were exhibited to intending bidders about the first of January, 1910, but the other Members of the Board did not fully approve of the plans, believing that a more practicable design could be produced and consented to tenders being called upon the design only on condition that bidders might submit tenders on their own plans if they so desired.

5 Photograph of the Phoenix Company's bridge taken August 28, 1907, showing condition of the structure just previous to its failure

6 General view after the collapse from the Main pier Southwards

7 General view after the collapse from the anchor pier Northwards

Plate 8 shows the other designs on which tenders were submitted.

During the discussion of the plans Mr. FitzMaurice resigned and Mr. Chas. MacDonald, then retired from active practice, was pers ed to join the Board until a design should be selecte. After tenders were received Mr. Vautelet still strongly contended for his design, while his colleagues favored the design of the St. Lawrence Bridge Company, and Messrs. M. J. Butler, C.M.G., M.C.S.C.E., and Henry W. Hodge, M.A.S.C.E. of New York, were called in to assist the Board in coming to a decision. Four Engineers of the Advisory Board so constituted recommended the design of the St. Lawrence Bridge Company, Mr. Vautelet alone dissenting and, when his colleagues' recommendation was adopted, he resigned from the Board.

The duties of Messrs. MacDonald, Butter and Hodge were discharged when a design was selected and after the contract was let, in April 1911, Mr. Modjeski was the only member remaining of the original Board. The Minister appointed a new Board about a month tater to supervise the construction of the Bridge. This Board consisted of Messrs. Ratph Modjeski, C. C. Schneider and C. N. Monsarrat, Chairman.

The magnitude of the disaster to the bridge being erected by the Phoenix Bridge Company with its lamentable toss of life and serious financial loss, coupled with the fact that the proposed bridge was targer and much heavier than anything that had heretofore been attem had caused serious misgivings in the minds of the Gov ment and the public as to the practicability of the construction, and from the outset the Government safeguarded itself in every possible way, a prominent clause of the Contract reading as follows:

"The Contractor must satisly himselt as to the sufficiency and "suitability of the design, plans and specifications upon which the "bridge is to be built as the Contractor will be required to guarantee "the satisfactory erection and completion of the bridge, and it is to be "expressty understood that he undertakes the entire responsibility "not only for the materials and construction of the bridge but atso for "the design, calculations, ptans and specifications and for the sufficiency of the bridge for the loads therein specified. And the enforcement of any part or all parts of the specifications shall not in any way "relieve the Contractor from such responsibility."

To implement the above guarantee, the St. Lawrence Bridge Company was required to make a cash deposit of $1,297,500, and, in addition, both the Canadian and Dominion Bridge Companies became joint and several guarantors for the completion of the bridge, putting their entire assets at stake.

The design of a cantilever structure of this magnitude does not differ sensibly in the calculations of the stresses from similar structures of much shorter span, but owing to the unusual size of the members it was necessary to keep constantly in view the manufacture and transportation of such large members and even more important to consider the erection of these members in the bridge. It was also necessary to consider the elastic deformation of the bridge as the erection proceeded.

There were no shops in Canada equipped to manufacture the large members required by the design and as soon as the contract was signed the Company proceeded to provide the necessary facilities for manufacturing the rolled material into finished bridge members. About half the manufactured material was destined for rail level at each side of the River and as there was no crossing below Montreal the shops were buitt at Rockfield, near Montreat, where short sidings connected the shop tracks to both the Grand Trunk and Canadian Pacific Railways. The Government Railway on

Fig-1

Fig-2

Fig-3

Fig-4

Fig-5

8 Other Designs on which tenders were submitted:

Fig. 1 is the Official Design exhibited when the call for tenders was advertised

Fig. 2 is a modification of the Official Design

Fig. 3 is one of the alternative designs submitted by the St. Lawrence Bridge Company

Fig. 4 is a German design submitted by Machinen-Fabrik. Augsburg. Nuremburg

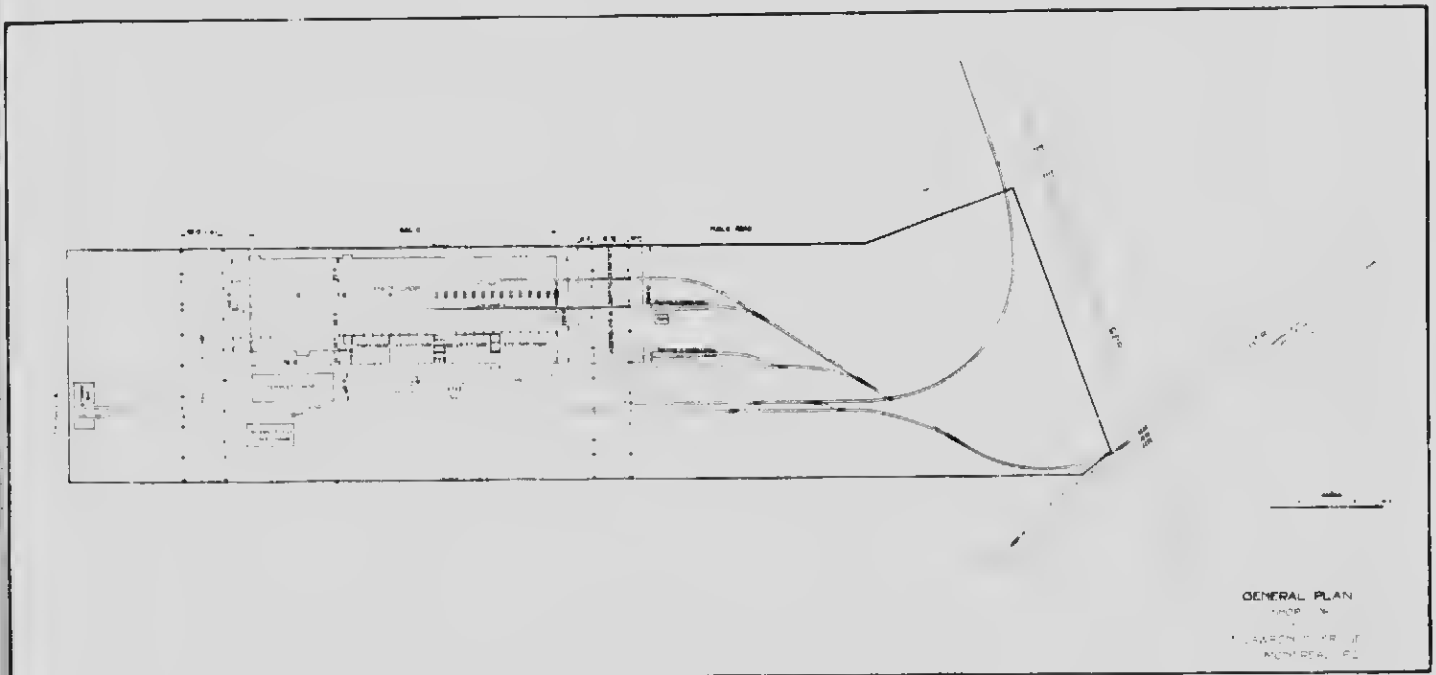
Fig. 5 is a suspension bridge submitted by the Pennsylvania Steel Company

Fig. 2 is a modification of the Official Design

Fig. 3 is one of the alternative designs submitted by the St. Lawrence Bridge Company

Fig. 4 is a German design submitted by Maschinen-Fabrik, Augsburg, Nuremburg

Fig. 5 is a suspension bridge submitted by the Pennsylvania Steel Company



9 Plan of shops showing rail connections to the principal railways

the South shore had running rights over the Grand Trunk Railway and the Canadian Pacific Railway served the North shore. Direct rail connection was thus established with the bridge on both sides of the River by the shortest routes. A good supply of efficient labor at Montreal also had its influence on the choice of a manufacturing site.

Plate 9 shows a general plan of the shops. The shops were constructed of steel and masonry and made fireproof throughout. Although they were established for the manufacture of this bridge only, it was considered prudent to incur the extra expense of fireproof buildings for the sake of minimizing the risk of delay through fire.

The cost of the shops and their equipment was about $1,300,000.

