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OF GENERAL INTEREST

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BRIDGES OF NEW YORK

BY O. H. AMMANN*

(Presented at a Meeting of the Designers Section held on April 12, 1944.)

The subject assigned to me, "Bridges of New York," is an almost inexhaustible one. It presents many interesting phases. New York's bridges have played an important rôle in the history, growth of population, wealth and commercial position of that great city.

The creation of the large bridges presented some unusual problems in finance and political expediency. The bridges are tied up intimately with the developments in transportation which in the course of time have revolutionized their design.

I shall in the course of my talk touch on some of these broader phases, but before this audience which I assume is composed largely of designing engineers, I shall confine myself principally to the design and construction problems encountered in the building of the more notable structures.

Even in this field I can only touch upon some of the high spots and in doing so I shall draw largely upon my personal experiences. Sketchy as it will be I trust my talk will convey an idea of some of the major problems involved and of the great advances made in the building of large bridges during the past 50 years.

GEOGRAPHIC CONDITIONS AT NEW YORK

New York is blessed with a magnificent harbor and waterways which give direct access to ocean-going steamers, as well as to inland

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shipping. The 700 miles of waterfront offer opportunity for terminals and other shipping facilities, as in no other city of the world.

But this very advantage, from the point of view of navigation, constitutes a great handicap to land communication between the different sections of the city and between the city and the continent. This handicap became more and more acute with the growing importance of land transportation, more particularly with the phenomenal development of the motor vehicle traffic in recent years.

Manhattan, which has always been the nucleus of the Metropolis, which houses a population of two million people and on which are centered the most important commercial, social and educational activities, is an island completely surrounded by navigable streams; the Hudson River on the west, the East River and the Harlem River on the east.

Between this island and the surrounding territory there has developed a steadily increasing flow of traffic, which has now reached enormous proportions. The people living in Manhattan depend in their livelihood upon transportation across the waterways of practically every commodity, food, raw materials and manufactured goods, from every part of the country. Many of these commodities are shipped to Manhattan in order to be redistributed from there to other parts of the Metropolis or transferred to steamers for export.

Millions of people travel daily between Manhattan and other parts of the city, the suburbs, and the remainder of the country in the pursuit of their activities.

Besides the great streams surrounding Manhattan there are numerous other navigable waterways in other sections of the metropolitan area which had to be crossed by highways and railroads.

Traffic Developments

The early transportation across these waterways was entirely by boats, and even today a comparatively large volume of passenger and freight traffic crosses the Hudson River by ferries, lighters and car floats. As the city developed water transportation proved inadequate. It is slow, subject to delays and congestion at traffic peaks, and dependent upon weather conditions. It was the complete freezing of the East River and the consequent tying up of traffic in the winter of 1867/68 which gave final impetus to the building of the first crossing of that river, the Brooklyn Bridge. In the winter of 1917/18 water transportation on the Hudson River was almost paralyzed due to ice conditions and the resulting congestion held back the shipment of war supplies and threatened a shortage of coal and other commodities in Manhattan. This situation hastened the construction of the Holland Tunnel, the first crossing of the Hudson River.

The earliest bridges were built across the Harlem River in the 17th and 18th centuries. They were designed for pedestrians and horsedrawn vehicles. They were short spans, of light construction and limited capacity. They were replaced and supplemented in the 19th century by larger and heavier structures, all of which, however, retained the character of local crossings for roadway and pedestrian traffic. Most of them are low level bridges with movable spans over the river channel.

Towards the latter part of the 19th century there developed the demand for passenger transportation by rail. This brought into existence several bridges carrying railroad tracks across the Harlem River, and rapid transit rail passenger traffic remained the most important factor in the planning of the first three East River Bridges.

In the last 25 years, with the development of the subway system the tracks across the rivers were more and more relegated to tunnels. During the same time, however, the volume of motor vehicle traffic on our highways grew by leaps and bounds. A few figures will illustrate this enormous growth in the flow of vehicular traffic. In the year 1910 about 20 million vehicles crossed the major waterways of New York. By 1925 the volume had grown to 125 million and before 1941 it was close to 250 million.

This growing highway traffic called for increased roadway capacity on the large bridges and eventually justified the expenditure of hundreds of millions of dollars for new great bridges and tunnels to accommodate this kind of traffic alone.

Bridges as Links in System of Traffic Arteries

The growing importance of vehicular traffic and in particular the demand for accommodating fast through traffic with speed, comfort and safety has revolutionized the planning of major crossings. Notwithstanding their great size, these crossings have become mere links in a vast system of modern highway arteries and the planning of the approaches and highway connections has become one of the major problems of every new project (Fig. 1).

Some of the most intricate engineering problems are involved in the planning of the approach ramps immediately adjacent to the crossing and of the connections with the highway arteries in the vicinity.

The old conception of the terminal of a bridge was a surface plaza which serves as an interchange of traffic to and from the various directions. This involves crisscross movements with resulting congestion, delays and accidents. The modern conception aims at avoiding grade crossing of traffic flowing in different directions, segregation of slow and fast traffic as far as possible, separate ramps between the bridge and the different main arteries and local highways in the vicinity.

This has led to some extremely complicated arrangements, composed of a series of spiral ramps, underpasses, and overhead crossing, sometimes three stories high. They might look confusing to the layman when seen in plan, but in reality they are usually simple for the driver to follow if he observes the traffic signs.

Design and Construction of the Bridges Proper

For the structural engineer the design and construction of the crossing proper form the most fascinating parts of a bridge project, and in this respect the great bridges of New York have contributed a rich share of unusual problems, new experiences as well as some disappointing vicissitudes.

From an engineering point of view, progress in bridge building is in a broad sense characterized by the boldness of span and traffic capacity, because engineering difficulties multiply progressively with these increasing proportions. Each structure which projects its span and capacity materially beyond precedents marks a new milestone in the progress of bridge building. New York possesses several such milestones and some still retain first rank among the bridges of the world, notably the Brooklyn Bridge, the Manhattan Bridge, the Hell Gate Arch, the Bayonne Arch and the George Washington Bridge.

In judging the engineering merits of a bridge consideration must be given to the time when it was built. Allowance must be made for the improvements in available materials, machinery and methods of

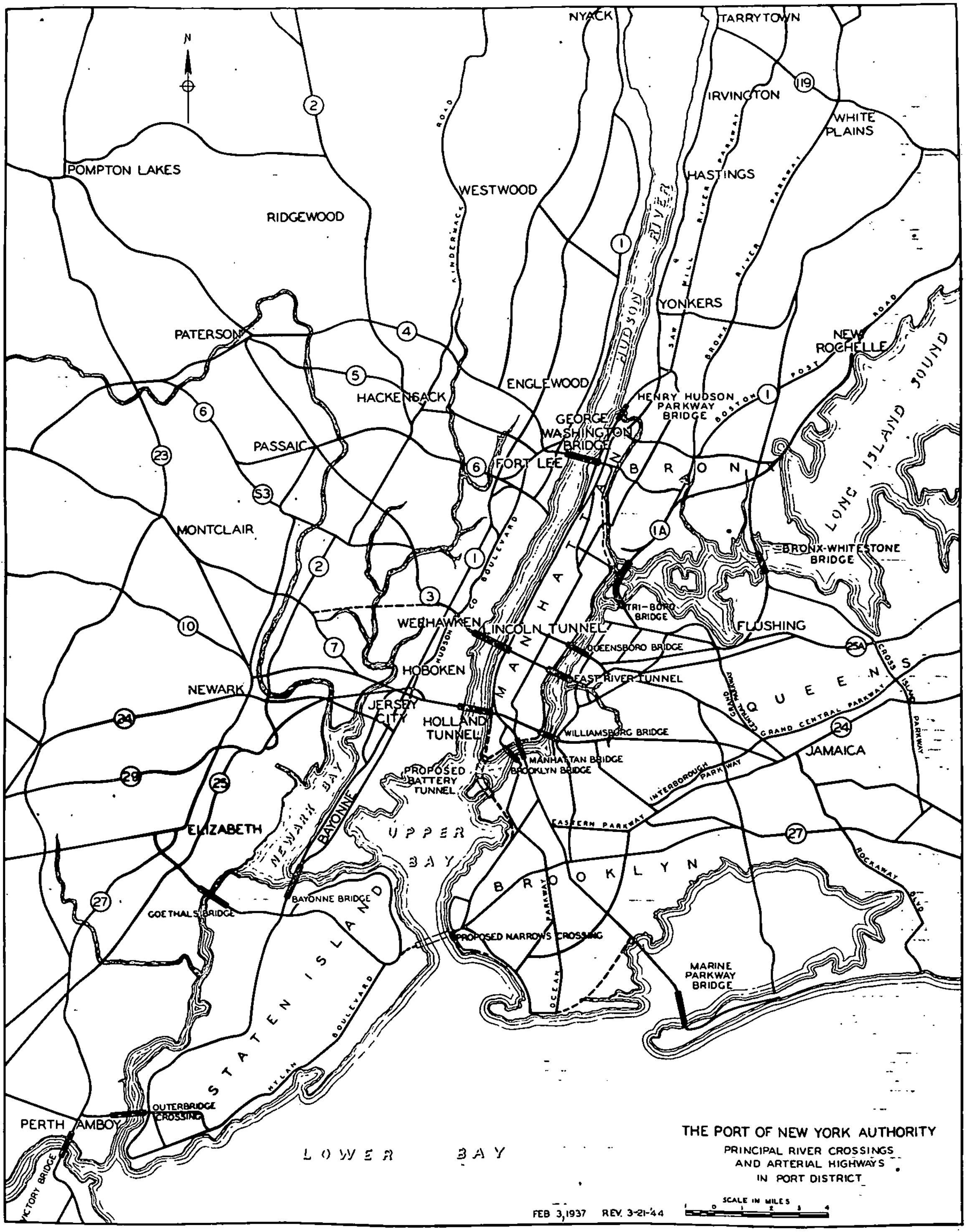

FIG. 1.—PRINCIPAL RIVER CROSSINGS AND ARTERIAL HIGHWAYS AT NEW YORK

construction. We have available today materials of far superior strength and quality than 50 or 100 years ago.

