Bridge Engineering

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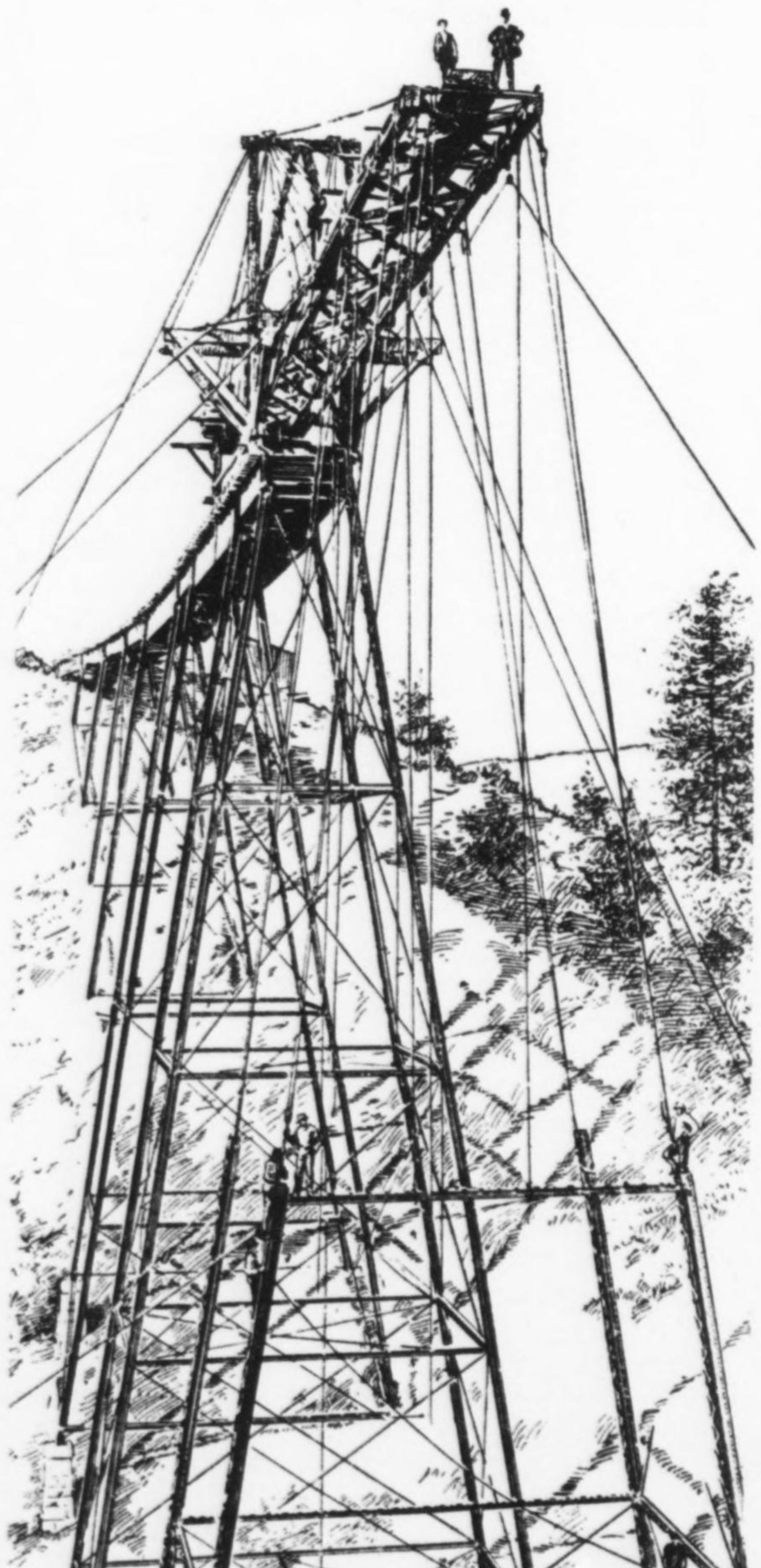
A RETROSPECT of bridge engineering during the last fifty years would present a record of unprecedented achievements, if space permitted. Only a few general facts and features can be given here. Let us consider what have been the distinctive features in the progress of design and construction of bridges in different countries during that period and what is their prospect for the future.

While bridge building as an art is as old as house building, bridge engineering as a science is hardly more than a hundred years old. The theoretical part had grown rapidly from empirical deductions and tests with models into the mathematical sciences of statics and graphics, which had already reached a high degree of perfection fifty years ago and have since then been developed so comprehensively that there is no field of stress analysis in bridge designing now left unexplored. What a rich mine of theoretical knowledge the literature of this field would appear to Telford and Stevensen, the first bridge engineers venturing to build long iron spans (1820-44), and even to Rankine, the great teacher of engineering (died 1872), whose theory of the stiffened suspension bridge came to America too late to influence the plans for Brooklyn bridge! Vast progress has also been made in the finesse of details and connections, in the testing and study of materials from which bridges are built.

Wood is passing out of use, with the indefensible wastage of our forests, as a material for bridges other than small or temporary structures. Fifty and more years ago wooden Howe trusses up to 200-ft. span (sometimes reinforced with wooden arches) and high wooden trestles were the prevailing pioneer types. Now the large sticks of lumber for them have become so scarce and dear that a Howe truss bridge would be a luxury, because more expensive than either an equivalent steel or concrete bridge. The latter materials have become dominant. Alloys steels, except for some parts in long spans, are, contrary to first expectations, little used in general bridge construction. Both theoretical and technological progress in bridge building have contributed to safety and economy.