The specifications adopted were exacting as regards quality of material and manufacture. The Contractors realized that the structure could be properly erected and without difficulty only if the utmost precision in lengths, fitting and connections should be attained. Special machinery was provided; all important holes were drilled; great care was taken in assembling and rivetting the material and to finish the ends and bore the pin holes of the members perfectly square as well as to the exact lengths.

Plates 10, 11, 12, 13 and 14 show interior views of the shops with some of the large members being manufactured.

The normal season at Quebec during which field work can be successfully carried on is so short some seven months each year that it was necessary to provide plant that would allow the erection to proceed at the maximum safe speed. Convenient storage yards were established both on the North and South shores of the River equipped with crane runways, 500 feet long, overhead travelling cranes, 83 feet span and of 70 tons capacity. Ample storage tracks were also laid for the lighter material to be operated by thirty-ton locomotive cranes. Offices and a completely equipped boarding-camp were erected in which the engineers and most of the erection force could be accommodated.

Plate 1 shows the locations of the main camp and the North and South storage yards.

The design of the main erection travellers received much consideration indeed the designs of the bridge and the travellers were to some extent interdependent.

These travellers are illustrated on Plates 15, 16 and 17, and will be seen in many of the progress photographs. The travellers were about 210 feet high from the rails on which they ran to the top of the hoists. The travelling cranes on top carried two 60-ton hoists which had a transverse travel of about 14 feet, the maximum spread at which they worked being 96 feet. The width of the tower was 54 feet centres, its length 37 feet, and the length of the upper trusses carrying the crane runway 151 feet. There were four booms each 90 feet long capable of handling 15 tons and there were small 7-ton auxiliary gantry hoists at the end of the cranes for handling cages, pins and light work. The weight of the traveller was 940 tons about equally distributed on the two tracks when the cranes were at the rear end for moving. When the traveller was lifting its maximum loads the total reaction at the front end was about 1,300 tons. The traveller was carried by two rails on each side, the inner rail being carried by the track girder of the permanent floor and the outer rail by a girder placed temporarily for the purpose, shown on Plates 17 and 37

Steel falsework was provided for carrying the erection travellers and the floor system of the anchor arm during its erection. The permanent floor beams and stringers were

10 Views showing the interior of the shops with bridge members in the process of manufacture

11 An end section of the bottom chord being removed from the vertical planing machine

12 Pier panel of the bottom chord assembled for drilling the splice connection holes

13 Sections of the centre pier post assembled and set for planing

14 The end section of the bottom chord being bored

used as far as practicable for the deck of this falsework, as may be seen by referring to Plates 16 and 18. Steel falsework was also used to support the anchor arm trusses during erection and until the river arms were completed

A large quantity of steel was required for this temporary work about 8,000 tons in all having been provided. This was distributed approximately as follows

Inner falsework .	1,500	tons
Outside falsework for both sides of the River	950	"
Travellers	1,400	"
Erection struts, temporary bars, supporting platform, storage yard cranes, runways, etc.	4,150	"

The shops were completed and manufacturing steel in 1912 in time to carry out the programme of erection laid down for the completion of the work.

The general programme of erection was as follows:

The storage yards, camp and field equipment, with the exception of the travellers, were completed early in the season of 1913 and the North approach spans were erected on falsework with locomotive cranes before the close of that season. The erection of the North traveller was also started in 1913 in order that it might be ready to erect the anchor arm early in the season of 1914. The traveller was erected on the shore and moved out over the approach spans to the anchor pier from which point it set its own falsework as it proceeded; the 90-foot swinging booms being used for this purpose. The outer falsework to carry the anchor arm trusses, although independent of the inner falsework, was set at the same time while the traveller was proceeding out. As soon as the main pier was reached the grillages and main shoes were set.

After the shoes were set the lower chords of the anchor arm were started at the shoes and erected towards the anchor pier, the traveller being moved back for this purpose as the chords were erected. The lower chords of the anchor arm at every panel point rested on shoes of a rocker type which capped the outside staging columns and the level of the falsework was adjustable in order that the chords might be kept in a perfectly straight line until all the joints had been fully rivetted. After this had been accomplished the elevation of the falsework was adjusted until the chords reached the position calculated to give the truss the necessary camber to make the chords straight when under full load. The traveller was again taken back to the main pier and erected the lower triangles of the " K " system as it was moved back towards the anchor pier. These triangles are shown on Plates 24 and 25. When the traveller reached the anchor pier the inclined end posts and the anchor bars were put in place. It was then moved towards the main pier, erecting the upper triangles, the upper chord and the sway bracing as it was moved outwards.

A difficulty here was overcome in a rather novel manner. Calculations had shown that with the lower chord in its cambered position the web members and upper chord could not be connected without forcing some of the members out of line or altering the elevations of the lower chord to make these connections. It was found, however, that a small elongation of the pin holes in the tension members would permit the connections to be made without trouble. After experiments had been made to determine that the elongation of the pin holes would not in any way weaken these members, this expedient was adopted, and no trouble was experienced in making all connections. A further result of these experiments was the decision to make a slight elongation of all pin holes in tension members, allowing the largest pins to be easily and quickly driven with a 400 lb. ram.

By the end of the season of 1914 the North anchor arm was completely erected with the exception of two upper triangles at the South end, as shown on Plate 26, and the work was left in this condition throughout the following Winter. The tide rising about 5 feet above the falsework foundations, it was necessary to sheathe the bottoms of the bents and the bracing to protect the falsework against ice. Work was resumed on 15th March, 1915, and the North anchor arm was completed, including the main pier posts, on 8th June, 1915. When these posts were erected the framing for camber caused the tops to be 15 inches out of the vertical. The erection of the cantilever arm was at once proceeded with and the traveller was moved over the first sub-panel point, C.M. 15, on June 24th, 1915.

In erecting the cantilever arm the design of the truss made each panel self-supporting as the work was projected out and it would have been possible to erect it without any temporary supporting members, but it was convenient to place the lower members first to avoid interference of the heavy hoisting tackles with members already set in place. The lower chords were spliced half way between panel points and were carried by a platform suspended by temporary eyebars and shifted from panel to panel as the work proceeded. This platform is shown on Plates 31, 32 and 34. It was equipped with two sets of four 100- and 60-ton jacks, the 60-ton set under the mid-panel splices and the 100-ton set near the end of the section to lift the lower chord to the required position for making connection to the vertical suspender. This platform greatly facilitated the erection and the alignment of the chords when making the splices as well as the subsequent matching of the pin holes to make the permanent web connection.

After setting the platform the first half panel of the lower chord was placed on it and the half panel of the compression diagonal was erected and supported by the sub-tension diagonal. The floor beam for this half panel was then placed and the traveller moved out with its front trucks over it. When the traveller was in this position its rear posts were clear of the main vertical post behind it, allowing the permanent sway bracing to be put in place. The outer half panel of the lower chord was then placed and lined up and the rivetting of the splice proceeded while the material above it was being erected. The upper half of the compression diagonal with its sway bracing, followed and was lined up and spliced before completing the triangle. The long tension diagonals were spliced on the floor of the bridge alongside the traveller, erected and connected in one piece. The vertical tension member was next placed and the pins connecting it to the bottom chord driven; the pins connecting it to the middle detail were not driven until later in order to avoid overloading the temporary top chord. The vertical compression member and the eye bar top chord were then placed and the pin connecting this section of chord to the section in the adjacent panel driven. The load carried by the temporary top chord was then transferred to the eye bars by slackening the two 100 ton jacks shown on plate 40. To make the panel self-sustaining it was then only necessary to drive the pins connecting the tension vertical to the middle detail. The double web floor beam was then placed and the floor completed to this floor beam, after which the traveller was advanced and the erection of the next panel commenced.

This procedure was followed, with only slight modifications, for all the panels from the main pier to the panel point 4. Panel 2-4 being short it was possible to erect it completely with the front legs of the traveller at panel 4. Panel 0-2 was erected with the front of the traveller at 2.

It was, therefore, not necessary to advance the traveller beyond this point.