The suspension bridges of the early 19th century were built with wrought iron wire having a strength of only 40 to 60,000 lbs. per square inch. In the Brooklyn Bridge, steel wire was used for the first time with a strength of 160,000 lbs., and in the George Washington Bridge the strength of wire reached nearly 240,000 lbs. This is four times the strength of the early wrought iron wire, with which it would be impracticable to build the long modern spans.

There have been equally far-reaching improvements in the methods of fabrication and erection with the result that the time of construction has been greatly reduced. A striking comparison is furnished by the Brooklyn Bridge, built 60 years ago, and its approximate equivalent of recent construction, the Whitestone Bridge. The erection of the cables of the Brooklyn Bridge by the so called "spinning" process consumed 21 months. Since then the method has been applied to practically every large suspension bridge in this country, but has gradually been so perfected that in the Whitestone Bridge the spinning of the cables consumed less than 1½ months. The Brooklyn Bridge foundations, which were sunk to depths of 78 feet by the then novel pneumatic caisson process, required two years; those of the Whitestone Bridge sunk to twice that depth, or 160 feet, consumed less than one year. The entire period of construction of the Brooklyn Bridge was 13 years, that of the Whitestone Bridge less than 2 years.

In passing upon the merits if the various great bridges of New York I cannot but touch upon their architectural or aesthetic value. Besides the monumental public buildings and the large skyscrapers, there are no structures which have influenced the appearance of the city and furnished historic landmarks as much as its great bridges.

Unfortunately, this has not always been recognized and engineers in particular are much to blame for the truly unattractive or even atrocious appearance of some of our bridges. This situation has changed in the last 25 years. Under pressure of public opinion, bridge engineers have been forced to give serious attention to aesthetic design. This effort has been creditably aided by the manufacturing industry, notably the American Institute of Steel Construction which since 1926 has instituted an annual prize award for the most beautiful steel bridges built during the previous year.

As a consequence, many of the bridges created in recent years are very creditable structures aesthetically and several of New York's great bridges are universally recognized for their fine appearance.

There are no particular laws or theories which govern the aesthetic design of bridges. It is largely a matter of artistic conception, which is intensely individual and changeable. Nor can it be dealt with on general principles without regard to the local scenery or landscape. We can only be guided by such precedents which appeal to our sense of beauty coupled with a common sense of what is simple and natural.

Some years ago a visitor to the George Washington Bridge looked admiringly at its cables and asked the speaker: "How did you or the architect come to design such a beautiful curve?" I had to reply that it was God's own work, that neither the engineer nor the architect could improve that beautiful natural catenary of the suspended cable. The same applies to the graceful parabolic curve of an upright arch or the simple straight line of a beam.

One of the first and major design problems which confront the planners of a large bridge is the type of structure most suitable and economical for any particular location. In some cases this question can be decided only on the basis of comparative preliminary design studies by the same engineers. This procedure was resorted to in the case of New York's two great arches, that across the Hell Gate and that over the Kill van Kull at Bayonne. In both cases the possibilities of the arch, cantilever and suspension types, were thoroughly investigated. In the final selection due weight was given to the respective aesthetic merits. For the Bayonne Bridge the comparison was even extended to different types of arches.

In the case of some of the other bridges numerous studies made from time to time by different engineers furnished a wealth of information which was helpful in the final selection.

Today it is well recognized that for very long spans and in particular for bridges carrying highway and electric rail traffic the suspension type, when properly designed, offers such outstanding merits that its superiority, both economically and aesthetically, is obvious. This was unmistakably so in the case of the George Washington Bridge so that no competitive designs were required. It is not surprising, therefore, that six out of the nine larger bridges of New York (those of 1,000 ft. span and over) belong to the suspension type. In the case of the other three bridges the suspension type proved a close competitor of the adopted design.

Brooklyn Bridge

The Brooklyn Bridge across the East River marks the first of New York's outstanding bridges. It was a formidable undertaking at that time and the culmination of many years of effort.

A bridge between Manhattan and Brooklyn had been talked about for more than a century, but it was not until after the experience of the severe winter of 1866/67 which tied up transportation across the East River that the two cities took definite steps toward its building. John A. Roebling was selected as the engineer who prepared the plans and initiated the building of the structure.

With its span of 1600 feet, 540 feet longer and a capacity far in excess of any bridge built before, it marked a milestone in bridge building and was hailed as one of the wonders of the world. On its opening in 1883, after 13 years of construction, a public holiday was declared in New York and Brooklyn and the event was celebrated by the greatest procession on land and water that New York had witnessed.

Besides establishing new records for span and capacity it embodied a number of novel features. Among them was the first use of steel wire for the cables with a strength of 160,000 lbs. per sq. in. (75% more than the previously used wrought iron wire). For the first time also the wires were protected by a galvanizing coating which is largely responsible for their excellent state of preservation. The method of "spinning" the cables in the air, which had been devised and applied previously by Roebling, was greatly improved in the Brooklyn Bridge. The building of the piers by the pneumatic process to a depth of 78 feet was one of the first applications of this process to a large bridge foundation.

The Brooklyn Bridge has more than fulfilled the expectations of its designers. It has now been in operation without major changes or repairs for over 60 years, and during many years it carried a load more than twice that for which it was originally planned.

Aesthetically, too, it has remained one of the finest structures of its kind and still forms one of the cherished landmarks of New York.

The bridge was recently subjected to a thorough investigation of its physical condition with a view to determine its present capacity