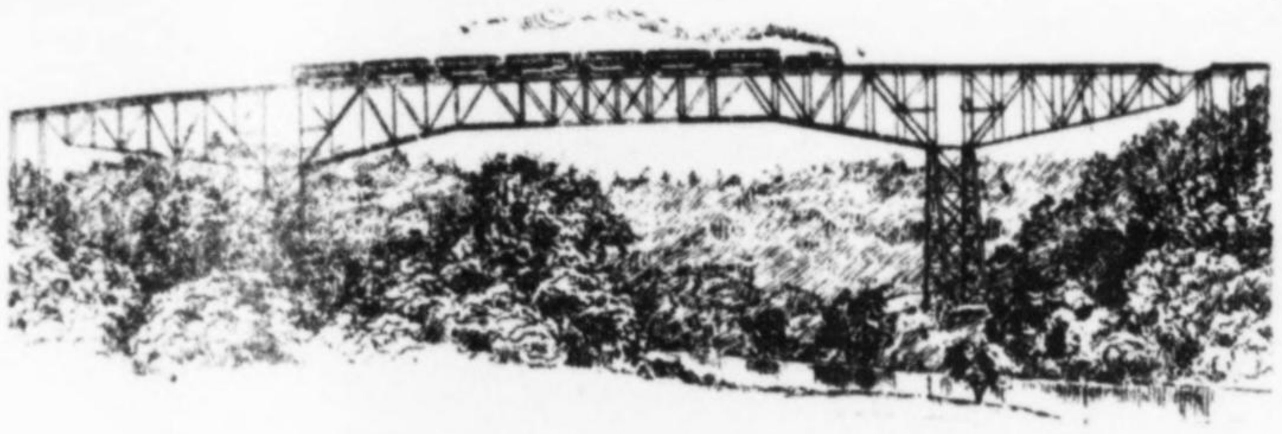


Erection of Buffalo Trace Viaduct
(From "Engineering News," May 25, 1889)

The oldest form, the stone arch, seems to have passed its apogee. Few large spans of that aristocratic type will likely be built, concrete being so much cheaper. The last and longest stone arch was the arcaded railroad bridge of 282-ft. span built in 1905 over the Isonzo river in Istria. That sterile region had for centuries produced highly skilled stone masons, whose work can be found all over Europe; with such labor it was feasible to erect the great arch to be self-sustaining in 48 hours. The bridge was destroyed in the war in 1916.

The greatest impetus to bridge construction in modern times came from the railroads. Since most countries have now all the railroads they can use, a decline in the number of new railroad bridges has already set in; but bridges for highways are being built in greater number than ever before, to meet the demands for improved road transportation with motor vehicles. All bridge construction, except for very long spans, has become standardized as to loads and stresses, quality of materials and workmanship.

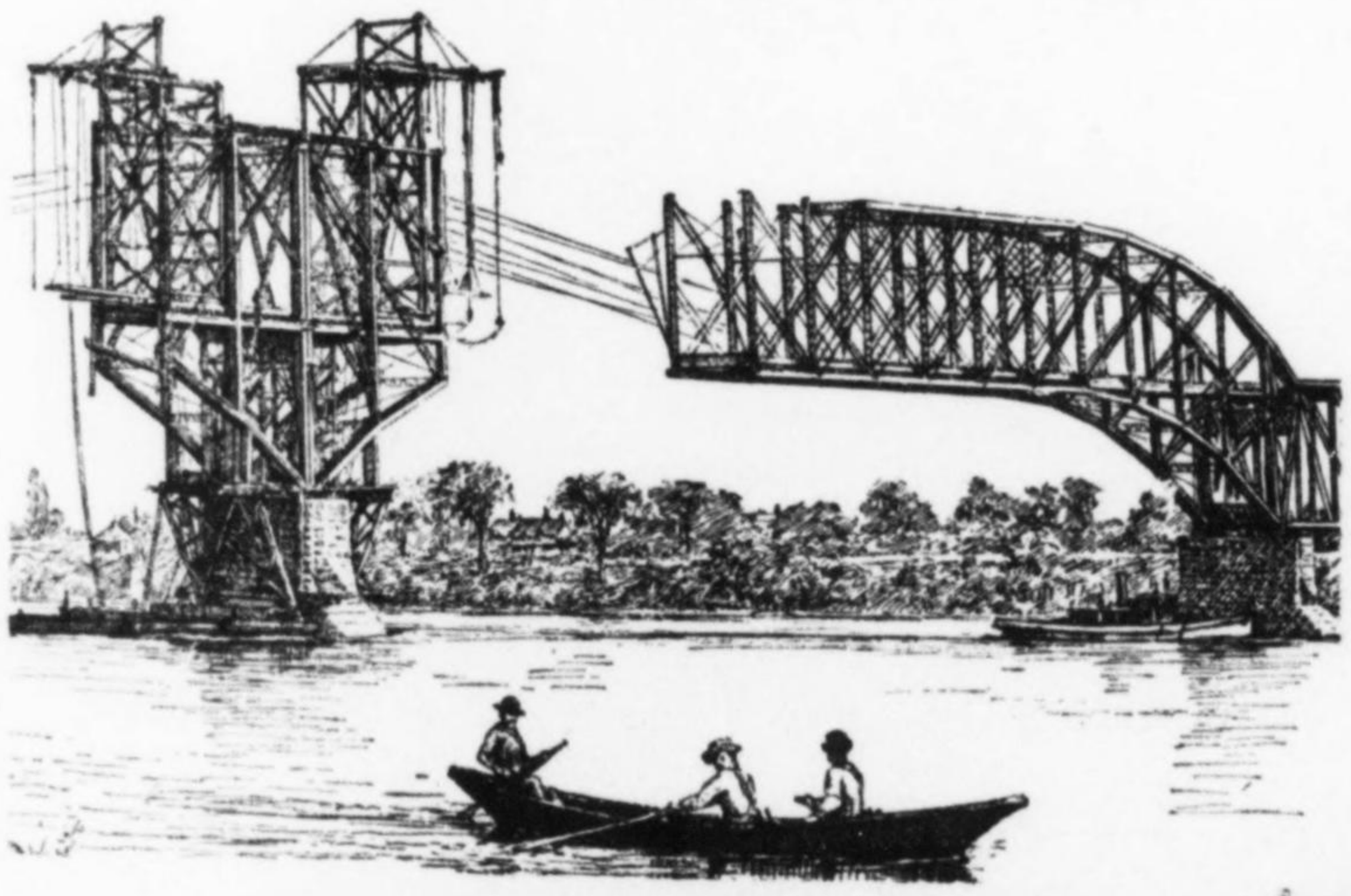
Up to half a century ago, cast iron was yet used in large quantities for compression members in building framed bridges. At the International Exhibition in Vienna (1873) the writer admired a fine model of the Ohio bridge at Louisville, showing the large Fink trusses with cast-iron compression members and with tension members of wrought-iron eyebars. It was the largest and last structure of this type. About the same time a stirring discussion was carried on in the technical journals here and abroad on the merits of the types used in this country and Europe, the European