When the truss system of the North anchor arm was completed and the traveller supported over the main pier, the floor beams were connected to the trusses, thus releasing the falsework bents put in to carry the traveller and floor system.

The falsework was then moved over to the South side for the erection of the South anchor arm. Meantime the South traveller had been erected. The erection of the South anchor arm falsework was started 20th May, 1915, and completed 3rd July, 1915. The South anchor arm itself was completely erected, including the vertical posts over the main pier, 3rd December, 1915, and the North cantilever was also completed that season.

The condition of the work at the end of the season of 1915 is shown on Plate 45. It may be noted that the load on the outer falsework carrying the North anchor arm was not fully relieved until the cantilever arm was erected and it was necessary to duplicate this falsework for the South anchor arm.

The design of the bridge was based on floating the suspended span into position and no provision was made for the stresses imposed and extra material that would be required if it were erected by cantilevering. There was so much risk attendant on attempting to float the span at the level it would occupy in the bridge that this plan was never seriously considered although strongly advocated by some after the accident in 1916.

The plan adopted was to erect the span at as low a level as practicable, float it to position and hoist it in place. The best site available for erecting the span was at Sillery Cove, about 3½ miles below the bridge site where excellent conditions existed. The railway connecting with the material yard, at this point was about the level required on the span; there was a good level rock bottom dry at Spring tides, making it easy to prepare the foundations for the steel falsework and for the pontoons. The site was also well protected from navigation risks by shallows, but over which there was sufficient water at high tides to float the pontoons loaded with the span. Steel bents were placed for each panel point of the span and it was erected by the lower part of the traveller that had been used on the North arm; the four booms being all that was required for the purpose, the upper trusses and travelling cranes were omitted.

The method of erection did not differ from that usually followed in a span of this character.

Heavy steel towers were placed under the four corners and after the bridge was completely assembled, with the exception of the permanent floor system, it was swung on these end supports and the other falsework removed. See Plate 49.

The span was erected at such a height that pontoons could be floated under it at high tide and allowed to rest with the receding tide on foundations prepared for them at a height that would permit the blocking and steel grillage girders for distributing the load on the pontoons to be placed under the trusses. See Plate 50.

The pontoons, really scows, six in number, each 165 feet long, 32 feet wide and 11 feet 6 inches deep, were built with heavy steel frames and steel plate girder bulkheads calculated to support the heavy concentrated load to which they were actually subjected and for possible bad conditions of weather. The wooden planking was considered to be only a skin to keep out the water and not as adding strength to the framework. Each of the scows had six valves in the bottom operated from the deck, which were left open to allow the tide to flow in and out while the scows rested on their foundations at Sillery and only closed when it was desired to float the scow.

For the operation of floating the span it was necessary to choose a tide sufficiently low to permit the scows to be drained clear of water at low tide and with sufficient rise to float the scows with 8 feet 2 inches of draft about two hours before the high tide, as it was necessary to traverse the distance to the bridge site on the flood tide and desirable to be in position before the current actually changed—the tide commencing to fall about an hour before the change of current. This condition of tide only obtained for a few days at the period of Spring tides. The span was controlled on its way from Sillery to the Bridge by five tugs on the down-stream side, one of 1,000 H.P. and four of 500 H.P., while two smaller tugs were used on the up-stream side to assist in placing the span transversely to the current. Other powerful tugs were held in reserve in case of a change of wind or the inability of the tugs attached to hold the span against the tidal current which runs at this point about six and one-half miles per hour, but the span was very easily controlled by the tugs attached and the extra tugs were not used.

Plates 55, 56, 57, 58 and 59 show the operation of moving the span out from its supports at Sillery and controlling it to its position at the bridge.

Heavy cantilever mooring frames, each calculated to carry a transverse load of 300,000 lbs. at the lower end, were hinged at the top to the ends of the cantilevers. To avoid risk of fouling the span while being manoeuvred into position these frames were drawn back by means of two nine part 7-8-inch diameter wire rope tackles, which had originally been the main hoists on the traveller, the lines of which were led to electrically operated drums on the floor of the bridge. When approximately in position the span was connected by four $1\frac{1}{4}$-inch plow steel ropes to the frames at each end, which were led diagonally from bollards on the ends of the span through sheaves in the bottom of the mooring frames to nine part $\frac{3}{4}$-inch diameter wire rope tackles operated by electric hoists on the floor of the cantilever. See Plate 59.

After the suspended span was attached by these wire ropes the frames were lowered to the vertical position and the span moored in exact position vertically under its place in the bridge.

The lifting chains were also drawn back to give clearance while the floating span was being placed and were only lowered into vertical position for connecting after the span was moored to the frames.

Provision was made for shifting the mooring tackles as the span was hoisted so that it could be safely anchored at any elevation in the event of a strong wind springing up while it was being hoisted, and recourse was had to this anchorage on the last day before the final connection was made.

Plate 58 shows the mooring frames and lifting chains drawn back and Plates 54 and 60 show the position of these parts after the span was connected and while being hoisted. Plate 54 also shows the lifting chains and their connection to the span.

These chains were spaced 16 feet apart centre to centre at each corner. Each was made up of four 28 x $1\frac{1}{2}$-inch carbon steel links, each link about 28 feet long. The links were bored for pins twelve inch diameter at 6 foot centres through which the lifting pins could be inserted for fastening them to the jacking girders. The links were connected to each other by pins 12 inch diameter 24-foot centres and each placed half way between a pair of the holes spaced 6-foot centres used for connecting to the jacking girders.

It was important that the load should be taken simultaneously on the eight hoisting chains and that the operation of connecting the chains to the lifting girders should not be complicated by having to jack the chains down to follow a dropping tide. The bottom holes in the chains were therefore elongated about 5 feet and when making the connection to the link projecting from the lifting girder the chains were set at an elevation to bring the pins near the top of the slot. The links having the oblong holes were made of Silicon Steel to cover possible increase of stress due to deformation.

Lifting girders, each weighing about 30 tons, on which the suspended span rested while being hoisted, were placed on the corner falsework bents at Sillery before the span was erected and were hung from the ends of the span in position for hoisting while the span was being transferred from Sillery to the site. Shoes were placed between the span and these girders, permitting angular motion both transversely and longitudinally. More extended reference will be made to these when describing the loss of the first span in 1916. At each corner there was placed across the end of the cantilever arm, vertically over the point of intersection, a heavy cross girder, supported on rocker bearings to equalize the load on each pair of chains, from which the jacking girders were suspended at about the level of the cantilever floor. The jacking and lifting girders were deep plate girders connected near each end by double diaphragms between which the hoisting chains passed.

A hydraulic jack was placed outside the hoisting chains at each end on top of these girders and resting on top of the jack plungers were placed lifting girders, practically duplicates of the jacking platform, with corresponding diaphragms, but the suspension bars which were fastened to the jacking pl orm passed through the lifting girders which were free to slide and were guided on these bars. The diaphragms both in the lifting girders and the suspension platform were each bored with three sets of holes spaced two feet centres vertically. The jacks had a lift of two feet and although the holes in the lifting chains were spaced six feet centres, the arrangement of holes in the diaphragms always enabled the registering of a pin hole in the chain with pin holes in both lifting and platform girder whether the jacks were at the top or bottom of their stroke.

The suspended span in condition for hoisting was estimated to weigh about 5,100 tons; the suspension and lifting appliances added about 440 tons, making a total load of 5,540 tons to be lifted by the jacks. The rams of the jacks were 22 inches in diameter and the working pressure about 4,000 lbs. per square inch. The jacks and the lifting girders were tested under a pressure of 6,000 lbs. per square inch by pinning the jacking platform and the lifting girder together.

Two hydraulic pumps placed at the end of each cantilever operated the jacks. The pumps were driven by compressed air supplied from the power houses on shore. There were separate control valves for each jack at each corner and control valves for each pair of jacks at each end. Multiplying tell-tales were installed to enable the valve operators at the corners to keep the lifting girder exactly horizontal and the valve operator at the centre of the bridge to keep the span itself horizontal. A telephone system was installed through which the lifts at each end of the span were reported to the Officer in general charge and the two ends thus kept at the same height. Four 12-inch diameter counterweighted screw-jacks worked by hand wheels were provided at each corner to follow up the hydraulic jacks and take the load in the event of a packing blowing or any accident to a hydraulic jack, so that it could be removed and repaired.