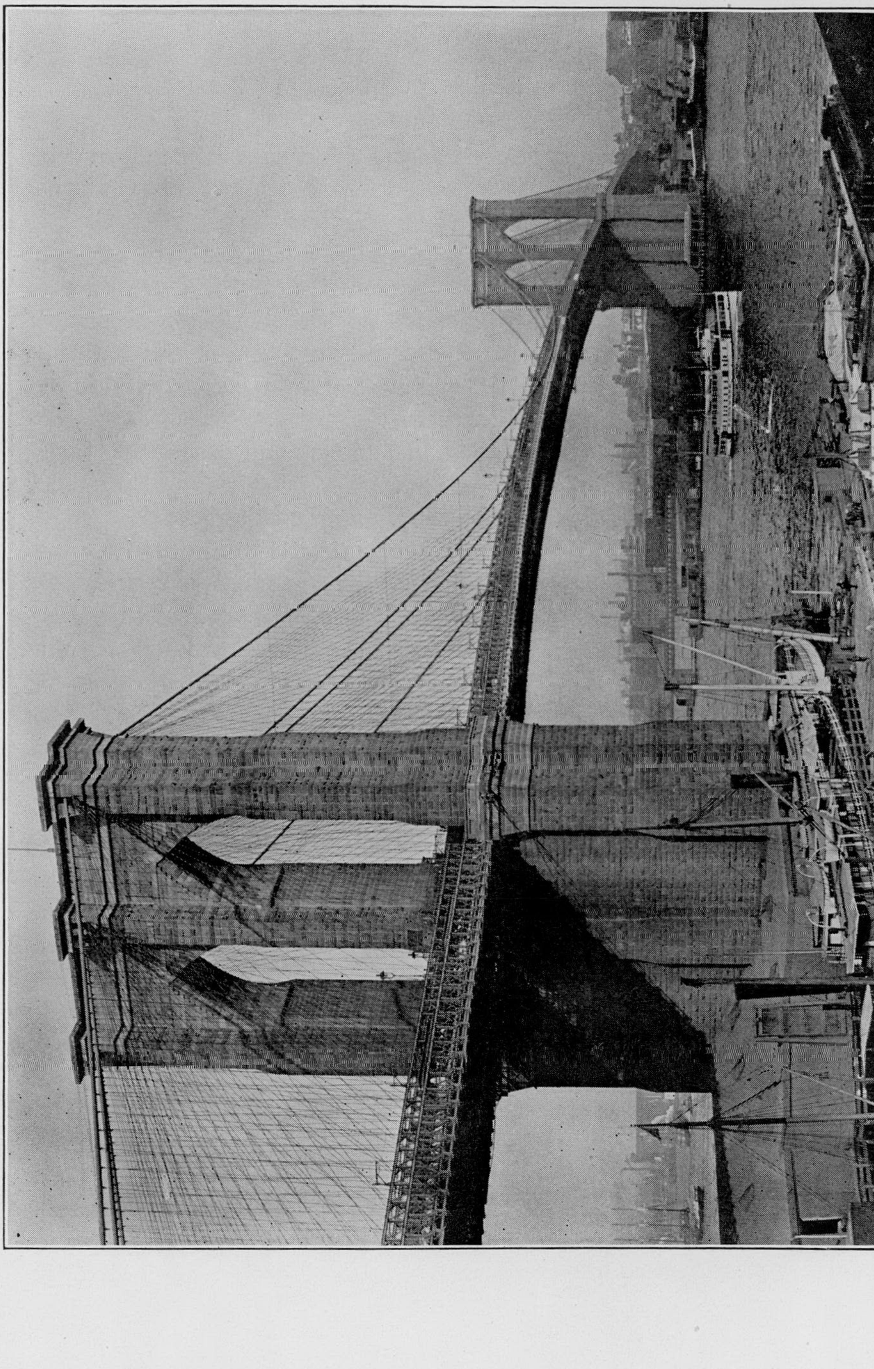

Fig. 2.—Brooklyn Bridge

to carry highway traffic alone, and the possibilities for increasing that capacity, the elevated railroad tracks having now been removed.

The examination revealed an excellent condition of the main carrying parts, the cables, towers and anchorages. The suspended structure, and particularly the stiffening trusses, however, have become very inadequate and antiquated. At the time they were designed the modern theory of suspension bridges had not yet been developed and very crude approximate methods were employed. Furthermore, the system adopted for the Brooklyn Bridge is an extremely complex and highly indeterminate one, so that it is impossible even today to determine the stresses with any degree of accuracy.

The bridge acts today as three independent single spans—interaction between spans is impossible because the roller bearings on top of the towers have become fixed or "frozen" and the towers are too rigid to yield longitudinally.

The stiffening system is a complex combination of trusses along the floor and diagonal stay ropes attached to the tops of the towers. The latter, together with the trusses, which are also fixed to the towers, form cantilever arms and thus relieve in part the loads carried by the cables. The interaction between cables, stays and trusses is thus very uncertain.

The trusses have double diagonals of which the counters are adjustable. In the course of time they have been adjusted rather promiscuously and thus uncertain initial stresses were imparted not only to them but also to the main diagonals and the chords.

The stress action is further complicated by the fact that there are six stiffening trusses. Two shallow ones are in the planes of the two other cables, two high ones are in the planes of the inner cables and two high ones are between the inner and outer cables. The distribution of loads between them has thus to be effected through the floor beams which subjects the latter to uncertain stresses.

It is not surprising, therefore, that in the course of time, and particularly during the period of heavy loads, many members of the floor and trusses broke and had to be replaced. This brings out the advantage inherent in the suspension type of bridge that such breakages did not result in failure of the structure or even in interruption of the traffic.

The Brooklyn Bridge will continue to serve limited automobile and trolley car traffic without major alterations for many years to come. By complete reconditioning of the suspended structure, and possibly the cables, but with retention of the towers and anchorages, it can be strengthened to serve unrestricted modern highway traffic without changing its characteristic appearance.

WILLIAMSBURG BRIDGE

For 21 years the Brooklyn Bridge stood as the only link across the East River. Towards the beginning of this century the demand for additional crossings became so urgent that within six years three more great bridges came into existence.

The first one, the Williamsburg Bridge, also of the suspension type, was completed in 1904. It has a central span about 5 feet longer than the Brooklyn Bridge and is simpler and more certain in its stress action. But that is about all that can be said in its favor.

Aesthetically it is the one bridge which New York can be least proud of. Apparently little or no attention was given to its appearance. Technically and economically also it is contrary to modern conceptions of design in almost every major respect.

The cables extend from the tower tops to the anchorages as long straight backstays, and the side span floor structure, instead of being suspended more economically from the cables, is supported on altogether too conspicuous independent steel trusses and bents.

The clumsy-looking main steel towers are the last representatives of the conception that suspension bridge towers must be rigid. Since such towers are not sufficiently flexible to bend under the longitudinal motions of the cable saddles, the latter had to be placed on rollers which are expensive and unsatisfactory. This conception had its justification in the case of masonry towers of the old suspension bridges, but not in modern steel construction.

The exceptionally deep, very rigid and therefore uneconomical stiffening trusses reflect the culmination of the tendency of that time to design suspension bridges as rigid systems, such as simple spans, cantilevers or arches. This tendency sacrificed the economic advantage of flexibility inherent in the suspension system, especially for long and heavy spans.

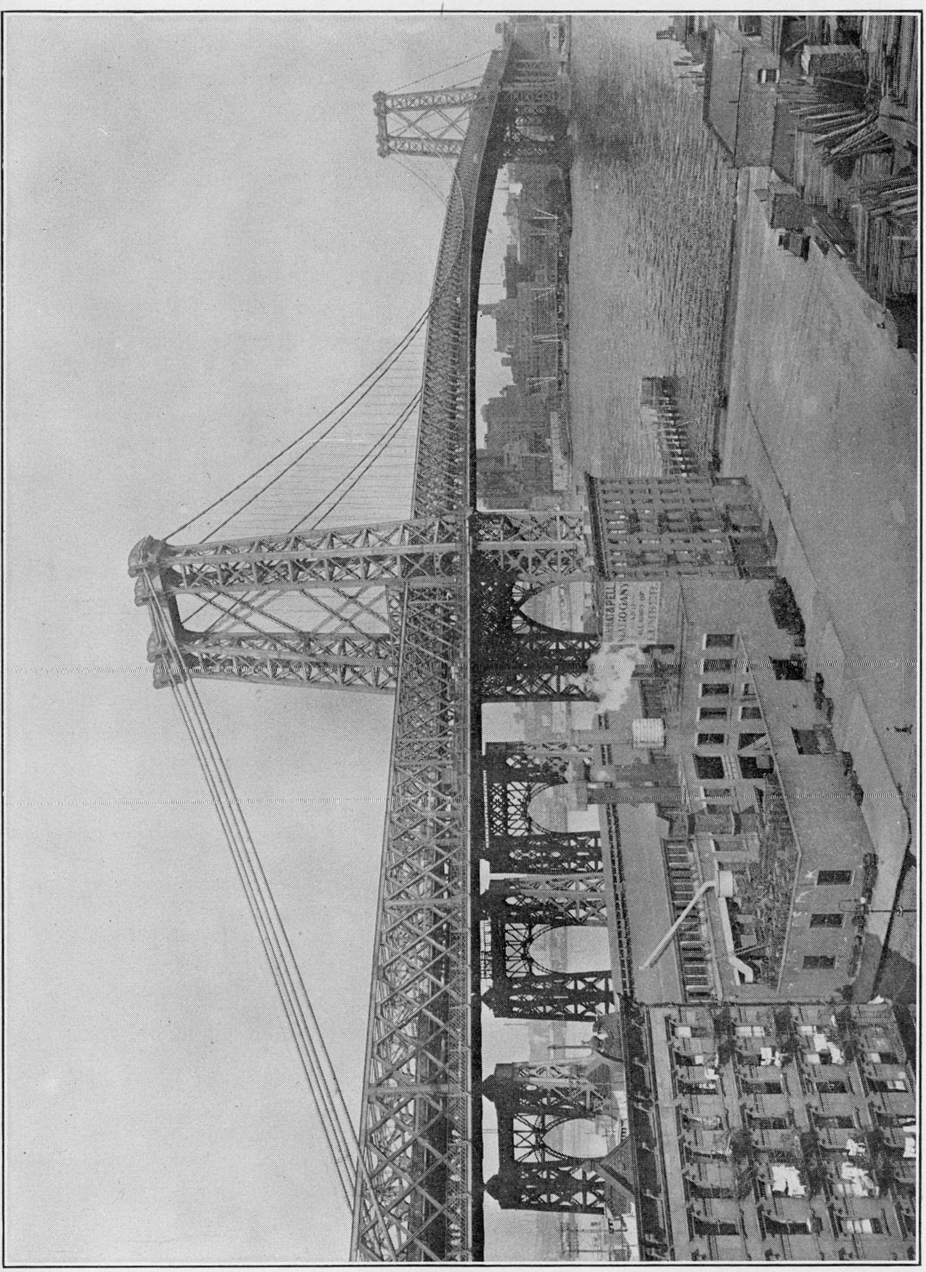

FIG. 3.—WILLIAMSBURG BRIDGE

MANHATTAN BRIDGE

The Manhattan Bridge, located only 1/4 mile north of the Brooklyn Bridge, is the third great suspension bridge across the East River. It was completed in 1910. Its span of 1470 feet is less than that of the two older bridges, but it outranks them in its great traffic capacity, viz., eight tracks for trolley cars and rapid transit, a four lane roadway and two footwalks. It embodies important improvements in design and may be considered the first large suspension bridge which was proportioned in accordance with modern theories. The objectionable features of the Williamsburg Bridge were avoided in this structure, viz.:

The floor structure in the side spans is completely suspended from the cables, which is more economical and produces superior appearance.