Tyrone Cantilever Bridge, Kentucky River
(From "Engineering News" of April 8, 1890)

riveted girder type and the specifically American type of pin-connected trusses. Professor Winkler in Berlin, Professor Steiner in Prague on one side, and Charles Bender, Thomas C. Clarke and other bridge engineers in the United States on the other, were among the champions in that controversy, in which *Engineering News,* then in its babyhood, did not participate. Later came the controversy about statically determinate truss types as against those for which the stress ascertainment is based on the elastic properties of iron. American and European conditions for bridging and of fabrication and erection differed in so many respects that differences in methods were justified and finally came to be recognized. The American bridge types were adjusted to wide and capricious rivers, to long distances of transportation, high cost of labor and capital, the necessity of the structure earning an income as soon as possible, all of which made rapid execution necessary—and no type could surpass the pin-connected truss bridge in that respect. The erection of 300 to 500-ft. girders in a few days to be self-supporting appeared a wonderful feat to European engineers, accustomed to more leisurely methods.

But as bridge shop and erection facilities improved it came to pass gradually that pin-connected bridges lost some of their prestige because the more rigid riveted structures could be erected cheaper than pin-connected structures, except for very long spans. Economy of



Lachine Bridge Construction

maintenance caused massive masonry and concrete structures to be preferred, for shorter spans, to the cheaper iron and steel bridges, which require continuous inspection and painting—a constant large expense.

The last fifty years show the transition from wood and cast iron to wrought iron, steel and concrete as the principal materials for longer spans. Steel was first used in the St. Louis arch bridge, but as hard crucible steel, not suitable for smaller structures. It took ten years longer before a softer steel was recognized (1880) as preferable to wrought iron for bridges.

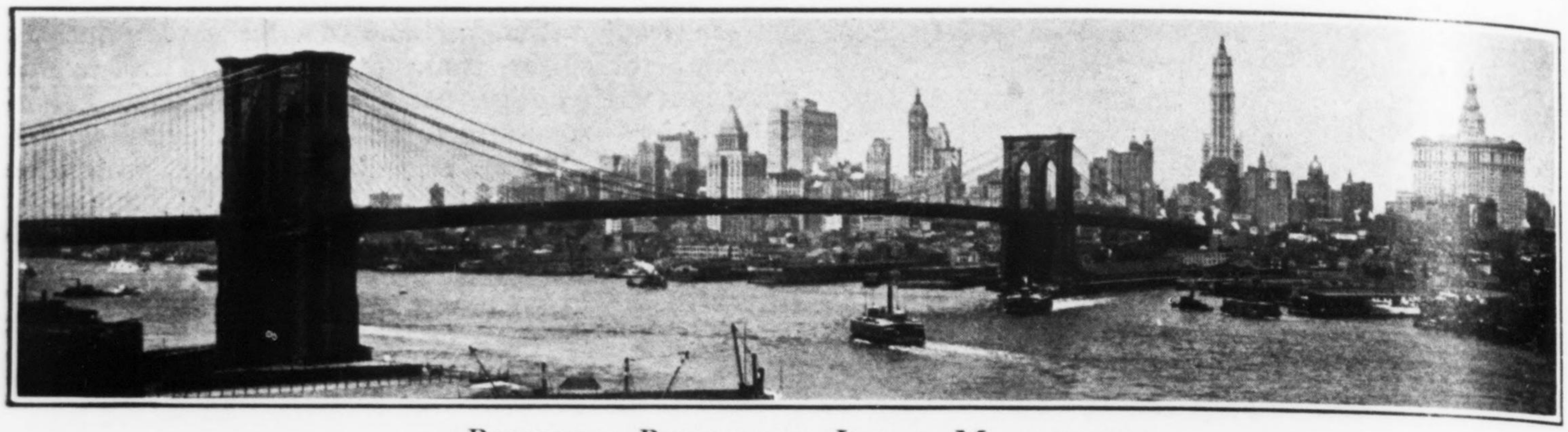
Two famous bridge structures in construction fifty years ago characterize the period; one was the great Brooklyn suspension bridge, which closed the period of massive high masonry towers, and the other the St. Louis steel arch bridge, which inaugurated the steel age for bridges. The plans of both structures evidence the desire for architectural dignity in contrast to unsightly commercial bridge types which had then commenced to acquire considerable prominence.

Eiffel's Garabit Arch

Iron, having little mass, is inferior to stone for esthetic forms. Iron towers would have been cheaper than stone towers for the Brooklyn bridge. The resources of the foundries, rolling mills and shops were adequate for their fabrication and erection. But fortunately solid granite towers were chosen, notwithstanding their greater cost. They are the largest and last of their kind. Their simple and rugged architecture give to the Brooklyn suspension bridge a distinction entirely missing in the two neighboring equally large suspension bridges built with steel towers, which appear prosaic and insignificant by comparison. If the Brooklyn bridge had similar iron towers it would appear in combination with its inferior suspended structure the shabbiest of all.