The operation of lifting was a very simple one: the hoisting chains were pinned to the lifting girder when the jacks were in their lower position. The jacks were then slightly raised to release the strain on the lower pins, and allow them to be withdrawn when the jacks were pumped up until the next pin hole came opposite a hole in the lower diaphragm a distance of two feet. The lower pins were then inserted again and the load allowed to rest upon them: the upper pins could then be withdrawn and the lifting girder returned to its low position for a repetition of the operation.

All preparations had been made for floating the suspended span before the 1st September, 1916, but it was getting near the end of the series of suitable tides and it was felt that it would be an advantage to drill the engineers and workmen for a few days before actually undertaking the operation. The next suitable tide was on the 11th September and the span was successfully floated into position on that date, connected to the hoisting chains and raised by the jacks until the load was taken off the scows, which floated out with the current leaving the span suspended on the hoisting chains.

Everything had worked as planned up to this point; it was thought all risk in the operation had been successfully overcome and that nothing remained but to jack the span to its final position. The workmen had been on duty since one o'clock in the morning and after the span was raised four lifts at the North end and five lifts at the South end, they were allowed a recess of an hour for breakfast and rest, the span at this time hanging about 30 feet above the water. The hoisting was resumed after recess and just after the first lift had been completed at 10:50 a.m. something failed at the Southwest corner of the span allowing that corner to drop into the water, twisting the bridge until the South end floor beam was almost vertical while the North end of the span still rested on the hoisting girders. The torsion of the bridge caused first the failure of the lateral bracing followed by the failure of the trusses and the Southeast corner was soon pulled off its supports; as the South end sank both corners at the North end were dragged off simultaneously and the whole span disappeared under the water. The successive release of load at the different corners caused violent vibrations in the hoisting chains and the cantilevers.

The opinions of observers differed greatly as to the original point and the sequence of failure, but a photograph was being taken at the moment which shows clearly what occurred. See Plate 62.

The hoisting chains and carrying girders remained in place unbroken as well as the lower portion of the bearing on which the span had rested, and an examination was at once made to ascertain the cause of the accident. The condition of the bearing at the Southwest corner showed that the span had first fallen vertically upon it before kicking the girder backward and allowing the corner of the span to slip off. This led to the conclusion that the failure of the cruciform steel casting forming part of the rocker bearing and shown on Plate 64, was the cause of the accident, probably having split under the upper pin. The castings at the South end of the span had stood the test of carrying the span for about five weeks while on its end supports at Sillery, under much more severe conditions than when it was being hoisted, the load at Sillery having been about 10% greater, due to a heavy temporary floor and subject to the shock of a locomotive crane weighing about 80 tons passing on and off the span. While the cause of the accident was being investigated, a careful examination was being made of the cantilevers to determine if any part of the standing structure had been injured by the severe but unknown stresses to which it had been subjected by the impact of the falling span and by the upward spring and vibrations when the weight of the span was suddenly removed.

A rigid examination of all the connections as well as levels taken on the floor beams showed there had been no injury or change in the cantilevers through the loss of the span. As soon as this had been ascertained it was determined to replace the span and material was ordered to exactly duplicate that which was lost. The point of failure having been located in the cruciform steel casting, this detail was revised to avoid the use of steel castings.

The transverse pins had been used to take care of the angular movement of the truss members at the shoe when the falsework supports were removed, as the span was necessarily erected in a cambered position. This movement was provided for in the new detail by making shallow shoes under the outer ribs of the end post which bore on a confined lead bearing, the bearing on the lead being proportioned to allow the material to flow and adjust itself to the altered conditions of load when the span was swung on its end supports. When the span was floated at Sillery and the load taken off the lead bearings, shim plates under these bearings were removed, which allowed the carrying girder when hoisting to bear against a nickel steel rocker centrally placed under the end post and thus prevent any unequal distribution of load on the two hanging chains at a corner.

Some small changes were also made in the method of operating the follow-up screws and the valve controls of the jacking apparatus, but these were more as a matter of convenience and precaution than of necessity or because the previous arrangements had been found in any way at fault.

Notwithstanding the scarcity of steel at that time, the Carnegie Steel Company, which had supplied all of the rolled material for the bridge, made a special effort and delivered the greater portion of the material for the new span before the end of 1916.

The falsework on which the span was originally built had suffered a good deal from ice shoves during the Winter and the repair of this delayed the commencement of erection in the Spring. Because of the impact of the span falling on the Southwest corner and the extra load imposed by the span rotating around the diagonal line joining the Southeast and the Northwest corners, all of the hoisting rigging at these points was subjected to heavy overloads. It was therefore considered prudent to replace the hoisting chains with new material and to reinforce the hangers and lifting and supporting girders.

The first suitable tide after the new suspended span was ready for floating occurred on Saturday, September 15th, and preparations were made for that day, but unfavorable weather reports and a strong breeze at low tide caused a postponement until Monday, the 17th, when the span was floated at about the same hour as in the previous year. On this occasion everything went smoothly except a slight delay in pinning some of the hoisting chains. Actual hoisting commenced at 9:10 in the morning and the scows floated out at 10:25. After the first few lifts, which were expected to take about 15 minutes each, the men gained confidence and in some cases the cycle was performed in much less time, but as it was not expected to hoist the span in one day, minimum times were set for each operation as a measure of safety and the span was lifted at an average of about four lifts or 8 feet per hour. Each link of the hoisting chains as it came through the jacking girder was taken off by tackles rigged for the purpose and deposited on the platform at the end of the cantilever. Plate 69 shows the last of these links being taken down

The removal of the links, the adjustment of the mooring tackles, inspection, etc., required nearly as much time as the actual lifting. Twelve lifts were made the first day, twenty-two the second day and twenty-six the third day, when the span was within thirty feet of its final position. At the end of that day the weather was threatening and the span was securely moored. The following morning the wind was blowing about 35 miles per hour, but after releasing the mooring tackles the horizontal displacement of the span was slight and there seemed no risk in proceeding with the hoisting, the mooring tackles being set to a slight stress to prevent swaying.

The permanent suspension bars for carrying the span were in two lengths connected by pins at the centre for convenience in handling the bars themselves, and for facility in making the final connection; the central joint permitting the bars to be deflected to bring the holes in exact position for driving the pins of the final connection. Before hoisting commenced the upper eyebar suspenders were connected to the cantilevers and the lower eyebars were connected to and stayed on the suspended span in a position for entering and passing through the jacking girders, the final connection being made above these girders. The connecting bars are shown on Plates No. 49 and No. 52; the entering of these bars as the span was hoisted on Plate No. 69 and driving the final pin on Plate No. 70.

The suspension bars were entered and backed at 3:10 p.m., the operation of driving the connecting pins was started twenty minutes later, and the span was securely connected at all points at 4 p.m., on the 20th September, 1917. The wind shear connections were put in as soon as possible to make the bridge secure against any conditions.

The floor system of the span was placed by locomotive cranes and one track was rivetted, permitting a train to be taken over the bridge on October 17th The bridge was handed over to the Operating Department for regular train service on the 3rd December, 1917, the only work remaining to be done being the concrete sidewalks on the suspended span and the painting, which could be carried on while the bridge was in service.

The executive officers of the Company desire to express their appreciation of the faithful and efficient service rendered by the members of its staff. The final success of this great undertaking was due to the efficiency of the organization and the spirit of co-operation between the different departments, all working together to the one end.

They also desire to express their appreciation of the spirit of co-operation and helpfulness of the Board of Supervising Engineers and their staff of inspectors.

It is a source of great satisfaction to the builders of the bridge to know that the workmanship of the structure shows a degree of perfection believed to have never before been approached. The excellence of the shop work and the exceptional precision in the lengths and fitting of the various members contributed much to the facility with which the bridge was put together in the field, and to the confidence that every part of the structure is performing its calculated duty. This result could only have been reached by the use of the most perfect shop equipment and great care in manufacture. The tool equipment was selected and installed under the supervision of Mr. Walter P. Ladd, who also had full charge of and responsibility for the manufacture of the structure.