One of the novel features of the Manhattan Bridge are the slender flexible steel towers. These towers are flexible enough so that they can bend safely forward and backward, in some cases several feet, without overstraining. This type has now become common in modern suspension bridges.

The stiffening trusses, while according to present knowledge still somewhat too deep and rigid, were made considerably more flexible than those of the Williamsburg Bridge. This was productive of greater economy and better appearance. The Manhattan Bridge is the first American suspension bridge in the proportioning of which the so-called "deflection method" was used in place of the previously common "elastic method". The economy of the deflection method is the greater the more flexible the stiffening girders or trusses and the greater the dead load to live load ratio. It becomes therefore particularly important in heavy long span bridges. In the case of the Manhattan Bridge it was found that the moments in the stiffening trusses were reduced at some points by nearly 40% by using the deflection method.

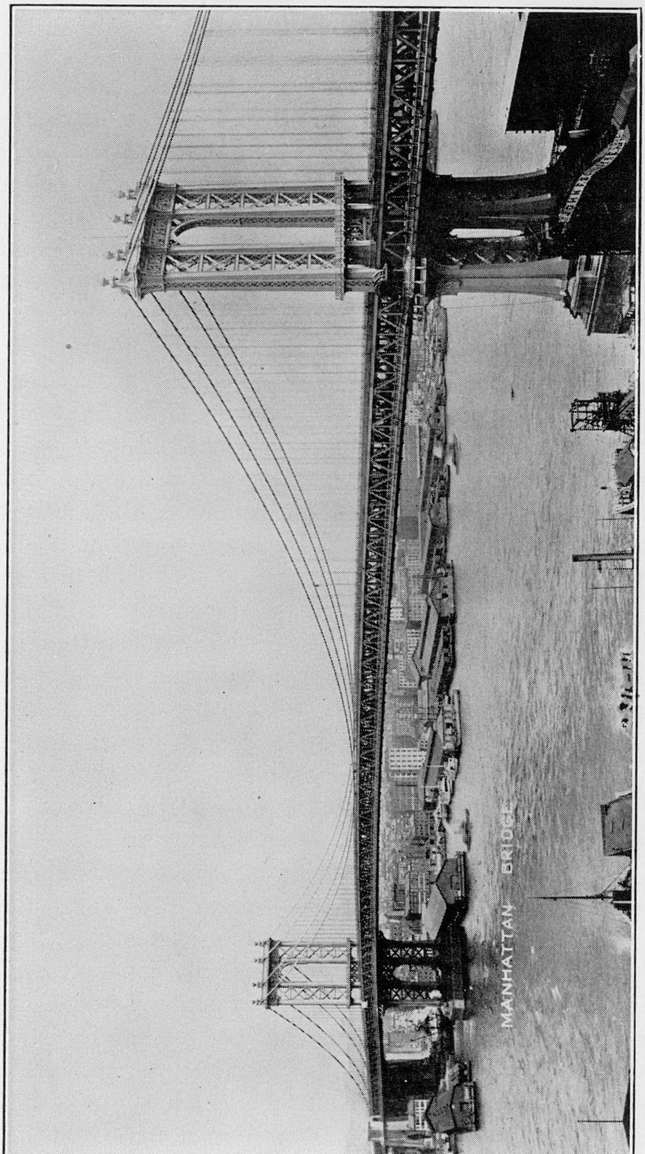

Fig. 4.—Manhattan Bridge

Triborough Bridge

The Triborough Bridge is the fourth suspension bridge across the East River. It was opened to traffic in 1936. With its center span of 1380 feet it is somewhat shorter than the older bridges, but with eight lanes for vehicular traffic it surpasses all in highway capacity. It is the first large bridge built for highway traffic exclusively.

The Triborough Bridge is the most outstanding example of a large modern bridge planned and built with extensive approaches and highway connections. Its construction involved an expenditure of over 60 million dollars, of which only about 8 millions were consumed by the bridge proper.

The approaches include a lift bridge across the Harlem River, one of the largest of its kind; also a fixed bridge across the Bronx River which can be converted into a lift bridge when necessary, and about 2½ miles of plate girder viaducts on concrete piers.

The Triborough Bridge is also notable as an example of radical and extensive changes made in the design while construction was under way. The original plans, prepared by the Department of Plant and Structures of the City, called for a double deck structure throughout with an aggregate capacity of 16 lanes of vehicular traffic.

Construction on the basis of these plans was started in 1929. By 1934 the foundations of the bridge proper and the approach viaducts had been completed, and the steel towers were in course of fabrication and erection, when the project was turned over to the newly formed Triborough Bridge Authority which was to finance the balance of the undertaking with the aid of the Federal Government on a self-liquidating basis. As Chief Engineer of the Authority I was asked to make a thorough review of the plans. This review, which included a traffic study, revealed that a 16-lane capacity was far beyond what would be required for a long time to come and far in excess of the traffic that could be economically concentrated at one crossing. Furthermore, the approaches and highway connections as planned, especially at the Manhattan end, proved utterly inadequate to accommodate safely even half that capacity.

It was therefore decided to limit the capacity to 8 lanes and to utilize the saving involved, over 10 million dollars, for the extension of the approaches and highway connections.

A completely new boulevard was added south along the Harlem

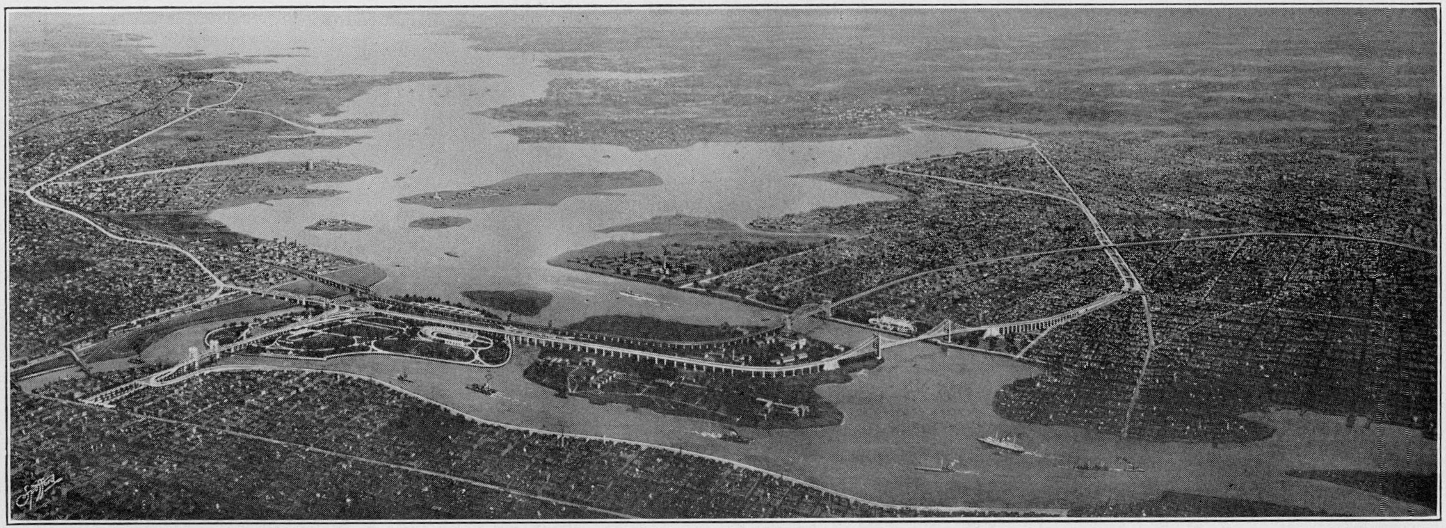

FIG. 5.—TRIBOROUGH BRIDGE AND APPROACHES

River through highly developed territory in Manhattan and the approach was so designed that it could eventually be connected with a corresponding boulevard to the north, as planned by the City.

In the original double deck design the bridge proper was to have four cables and four deep stiffening trusses. Correspondingly the towers consisted of frames with four legs, the inner ones forming a joint column. In the new design the number of cables of the main bridge was reduced to two and the tower design changed accordingly, but in such a way that very little of the material already manufactured had to be scrapped.

The four stiffening trusses, which appeared to be excessively deep and rigid, were reduced to two considerably shallower and more flexible ones. This reduced their cost to about one-fourth and in itself permitted a saving of about 1 million dollars. Experience has shown since that they could safely have been made even more flexible.

The old rather ornamental design of the anchorages was greatly simplified and an attempt was made to give them a modernistic functional appearance.

George Washington Bridge

Bridging the Hudson River, which has about twice the width of the East River, was a more formidable undertaking. It had been the dream of engineers for more than a century. Toward the end of the last century, concrete efforts were made to promote a bridge principally for railroad traffic and as a private undertaking.

Best known among them was the project of Gustav Lindenthal, who, for the first time, proposed a single span 3000 feet long without piers in the river. He obtained a Federal Charter in 1890, after a thorough investigation of its practicability had been made by a board of eminent engineers appointed by President Cleveland. Several attempts to finance the project failed, largely because it proved impossible to secure the essential participation of the principal railroads.