In the St. Louis arch bridge architectural beauty is likewise enhanced by the massive granite masonry of the river piers, flanked by the arcaded masonry approaches. The happy proportions of the three spans to each other, the middle span slightly larger and higher to produce a neat camber line for the roadway, the esthetically satisfying flat and slender arch ribs, and the altogether pleasing ensemble, evidence the thoughtful effort of the designer to create a magnificent structure. It also had many novel features of construction. It had the first and deepest pneumatic foundations in America, the diggers being exposed to over 50 lbs. of air pressure. The arch ribs have fixed ends and are of crucible steel, and were erected without falseworks by cantilevering. All

Construction of Washington Bridge, Harlem River, New York

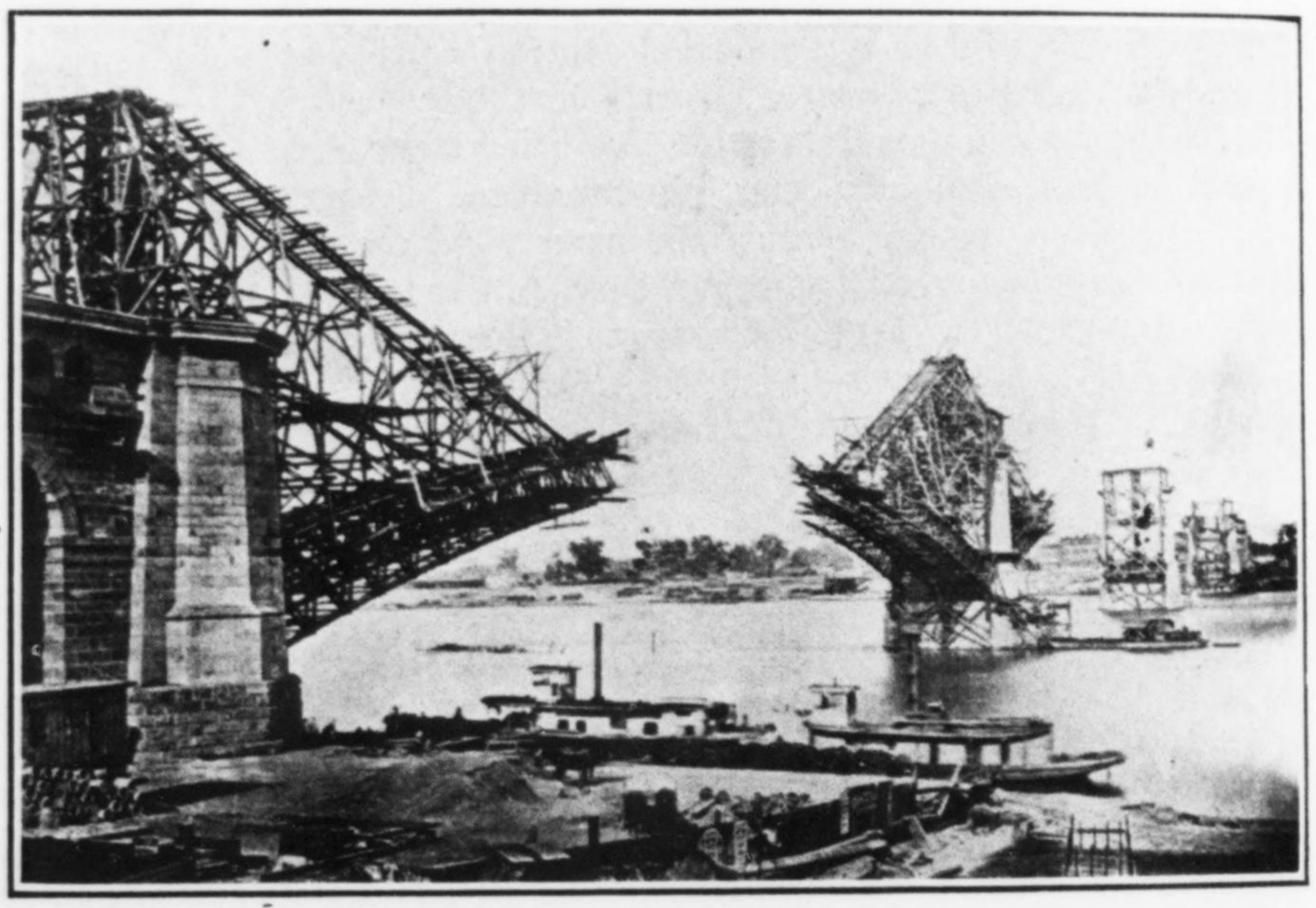