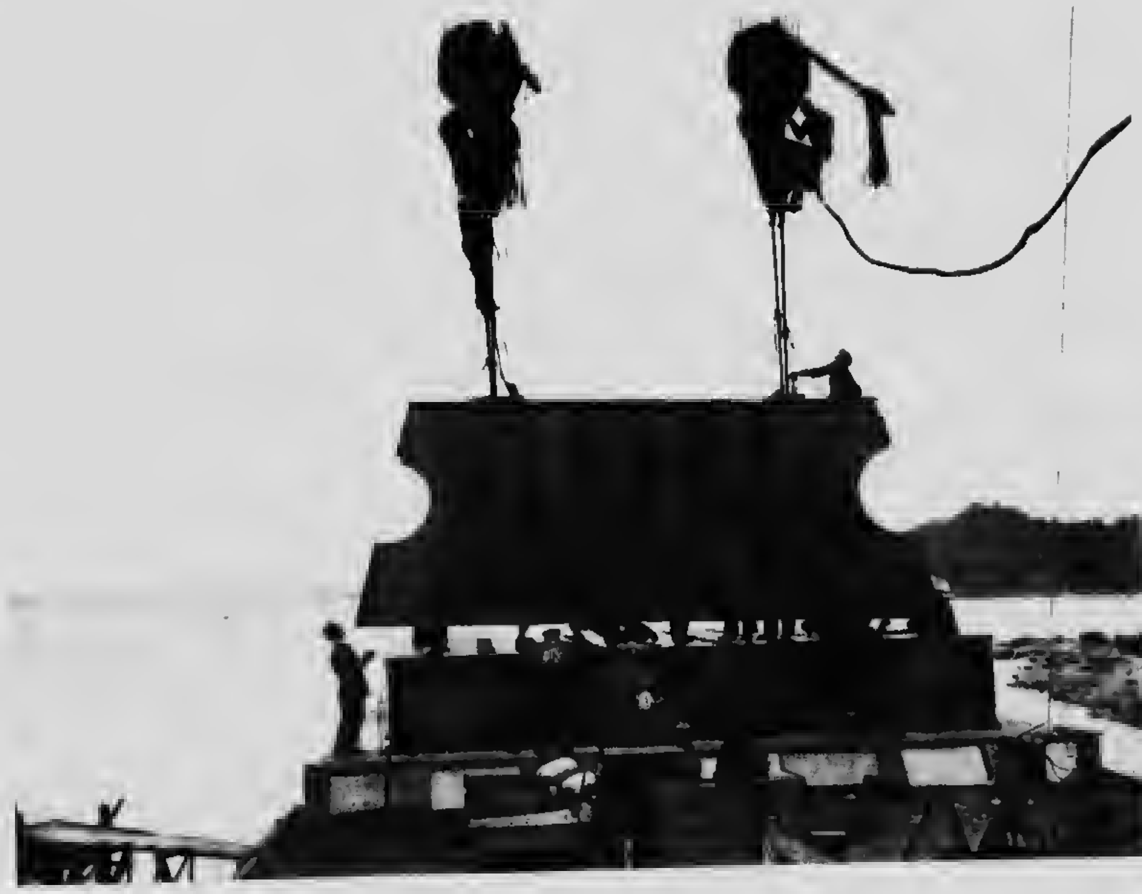
Hearty thanks are due to the management of the Carnegie Steel Company for their very prompt delivery of the steel for replacing the suspended span, and also to the Midvale Steel Company for their prompt delivery of pins.

45. The North Shore traveller erected being equipped, also showing the office building and power house to the left

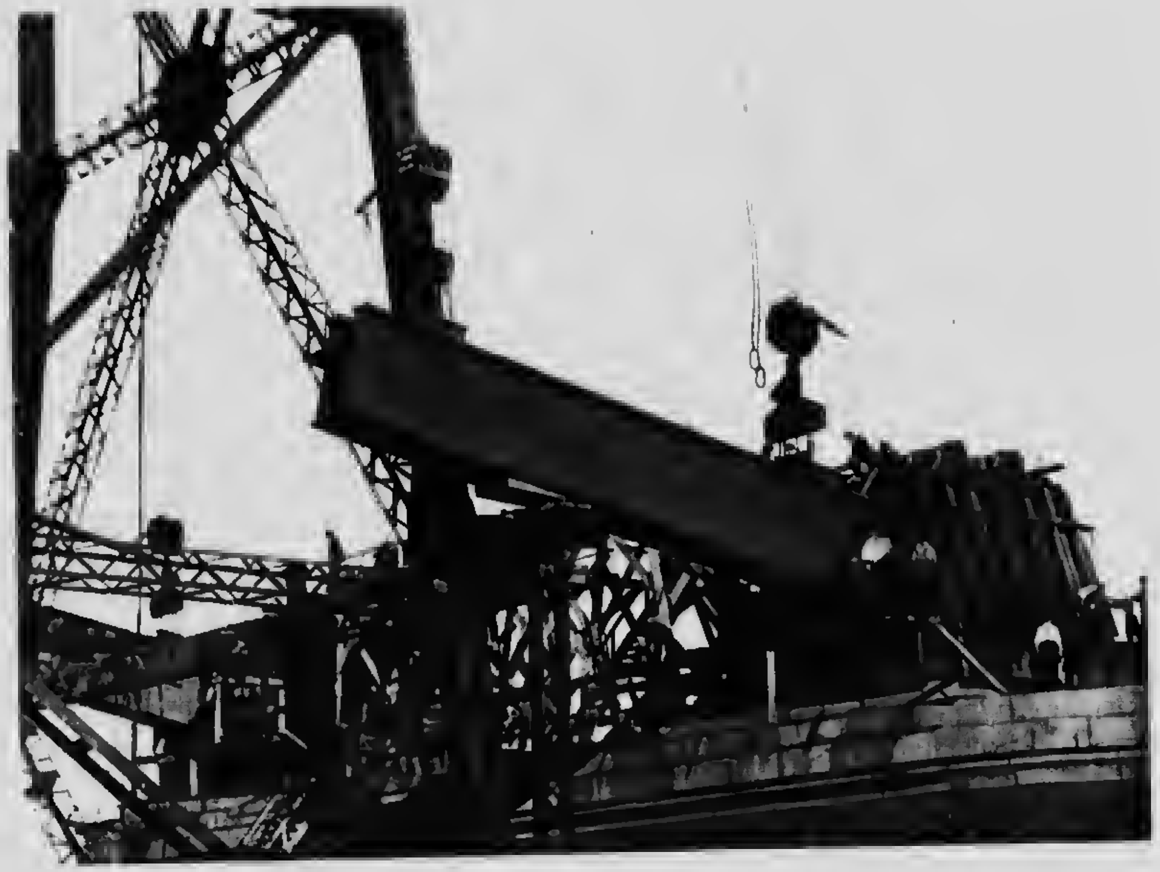
16 The traveller in use setting the falsework for the anchor arm trusses and permanent and temporary floor

17 End elevation of the traveller at the same position as on plate 16, showing the four tracks on which it was carried and the temporary outside girders to support the outside tracks