In the meantime, the art of building subaqueous tunnels had been advanced so that it became practicable, and for railroad tracks more economical, to tunnel through the bed of soft silt of the Hudson River.

In 1906 the States of New York and New Jersey appointed Interstate Commissions to study the practicability of a highway crossing. This resulted in 1918 in the financing by the two States of the "Holland

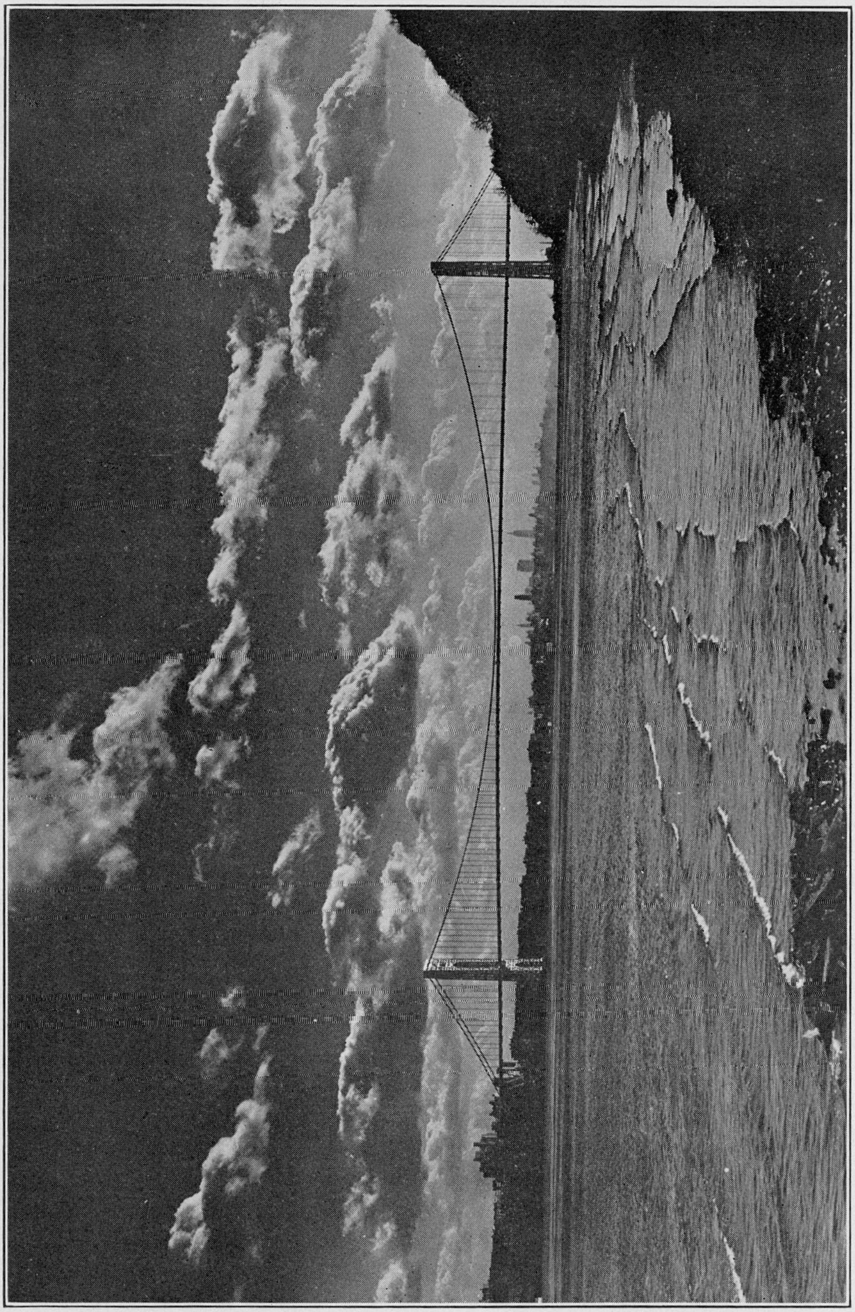

Fig. 6.—George Washington Bridge

Tunnel" in the lower part of Manhattan. This location was at that time the center of the heaviest trans-river vehicular traffic and the logical location for a tunnel on account of the low land on both sides of the river.

Before the Holland Tunnel was completed in 1927, however, a tremendous automobile traffic had developed between New Jersey and the upper part of Manhattan, and again various proposals were advanced to meet this situation. As a result of a proclamation by the Governors of New York and New Jersey in 1924 The Port of New York Authority was authorized to build the first bridge across the Hudson River, now named the George Washington Bridge. Its construction was started in 1927 and completed at a cost of about 60 million dollars within 4½ years.

The George Washington Bridge is located in a magnificent landscape, between two historically interesting points, Fort Washington in New York and Fort Lee in New Jersey. Although the river is narrowed at that point by the projecting rock ledge of Fort Washington Park it required a length of 3500 feet to span the river. This nearly doubled the longest span which had been built up to that time, and marked another important milestone in bridge construction. On the basis of its suspended mass, reflecting its longer span, as well as its great carrying capacity, the George Washington Bridge has a magnitude about eight times that of the old Brooklyn Bridge. To use another popular comparison, the cable wires of the Brooklyn Bridge, stretched out, would reach about half way around the earth, those of the George Washington Bridge would go four times around it, or half way to the moon.

The bridge is designed for two decks of which only the upper one is now built and the lower one can be added in the future. The upper deck provides for an eight-lane roadway and two footwalks. The lower one can be utilized for four rapid transit tracks or for additional roadway lanes.

In spite of the great advance in magnitude the construction of the George Washington Bridge presented no major new problems, although it gave ample occasion for controversies among engineers and architects.

One of the most heated discussions centered about the question of wire versus eyebars for the great cables. Up to that time all long span suspension bridges had been built with wire cables, although a number of designs with eyebars had been proposed. There were then available at relatively low price heat-treated eyebars of a minimum ultimate strength of 105,000 lbs, per sq. in., almost twice the strength of ordinary carbon steel, and comparative estimates indicated that, although heavier, they could well compete with wire cables. In order to widen competition, it was decided to prepare complete competitive detail plans for the two types of cables, which also involved double plans for towers and anchorages. The bidding revealed the wire cables to be cheaper, but only because in the low bid the previously prevailing price of wire had been so reduced, undoubtedly as a result of the competition, as to effect a reduction in cost of 2 million dollars.

The two pairs of wire cables have the unprecedented size of 36 inches in diameter and the average strength of the wire is over 230,000 lbs. per sq. in., nearly 50% greater than that used in the Brooklyn Bridge. The cables were erected by the now familiar and highly developed method of spinning in the air.

As in several previous bridges the wire rope suspenders (3 in. in diameter) were utilized temporarily as cables to support the so-called catwalks, but a novel feature was introduced by prestressing the ropes. This eliminated permanent stretch which, on account of their great length of the suspenders, could cause appreciable uncertain stresses in the suspended structure. Prestressing of such ropes has now become a common practice.

The most important departure from conventional design is embodied in the stiffening system of the George Washington Bridge, or rather in the absence of such a system in its present state. Preliminary studies indicated that because of the great weight of the cables and floor structure, which is five times the heaviest moving load that can possibly come on the bridge, the deflections under live load were relatively so small that for the ultimate double deck conditions with rapid transit tracks exceptionally shallow stiffening trusses, located between the two decks, would provide ample rigidity and that for the initial single deck for highway traffic only, stiffening trusses could be omitted altogether. This, incidentally, is in part responsible for the extremely light appearance of the bridge in spite of its great suspended mass.

Compared to the conventional stiffening trusses, such as were used in the Manhattan and other more modern suspension bridges, this permitted a saving of around 10 million dollars, for, as I have previously explained in connection with the Manhattan Bridge, the greater the flexibility of the trusses the greater the reduction in the moments and stresses if the correct deflection theory is used. Furthermore, in a span of this size every pound saved in the suspended structure saves a pound of more expensive material in the suspenders, cables, towers and anchorages.

I must point out that in determining upon this relatively great flexibility only the effect of live load was kept in mind, and experience in the 12 years existence of the bridge has fully demonstrated that it has ample rigidity under all conditions of traffic. I shall later refer again to this question of flexibility of the stiffening system in discussing its bearing on dynamic wind reaction.

Bronx-Whitestone Bridge

The Bronx-Whitestone Bridge across the East River near its juncture with the Long Island Sound is the latest and most modern of the suspension bridges of New York. It was completed in 1939 after only 2 years of construction.

With its span of 2300 feet it surpasses all other East River bridges and, with the bridge across the San Francisco Bay, now ranks third among the great suspension bridges of the country.

Like the Triborough Bridge it was planned not merely as a river crossing, but as a new traffic artery, five miles long, and includes, among other interesting structures, a modern bascule bridge across Flushing Creek. It also accommodates highway traffic only, but has a capacity of only six vehicular lanes.