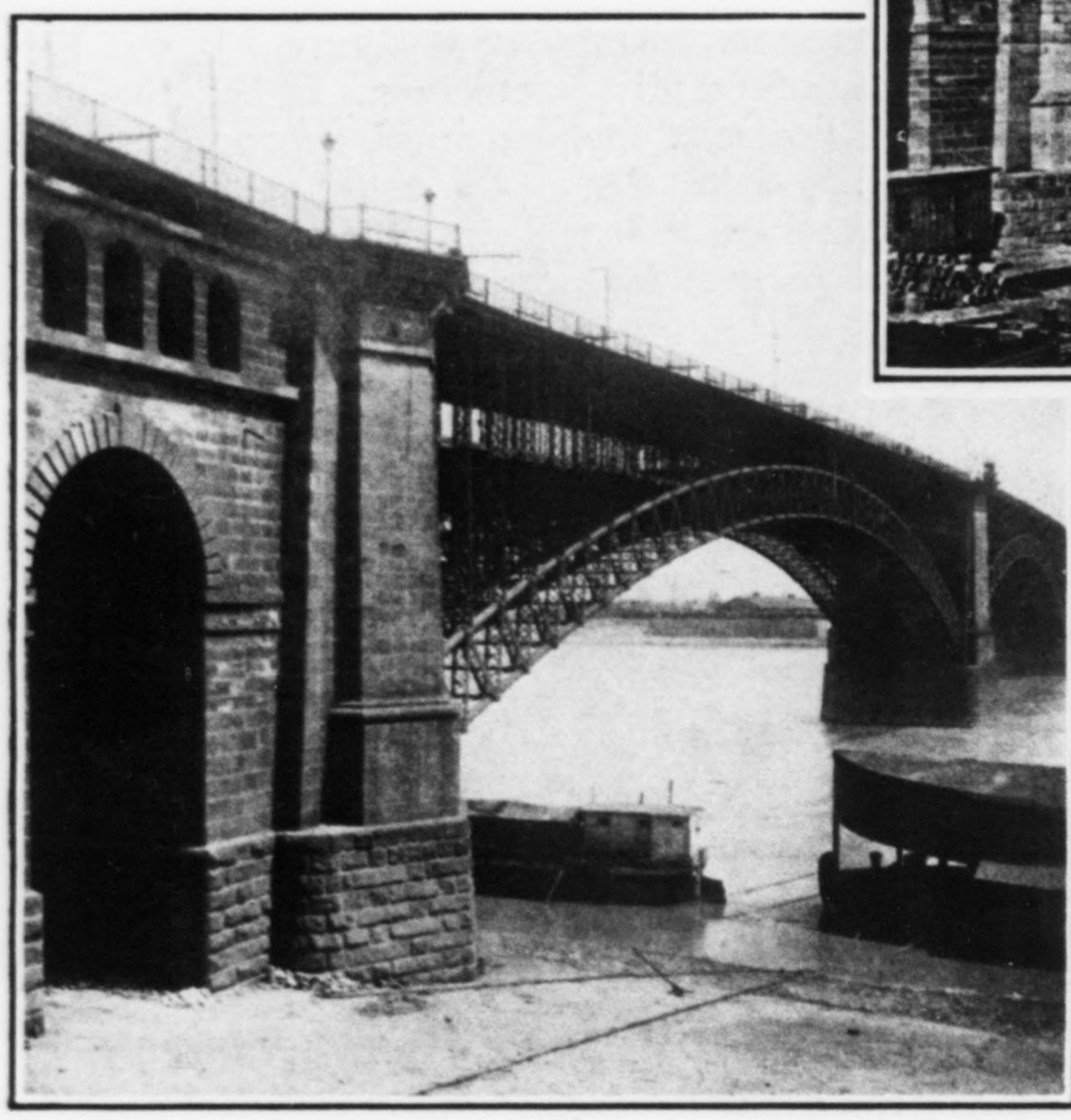
BROOKLYN BRIDGE AND LOWER MANHATTAN

material and work was tested with unprecedented precision.

The writer remembers with pleasure a call on Jacob Linville in 1874—Linville was one of the leading bridge engineers at that time and president of the Keystone Bridge Co., that had fabricated the superstructure for this bridge—and recalls the pride with which he exhibited and explained the plans and difficulties of this bridge, of which he and other prominent engineers had been severe critics during its execution. It was the writer's privilege to discuss later with Captain Eads and his loyal assistant Henry Flad the plans for this master work. Captain Eads, who had the true native engineering genius, and who originated and executed other engineering achievements, fully deserved the honor of the perpetuation of his name in the Hall of Fame.