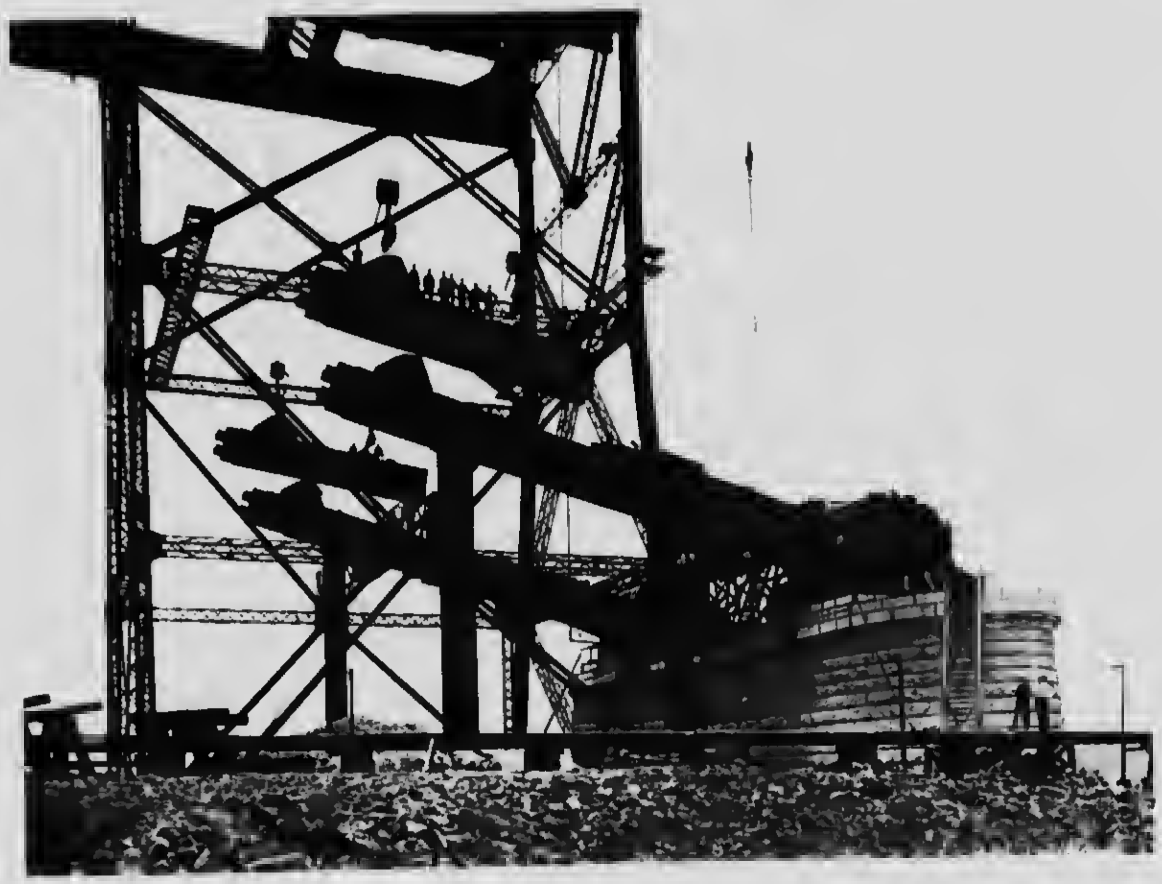
18. Permanent track girders and floor beams supported by the falsework; also shows the bushed pin holes in the end of floor beams



19 The main shoe grillage already set, one rib of the main shoe being placed



20 The Northwest shoe erected complete except the cover plates over the stiffening ribs. The first section of the lower chord of the anchor arm is being placed



21 Setting the fourth section of the lower chord to complete the first lower chord panel of the anchor arm

22 The anchor arm lower chord completed. Lowering anchor bars into the wells of the anchor pier

23 Starting the erection of the anchor arm web system

33 Starting the erection of the anchor arm web system

34 Two lower triangles of the web system of the anchor arm erected

25—All of the lower triangles of the anchor arm erected. Starting the erection of the upper triangles and upper chord

26 Condition of the North anchor arm at the close of the season of 1914

27 Connection of web members at the centre of the large post over the main pier

27 Connection of web members at the centre of the large post over the main pier

28 Placing one section of the large link at the top of the main pier post

19.—The large link at the top of the main pier post in place

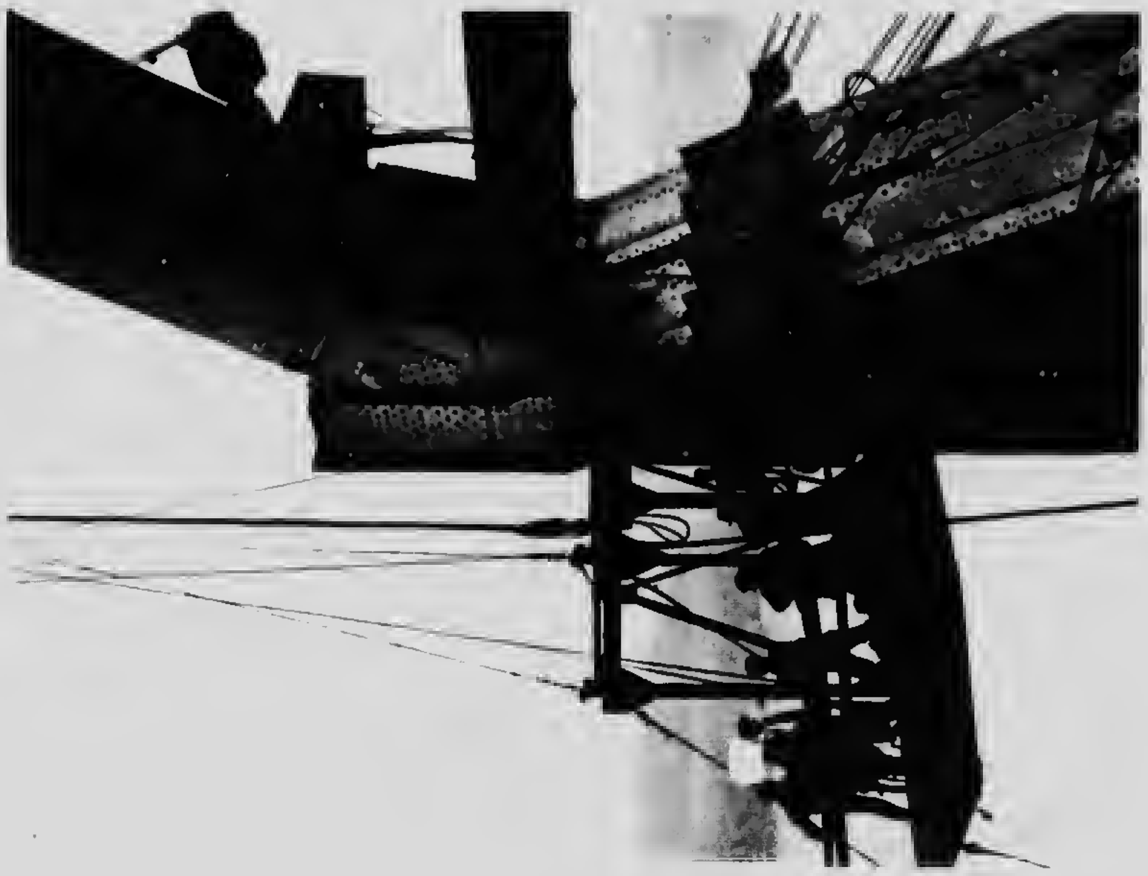
29.—The large link at the top of the main pier post in place

30 The erection of the North Shore anchor arm completed June 7th, 1915

31.—Starting the erection of the North Shore cantilever arm, showing the supporting platform in place carrying the first sections of the lower chord

31 Starting the erection of the North Shore cantilever arm, showing the supporting platform in place carrying the first sections of the lower chord

32 Half panel of the cantilever arm erected with the members of the outer half of the panel in place



33.—Connecting the first panel of the cantilever arms

33—Connecting the first panel of the cantilever arms

34 The first half of the second panel of the cantilever arm erected

35 Detail of the large link and connection at the top of the main pier post

35. Detail of the large link and connection at the top of the main pier post

36. Erecting the third panel of the cantilever arm

37 Lifting the upper chord eyebars assembled in permanent supporting lattice box girders. Also shows the floor system, the traveller trucks and the switch house

38. Another view of the upper chord eyebars being hoisted, assembled in the supporting box girders. Shows in the distance the South Shore traveller erecting the lower triangles of the South Shore anchor arm truss

39 Placing the upper chord eyebars of the cantilever arm

40 Detail of the temporary connection for holding the upper chord eyebar supporting girders in place and for adjusting the pin hole centres

41. The end post C.M.1-U.0. of the cantilever arm being put into place. The reach of the traveller in this last position was not sufficient to place the member so a temporary hinged joint was introduced and the member swung on the hinge into place