Structurally it is of utmost simplicity. Every effort was made to avoid all trussing, diagonal bracing and latticework. All members of the steel floor structure and towers are built up of solid plate sections. In place of the customary diagonal bracing the tower frame has solid web portals above and below the floor. Care was taken also to avoid obstruction to view from the bridge floor, sideways and overhead, so that in riding over the bridge travelers might enjoy to the fullest extent the spendid scenery and an unobstructed sky. The anchorages, in contrast to the elaborate architecture of other suspension bridges,

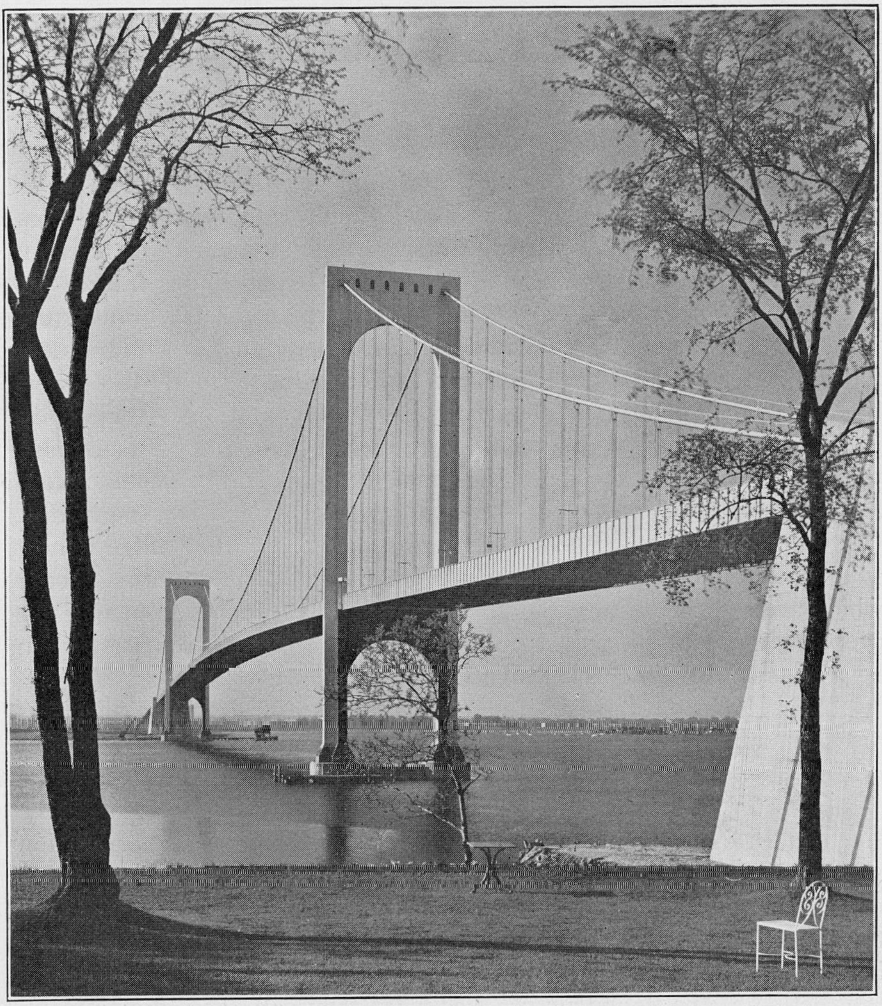

FIG. 7.—BRONX-WHITESTONE BRIDGE

were designed as plain concrete blocks indicating clearly their function to resist the pull of the cables.

A novel feature for a span of this length was the use of relatively very flexible, solid-web, stiffening girders in place of the customary deeper and more rigid stiffening trusses. I shall discuss this feature somewhat at length because it involves a problem which has been drastically brought to the attention of the profession by the failure of the Tacoma Bridge in 1940.

In adopting this greater degree of flexibility for the Whitestone Bridge the designers were encouraged by the experience with the George Washington Bridge which, although heavier, has now no stiffening whatsoever and which had shown ample rigidity under all conditions of highway traffic. In that respect their judgment was correct. The Whitestone Bridge too has proven amply rigid under traffic.

The designers were not aware, however, of the possibility that the bridge might not be sufficiently rigid under dynamic wind action. Shortly after the floor was erected and became a solid deck wave motions began to appear under certain wind conditions. While perfectly harmless, as far as their effect on the structure is concerned, they were on a few occasions of sufficient amplitude to be objectionable in their effect on people standing on or crossing over the bridge. Certain stiffening devices were then introduced and the bridge is now sufficiently rigid so that only on very rare occasions do motions occur which are noticeable to the public. Plans for additional stiffening are prepared and will be carried out as soon as the necessary material can be released by the Federal Government.

While this developed, the Tacoma Bridge of similar design was already under construction. However, while its span was 500 feet longer, its weight was only half that of the Whitestone Bridge and the flexibility of its girders much greater. Following the failure of the Tacoma Bridge under wind actions there developed much speculation and theorizing about what features or deficiencies in the design were responsible. The first general reaction was that the bridge was much too narrow, its width to span ratio of 1:72 having been far less than in any other suspension bridge. Others advanced the opinion that the section of the floorstructure was what they call "aero-dynamically unstable", blaming in particular the solid plate girders as the cause.

There have since followed several official investigations, as well as many individual theoretical studies and some experimental research. Under the auspices of the Federal Public Roads Administration a committee of engineers has been formed which has already done considerable work towards clearing up the problem and the setting up of appropriate design limitations.

From the mass of data and expressions of opinion already on hand it is evident that the profession is confronted with one of the most complex problems and one which can only be solved fully by empirical experience derived from actual structures, supplemented by extensive experiments on large scale models.

Such data as are available indicate unmistakably that neither the narrowness of the bridge, nor the particular shape of the floorstructure is the primary cause of excessive motions. The predominant factor is vertical rigidity, which is controlled by the dead weight suspended from the cables and the stiffness of the stiffening girders.

I have made a study of some 40 suspension bridges of widely varying spans and other properties, including all of some 17 bridges for which I have been able to find data and which have either failed or experienced motions under wind action. These bridges have been classified in accordance with a stiffness index which I believe is a rational approximate expression of their relative resistance against dynamic wind.

This classification shows remarkable consistency with the actually observed behavior of at least those bridges which have shown motions. Based on this empirical analysis it is possible to design any suspension bridge with safety and adequate resistance against aerodynamic motions and with greater economy than has been applied in the majority of existing suspension bridges. Further investigations will undoubtedly furnish data which will permit refinements in design and economies which may be appreciable in very long spans.

One important lesson has been learned, viz. that in long span suspension bridges, in particular, those carrying highway traffic only, the required degree of rigidity is no more determined by the moving loads, but by dynamic wind action.

Queensboro Bridge

Besides the six great suspension bridges New York has three large bridges of the rigid type, all of which are unusual structures and embody important advances in design and construction.

The Queensboro Bridge, the only one of the cantilever type, was the fourth bridge across the East River. It was completed in 1909 almost at the same time as the Manhattan Bridge, but about four miles farther north across Blackwell's Island.