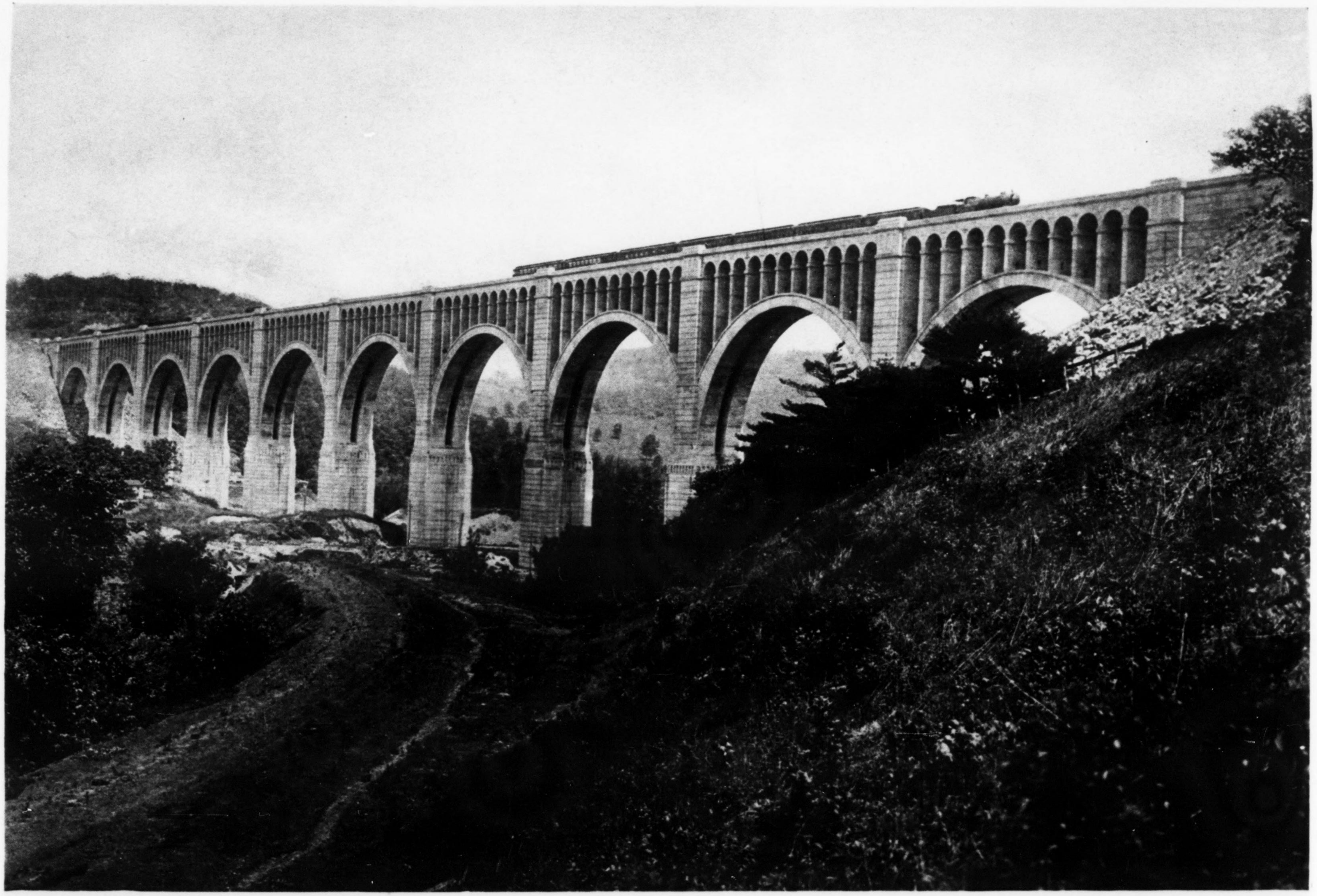
A word here on business morals of the past age. The Brooklyn Bridge was built with public money. It was the custom of the politicians of those days to send before election day a few hundred men to be employed as laborers, who were kept upon the payrolls until after the day after election. The engineers did not seem to know what to do with these voters, but they were satisfied to let them sit around and smoke their pipes, so long as they did not interfere with the regular workers. Was it any wonder that the bridge cost more than twice its estimated cost and took fourteen years for completion? It is only proper to say that in the last half century honesty in public work has greatly improved. The St. Louis bridge is an instance of an undertaking by private capitalists convinced of the great merit of the investment and confident of its ultimate profitableness. But for months after its completion railroad cars were ferried across the river as before. The company was deliberately forced into bankruptcy. The reward to the enterprising stockholders was the loss of their investment. The wealth created by genius and hard work went to a "great financier," all in perfect compliance with the tenets and tricks of law, as practiced by an old profession. Compare the reward of the sacrificing, idealistic builders with the reward of the disciples of high finance and practical business!