42. Progress of erection, August 18, 1915

43 Progress of erection, September 30, 1915

44 The North cantilever arm erected, November 7, 1915

45 Progress of erection at the close of the Season 1915

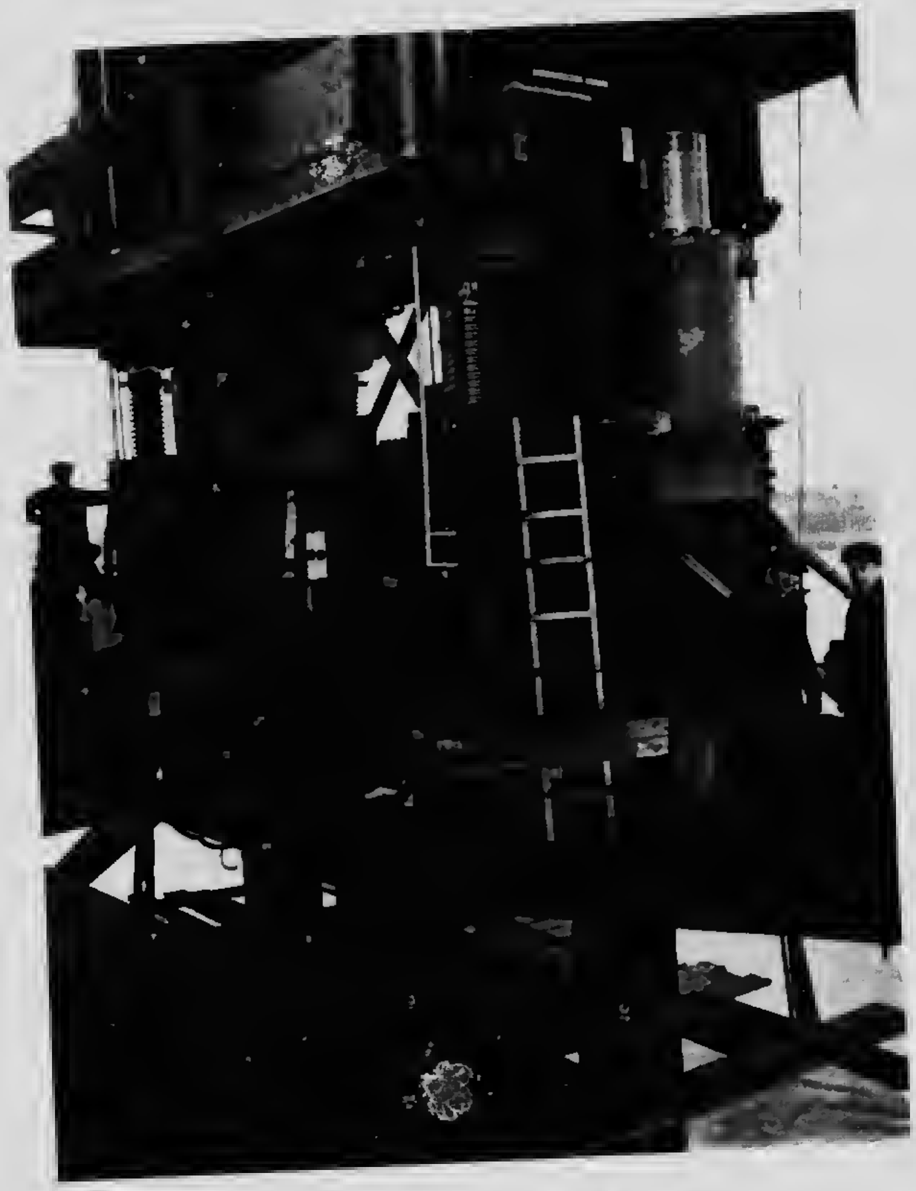
46—Cantilevers completed, hoisting apparatus partly assembled

47 – Progress of erection, August 11, 1916

48—The suspended span erected on falsework at Sillery

49 – The falsework removed with the suspended span resting on the end supports

58. The suspended span resting on the end supports at Sillery. The falsework removed and the scows blocked under ready for floating



51—Details of the jacking apparatus

51 —Details of the jacking apparatus

52 · The hoisting apparatus on the end of the cantilever arm showing the pumps, jacking platforms, tell tales, etc.

5.3 The jacking platforms

53 The jacking platforms

54 General view of the hoisting and mooring apparatus; also shows permanent eyebar hangers in place, the lower half of them on the suspended span and the upper half suspended from the outer end of the cantilever arm.

55 The suspended span moving from Sillery berth

56. The tugs taking hold of the suspended span

57—The suspended span being guided up the river

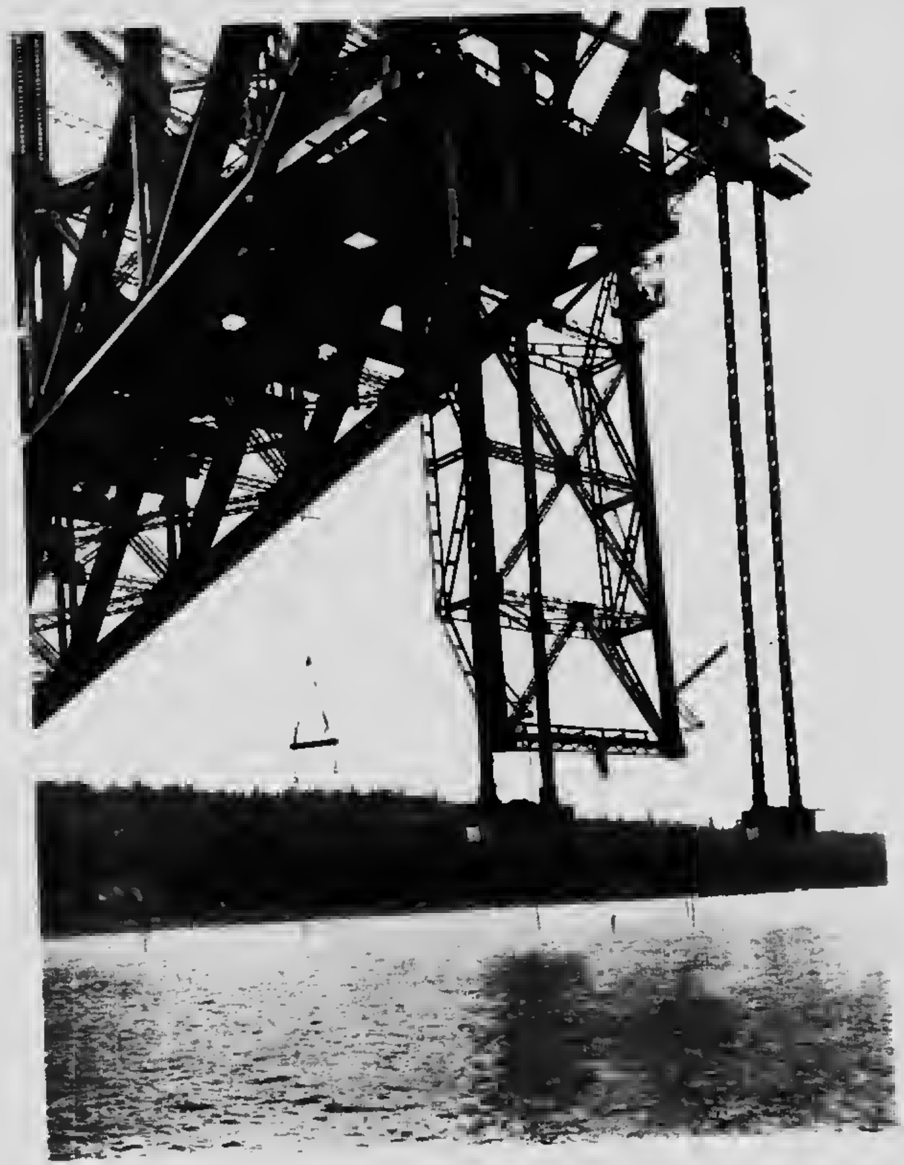
58—The suspended span being guided to position