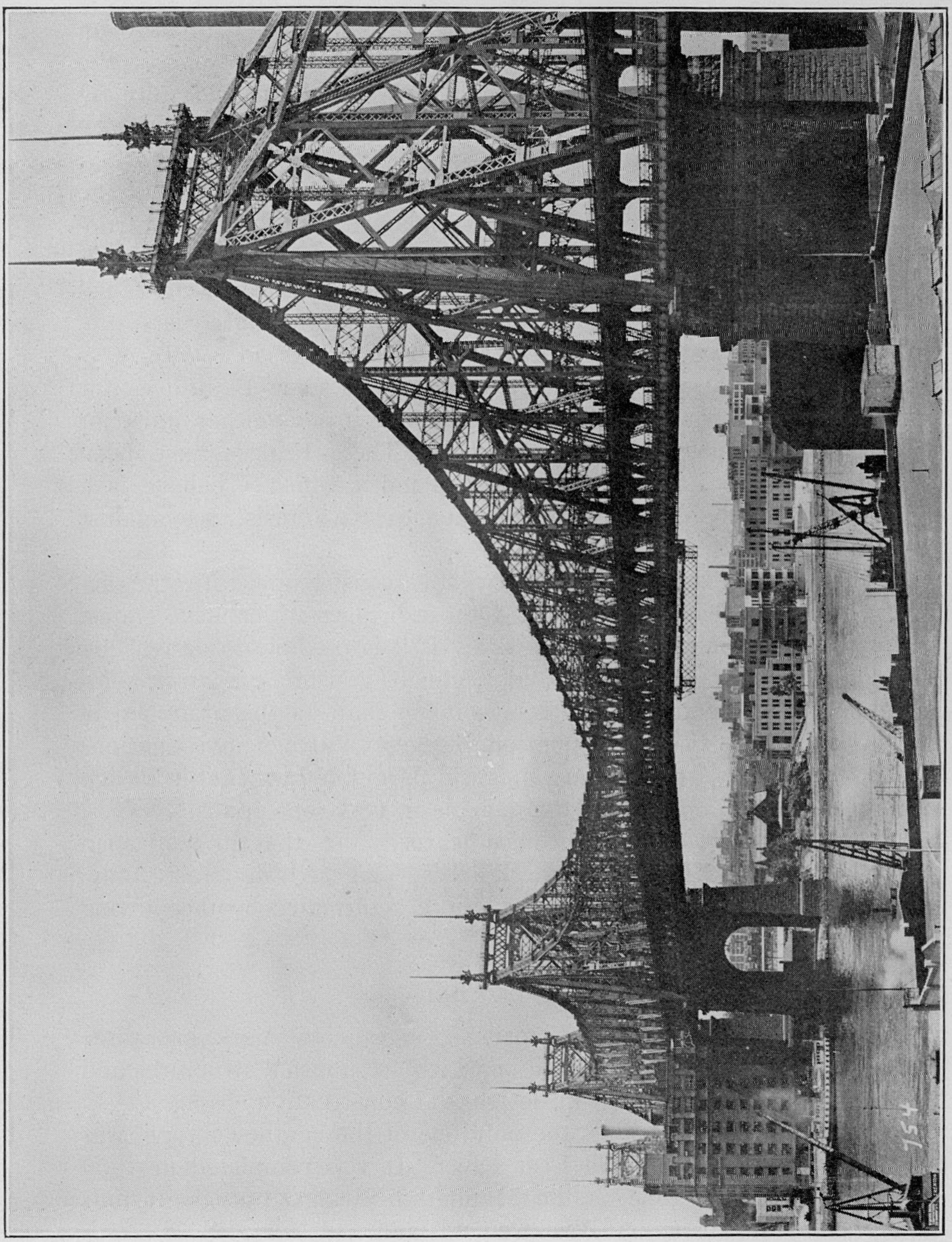

FIG. 8. QUEENSBOROUGH BRIDGE.

The island offered opportunity for intermediate piers and comparatively short spans about 1200 and 1000 feet across each of the two arms of the river and thus favored the cantilever. The design is unique. It is the only large cantilever bridge with five spans. Another unique feature is the omission of suspended spans, the cantilever arms meeting at the centers of the two main spans.

As a cantilever the Queensboro Bridge is well proportioned. However, it cannot hide the general clumsiness inherent in this type of bridge with its massive proportions and its dense network of truss members and bracings, when compared with the graceful arch or a suspension bridge of modern design.

Among its novel features was the first practical application of nickel steel for the eyebar chains which form the tension top chords. This boosted the strength of material available for such members about 50% and marked an important advance in long span bridge construction.

The Queensboro Bridge was still under construction when in 1907 the world was startled by the collapse of its nearest relative, the greatest cantilever bridge then also under construction across the St. Lawrence River at Quebec. That failure was caused by the buckling of one of its main compression chords. The buckling occurred under a unit stress of only 18,000 lbs. per sq. in., about ½ the yield point or 1/3 of the ultimate strength of the material. The most thorough investigation which followed revealed certain serious defects in the design, fabrication and method of erection of such chords of large size. The latticing which connected the various parts composing a compression member was at that time proportioned entirely by rule of thumb method and proved to be utterly inadequate in members of the then unprecedented size used in the Quebec Bridge. Coupled with this the joints of the chords were inadequately spliced and they were fabricated and erected in such a manner that reliance had to be placed on the gradual closing of the joints as the stress increased. This gave rise to large and very uncertain secondary stresses.

These disclosures gave rise to concern about other large cantilevers, above all the Queensboro Bridge. Two independent investigations were instituted and while they revealed defects similar to those of the Quebec Bridge they were found to be far less serious. Nevertheless it was considered advisable to open the structure with two of the four proposed rapid transit tracks omitted and in their place much lighter footwalks were eventually erected.

The Queensboro Bridge is now carrying the most voluminous highway traffic of any of New York's bridges, over 20 million vehicles per annum.

Hell Gate Bridge

When in 1910 the Pennsylvania Railroad extended its line from New Jersey into and through Manhattan to Long Island it decided to connect its system also with the New Haven Railroad in the Bronx so as to gain direct access to New England. This necessitated crossing the East River at the so-called Hell Gate, where the river is narrowed by Wards Island.

Gustav Lindenthal, the builder of many notable bridges, designed the magnificent arch with the then unprecedented span of nearly 1000 feet. It was 160 feet longer and many times heavier than the famous arch across Niagara Falls which was swept off its bearings by a mass of moving ice a few years ago.

The Hell Gate Arch is a sturdy looking structure because it carries four tracks for heaviest railroad traffic, which required great rigidity. Nevertheless the arch has graceful lines and with its monumental tower portals is an impressive structure.

The Hell Gate Bridge is a two-hinged arch of which the bottom chords form the main carrying members. Because of the exceptionally heavy load and the long span these members required unprecedentedly heavy sections, 80% heavier than those of the old Quebec Bridge which had failed. The lessons learned in that failure were applied by setting up severe requirements for the detail design, fabrication and erection of Hell Gate Bridge trusses, and in this respect the Hell Gate Bridge marked a great improvement over previous practice.

The sections were made up as far as practicable of solid webs, latticing being avoided where possible. Where that was not practicable the latticing was made of rigid sections instead of the previously customary flat bars and they were proportioned by a scientific formula instead of by rule of thumb.

Instead of the previously customary practice of splicing compression chords by nominal splicing material of only 25% of the section of the member or even less, the splices in the Hell Gate Arch were proportioned for 100%.

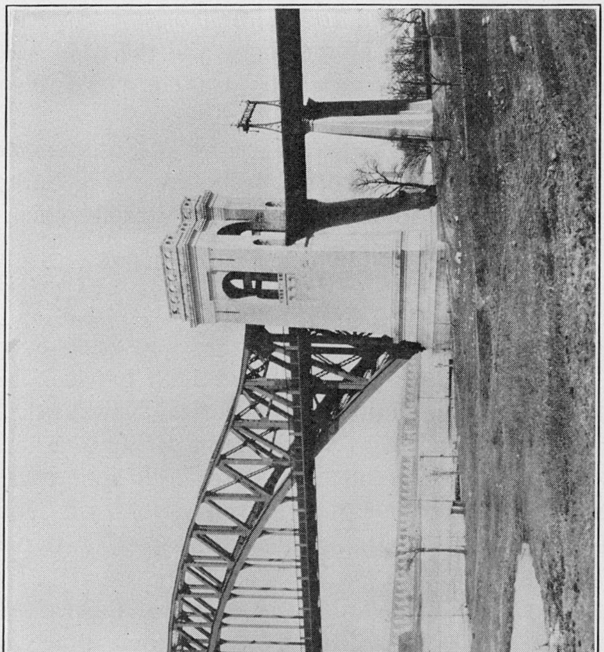

FIG. 9.—HELL GATE BRIDGE

To assure perfect fitting of the joints and riveted connections large sections of the trusses were, for the first time in American bridge practice, completely assembled at the shops and the rivet holes drilled or reamed in that position. Large gantry travelers of 150′ span were especially built for this purpose.

The Hell Gate Bridge was also an example of unique erection by the cantilever method. The temporary backstays were built with the use of exceedingly small amount of extra material which did not form part of the permanent structure.

Bayonne Bridge

The record breaking Hell Gate Arch has now been outranked in span by the great arch across the Kill van Kull between New York and New Jersey at Bayonne built by The Port of New York Authority simultaneously with the George Washington Bridge. The Bayonne Arch is 700 feet longer than the Hell Gate Arch and, together with the almost simultaneously completed arch across the entrance to Sydney Harbor in Australia, its span of 1850 feet is at present the longest arch in existence

It carries now a four-lane roadway and two footwalks, but has provision for two rapid transit tracks or in their place additional roadway lanes.

Besides its great span the Bayonne Arch embodies a number of innovations and improvements in design. Important among them is the introduction of a new high strength steel for compression members, the so-called manganese steel. It was used in the principal chords of the arch trusses. It was offered in competition with nickel steel of equal strength, but at a considerably lower price. The chord has a full-web box section. A half size member was tested in the 10 million compression machine of the Bureau of Standards in Washington as the heaviest column so far tested. It developed a buckling strength close to the capacity of the machine, or over 60,000 lbs. per sq. in., which is 10% higher than the prescribed yield point of the material. The great efficiency of the member is realized when we compare this strength with the 18,000 lbs. per sq. in., or less than one third, at which the chord of equivalent area of the old Quebec Bridge failed.

Another innovation in a bridge of the arch type was the use of prestressed wire ropes for the long floor suspenders in place of the

FIG. 10.—BAYONNE BRIDGE

customary stiff, riveted-up I-section. While construction of the bridge was already under way the report was received of the breaking of built-up floor suspenders in the smaller, but similar, arch bridge at Tacony Palmyra near Philadelphia which had just been completed. Investigation indicated that the breaking of these built-up, but relatively slender, suspenders was due to horizontal oscillations set up by aerodynamic action. As a result of this experience the Bayonne Arch suspenders were redesigned by substituting wire ropes which have proven entirely successful.

A third unusual feature is the complete omission of sway bracing between the two arch trusses for the length of the suspended portion of the floor. The efficiency of such bracing had long been a controversial question. In order to test it and also to check the complex stress condition in the arch, principally that due to horizontal loads, a complete brass model of the arch with its bracing was made and the stresses under both vertical and horizontal loads were measured by extensometers. The results were highly satisfactory and left no doubt about the propriety to omit the sway-bracing.