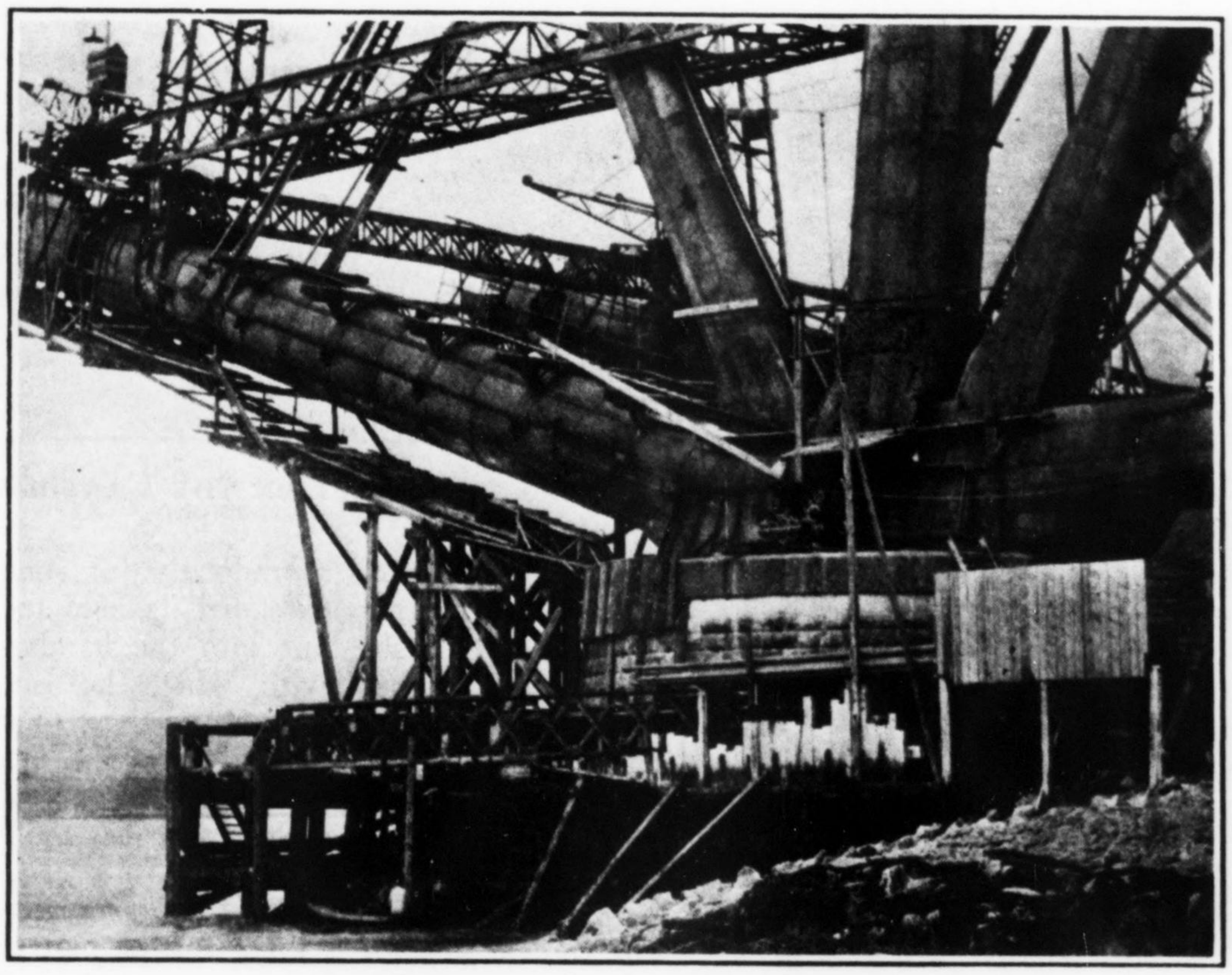


EADS BRIDGE IN 1874 (ABOVE) AND TODAY (LEFT)

Let us now note the efforts made in Europe during the last thirty years to obtain architecturally pleasing bridge structures. The rivers Rhine and Elbe are crossed by numerous beautiful structures; stately arch bridges at Coblenz and Mayence; turreted truss bridges at Strassburg and Cologne. Several arched girder and cantilever structures show tasteful architectural treatment. A noteworthy effort to obtain esthetic structures was made in connection with two large bridges over the



Tunkhannock Viaduct on the Lackawanna Railroad

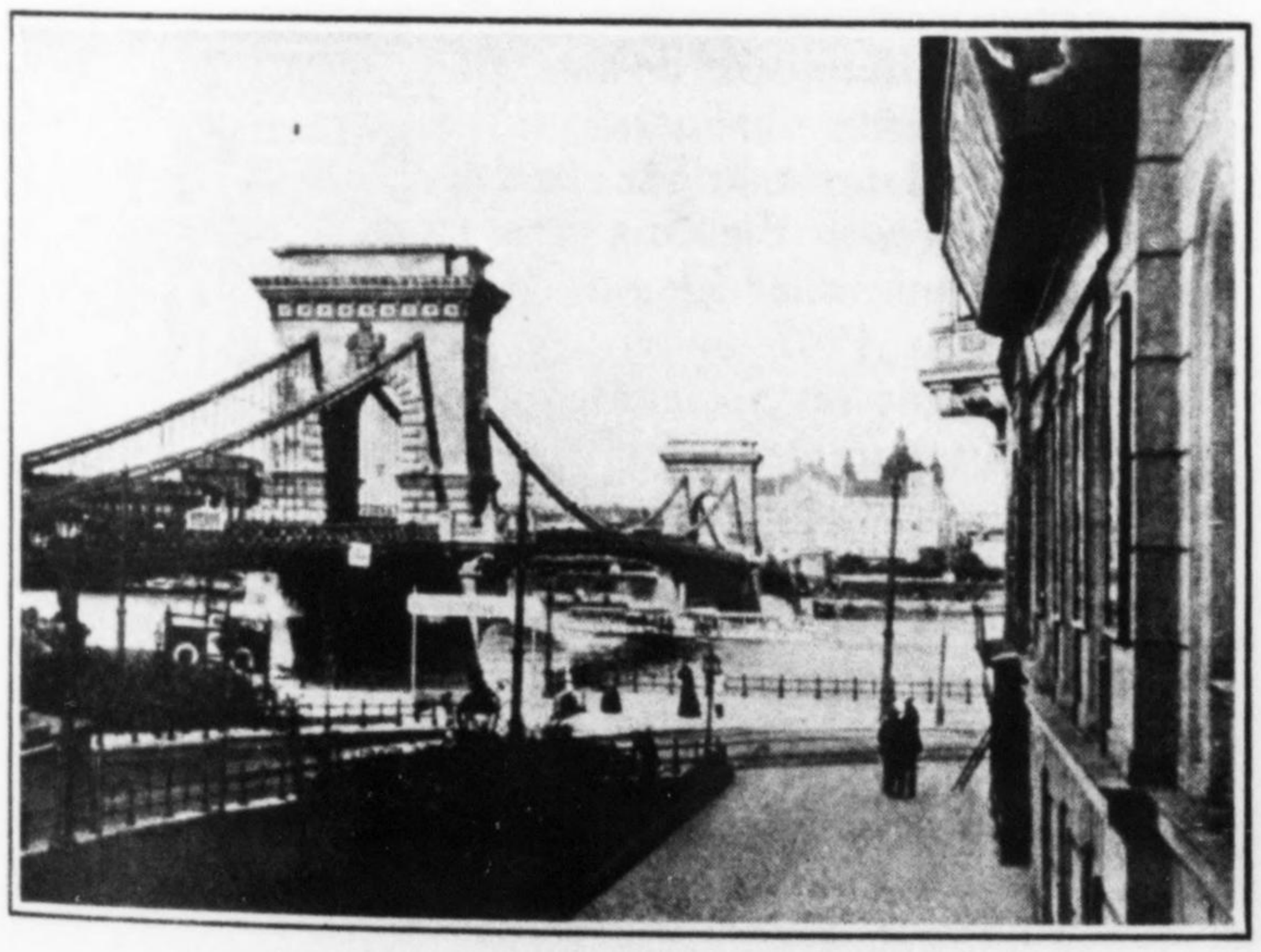


BUILDING THE FORTH BRIDGE

Danube in Budapest, one an eyebar suspension bridge and the other a cantilever bridge. As the result of an international competition with prizes, over fifty designs were obtained, but in the end both bridges were built from designs prepared by the government engineers. These structures, while handsome, nevertheless leave the beholder cold, alongside the old chain suspension bridge (built in 1846) with its beautiful molded stone towers.