59.—The suspended span moored. Note the mooring ropes, also the hoisting chains being connected

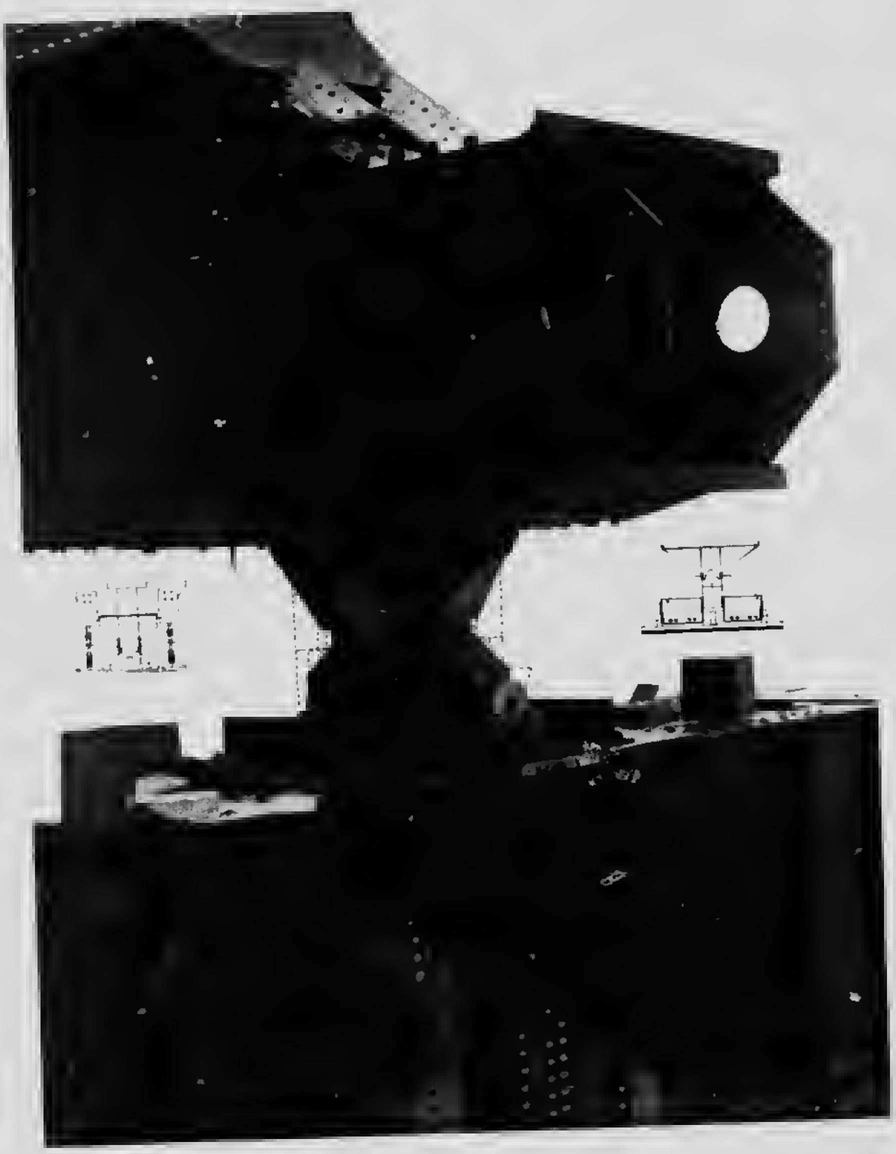
60 The suspended span carried by the hoisting chains; scows floating out

61.—September 11, 1916, 10 40 a.m. Just before the loss of the suspended span

62 The suspended span falling



63 The chains and mooring frame after the loss of the suspended span



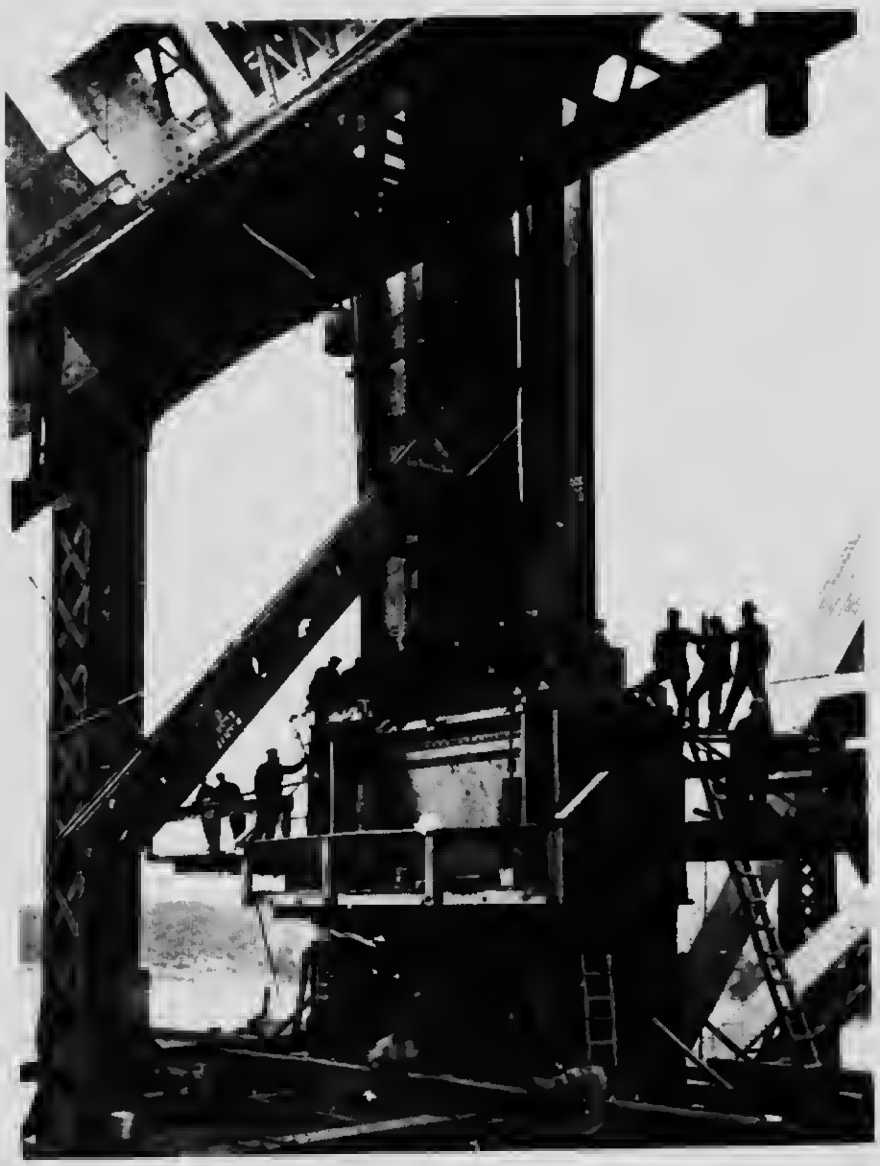
64 Details of the shoe which failed when supporting the suspended span during erection

65 Condition of lower shoe and carrying girder after the loss of the suspended span

66. The suspended span about half way up, September 18th, 1917

67 The top of the suspended span appearing above the cantilever floor, September 18th, 1917

68 The suspended span higher up, September 19th, 1917



69.—Entering the permanent suspension bars and removing the last link of the hoisting chain, September 20th, 1917

70 Driving the last pin. 4 P.M., Thursday, September 20, 1917

71 Eyebar Hanger supporting one corner of the suspended span from the end of the cantilever arm

72 Detail at the top of the Main Post

73 View showing the connections to one of the Main Pier Shoes

74 Detail at C.M 14 The middle panel point of the cantilever Arm adjacent to the Main Post

75 · Detail at AL2, showing the floorbeam connection to the outer end of the Anchor Arm bottom chord

76 View from the top of the N.W. Main Post, showing inspector's walk, which is reached by means of 12 steel stairways

77 View of the Channel Span from one of the Main Piers

78 End view of the Bridge

79 View of the Bridge from the North Shore