The Bayonne Arch also offered opportunity for a unique erection procedure, a combination of temporary falsework and cantilever erection. Over the portions of the river which permitted temporary obstructions single falsework bents, successively moved to different positions, supported the arch in such a manner as to avoid a statically indeterminate condition at any stage. The falsework bents were made up almost entirely of floor members of the permanent structure. Over the river channel the arch was completed by cantilevering out from both sides.

Conclusion

This completes a sketchy picture of the notable bridges of New York and some of the unusual problems which were encountered in their design and construction. The thought I should like to leave behind is that bridge engineering is not, as popularly assumed, an exact science. While ordinary structures are closely controlled by ample experience and experiments, every structure which projects into new and unexplored fields of magnitude involves new problems, for the solution of which neither theory nor practical experience can furnish an adequate guide. It is then that we must rely largely on our judgment and if as a result errors or failures occur we must accept them as a price for human progress.

OF GENERAL INTEREST

PROCEEDINGS OF THE SOCIETY

MINUTES OF MEETING

Boston Society of Civil Engineers

APRIL 17, 1945.—A Joint Meeting of the Boston Society of Civil Engineers with the Northeastern Section, American Society of Civil Engineers was held this evening at the 20th Century Association. Sixty members and guests attended the meeting and dinner.

President William M. Bassett of the Northeastern Section, American Society of Civil Engineers presiding at the Joint Meeting called upon President Carroll A. Farwell, of the Boston Society of Civil Engineers to conduct any BSCE matters of business.

President Farwell announced the death of the following member:—

William F. Covil, who was elected a member February 19, 1930, and who died March 23, 1945.

President Bassett then resumed the chair and called upon Mr. Howard Williams. Secretary, for announcements.

President Bassett then introduced the speaker of the evening, Honorable Jarvis Hunt, former President of the Massachusetts Senate Counsel for Massachusetts Committee for Port Development, who gave a talk on "The Port of Boston and Its Redevelopment."

Adjourned at 9:10 P. M.

EVERETT N. HUTCHINS, *Secretary*

JUNE 6, 1945.—A regular meeting of the Boston Society of Civil Engineers was held this evening at the Twentieth Century Association, this date having been adopted in place of the regular third Wednesday of May. One hundred six members and guests attended the dinner and meeting.

President Carroll A. Farwell presiding, introduced the speaker of the evening, Major Waldo J. Bowman, Editor *Engineering News-Record,* who gave a talk on "The Engineering Contribution to Victory in Europe."

Mr. Bowman went over to the European Theater of Operations last December, arriving at the time of the Battle of the Bulge, and stayed through the winter and early spring living with various Engineer units that were doing the work described in his address. He was at the Remagen bridge the day before it fell and spent the next ten days before the assault crossing at Wesel on reconnaisance with the Engineers along the two hundred mile stretch of the Rhine from Remagen to Wesel.

The talk was illustrated by about 50 slides portraying the Engineering achievements that permitted us finally to gain the great objective—the crossing of the Rhine—achievements which included the rebuilding of the Atlantic ports and of the transportation systems —highway, rail, canal and pipe-line— that connected these ports with the front.

Many interesting phases of these great undertakings were brought out further by questions which Mr. Bowman answered very graphically.

The meeting adjourned at 9:15 P. M.

EVERETT N. HUTCHINS, *Secretary*

SANITARY SECTION

OCTOBER 4, 1944.—A meeting of the Sanitary Section was held this evening at the Society Rooms at 7:00 P. M., following an informal dinner gathering at Patten's Restaurant. Twenty-six persons attended the meeting.

Chairman Gibbs introduced the speaker of the evening, Mr. Ralph M. Soule, Assistant Sanitary Engineer, Massachusetts Department of Public Health, who gave a very interesting talk on "Effects of 1944 Hurricane on Water Supplies in Southeastern Massachusetts."

After a considerable discussion, the meeting adjourned about 8:40 P. M.

GEORGE C. HOUSER, *Clerk*

MARCH 7, 1945.—A meeting of the Sanitary Section was held this evening at the Society Rooms at 7:15 P. M., following an informal dinner gathering at the Ambassador Restaurant. Thirty-eight persons attended the meeting with twenty-seven at the dinner.

The report of the Executive Committee on the activities of the Section for the past year was read by the Clerk, accepted and placed on file.

The Chairman then called upon Mr. Joy to read the report of the Nominating Committee. This committee, consisting of C. F. Joy, Jr., Chairman, C. O. Baird, Jr., and G. W. Coffin, submitted the following nominations for officers for the ensuing year:

Chairman: Murray H. Mellish
Vice-Chairman: Walter E. Merrill
Clerk: George C. Houser
Executive Committee: George F. Brousseau, Frederick S. Gibbs, William E. Stanley

Upon motion duly made and seconded, it was voted that the Clerk cast one ballot for the list of nominees submitted by the Nominating Committee.

The speaker of the evening was Walter E. Merrill, Major, C. E., U. S. Army—Senior Sanitary Engineer, Massachusetts Department of Public Health. Major Merrill presented a most interesting, illustrated paper, entitled "Water Supply and Sewage Disposal at Uncle Sam's Army Bases in the Caribbean Area."

After some discussion the meeting adjourned about 8:40 P. M.

GEORGE C. HOUSER, *Clerk*

DESIGNERS' SECTION

APRIL 11, 1945.—A joint meeting of the Designers' Section, the Highway Section and the Northeastern University Section of the Boston Society of Civil Engineers was held at Northeastern University, 360 Huntington Avenue, Boston, at 7:15 P. M., following an informal dinner at Childs Old France Restaurant. Chairman Frank L. Lincoln of the Designers' Section presided.

Reading of the minutes of the previous meeting and the presentation of new business was dispensed with by all three sections in view of the lateness of the hour and the fact that the speaker had to catch an early train to Bangor, Maine.

Mr. Lincoln introduced the speaker of the evening, Mr. William L. Shannon of the Boston District Office, United States Engineer Department. Mr. Shannon, who is Chief of the Soils and Geology Section of that office, presented a very informative paper entitled "Frost Investigations at Dow Field, Bangor, Maine". The subject matter was illustrated by slides which tabulated the results obtained by the tests under various design and loading conditions and by a colored movie which demonstrated the actual testing operations and the reactions of the pavement under load. After a short open discussion period, the meeting, which was attended by 60 members and guests, adjourned at 9:20 P. M.

HENRY I. WYNER, *Clerk*

APPLICATIONS FOR MEMBERSHIP

[July 20, 1945]

The By-Laws provide that the Board of Government shall consider applications for membership with reference to the eligibility of each candidate for admission and shall determine the proper grade of membership to which he is entitled.

The Board must depend largely upon the members of the Society for the information which will enable it to arrive at a just conclusion. Every member is therefore urged to communicate promptly any facts in relation to the personal character or professional reputation and experience of the candidates which will assist the Board in its consideration. Communications relating to applicants are considered by the Board as strictly confidential.

The fact that applicants give the names of certain members as reference does not necessarily mean that such members endorse the candidate.

The Board of Government will not consider applications until the expiration of fifteen (15) days from the date given.

For Admission

LOUIS H. BERGER, Dorchester Center, Boston, Mass. (b. March 21, 1897, Boston, Mass.) Educated in grammar school, received private tuition by my father, private tutors at home and private tutors from the Massachusetts Institute of Technology. Began to learn the manufacture of large automatic rotary cylinder and flatbed printing presses, as well as of automatic machinery, at the age of 16, continuing for about five years. At age of 21 entered my father's business as a partner and also served as Vice-President until my father's death in 1922, when I was elected President of C. L. Berger & Sons, Inc. Member of Military Engineers; Charter member of the American Congress for Surveying and Mapping; Member of the American Society of Civil Engineers; Member of the American Society of Photogrammetry. At present President of C. L. Berger & Sons, Inc. Refers to *C. O. Baird, C. B. Breed, A. Haertlein, E. A. Gramstorff.*

Transfers from Junior

WILLIAM G. STEPHENSON, Needham, Mass. (b. August 9, 1904, Boston, Mass.) Graduated from Northeastern University, 1925, with degree of B.C.E. Experience, 1925-1934, construction engineer and building superintendent with such concerns as J. W. Duff, Inc., Simpson Bros. Corporation, also assistant town engineer at Watertown, Mass.; 1934-1942, self employed, designing, manufacturing and installing maps, system for merchandising transportation and communication systems, 1942 to present, construction engineer with Liberty Mutual Insurance Company, Boston, Mass. Refers to *C. O. Baird, C. E. Ell, C. J. Ginder, E. A. Gramstorff.*

DEATHS

WALDO E. BUCK	April, 1945
LOUIS F. CUTTER	June 26, 1945

ADVERTISEMENTS

The advertising pages of the JOURNAL aim to acquaint readers with Professional and Contracting Services and Sources of Various Supplies and Materials. You would find it of advantage to be represented here.

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BOSTON SOCIETY OF CIVIL ENGINEERS

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