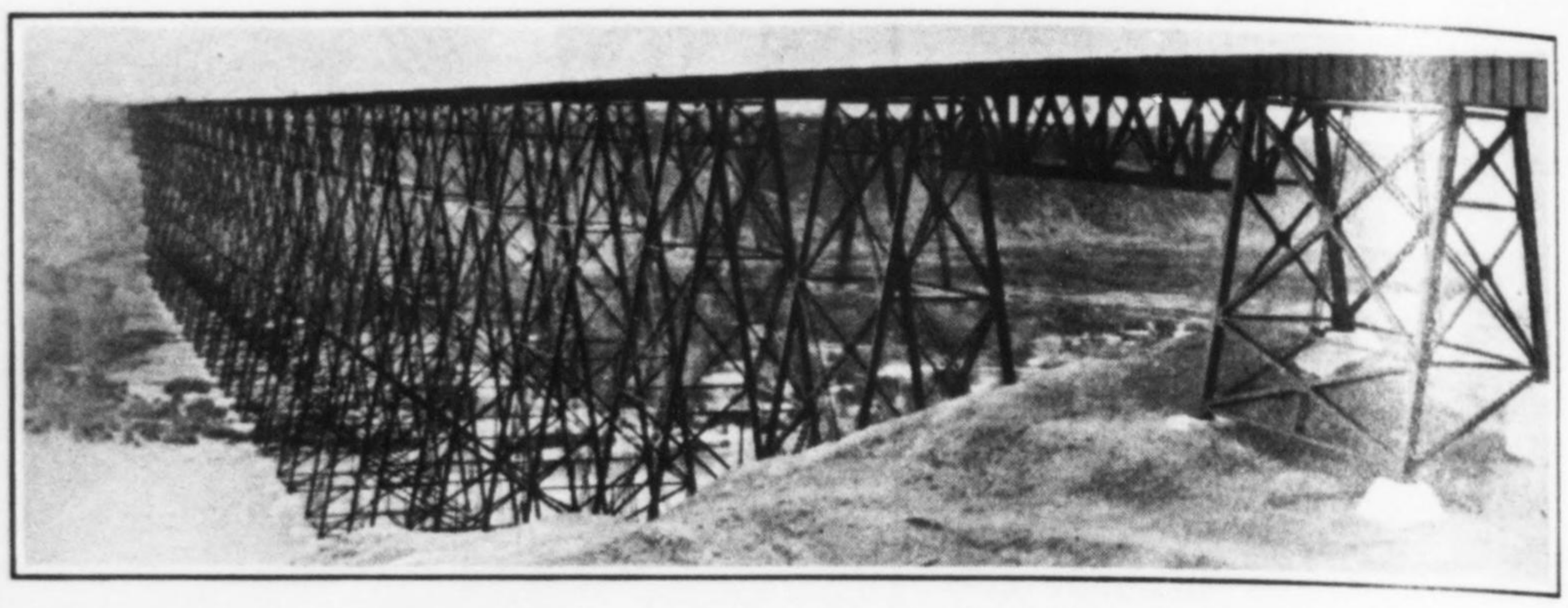
No wire suspension bridges of any size were built in Europe during the last fifty years. There is only one suspension bridge over the river Rhine. It is at Cologne and was completed in 1916. A determined effort was made to get a pleasing design, but it seems not to have been very successful. The cables are composed of plates and angles, riveted up into tension members, of which the horizontal thrust at the ends is taken up by box stiffening girders running from end to end, so that the anchorages resist only vertical forces. Its steel towers are plain and featureless.

The Tower Bridge in London, a unique combination of suspension and bascule bridge, is one of the few bridges with stone towers in the last thirty years. The stone is only veneer over steel frames, yet the towers give a monumental character to the bridge in harmony with its historical background. That iron and steel is not a cold, expressionless material for towers in the hands of skillful architects is proved by the colossal and yet graceful Eiffel Tower in Paris. It plainly expresses to the beholder that its airy form is not intended to carry a heavy load at the top like a bridge tower—for that purpose it must have a stouter form, as for instance in the new Budapest chain suspension bridge, or as in the design for the massive double iron towers of the first plans (1888) prepared by the writer for the proposed Hudson River bridge, before the Eiffel Tower was built. Another original structure, by Eiffel, typical of French elegance, is the Garabit railroad viaduct in the south of France, a bold crescent steel arch over a deep gorge supporting continuous lattice girders in an unbroken line on latticed towers. The whole design is exquisitely adapted to the locality. American engineers would cross such a gorge with a trestle bridge. Just as in most French bridge designs for longer spans, elegance of form and neatness of detail are typical characteristics, so in many English bridge designs may be observed as typical a certain heaviness of form and a tendency of massing the stresses into fewer stout members rather than into a larger number of lighter members. In this sense the English type was exemplified even in the old long-span



OLD AND NEW SUSPENSION BRIDGES AT BUDAPEST

NORTH RIVER BRIDGE TOWERS
(1888 Design)



LETHBRIDGE VIADUCT ON THE CANADIAN PACIFIC; HIGHEST YET BUILT

structures like the Britannia bridge and the Saltash bridge, but the same characteristic appears in the bridges of the last fifty years, like the Forth bridge, the Indus bridge at Sukkur and others.

Among the great bridges of originality and bold conception the Firth of Forth bridge in Scotland, still the largest and longest steel bridge structure, is remarkable. Its unadorned architecture is without an artistic silhouette. It expresses brutal power and strength, in full harmony with its conception as a riveted cantilever bridge. It was built up by methods of fabrication and erection more indigenous to iron shipbuilding than to bridge-building. The design was skillfully adapted to the local conditions; but it is safe to say also of this bridge, as of the Brooklyn and the St. Louis bridges, that for economic reasons it will not be duplicated. The only bigger span of the cantilever type, the Quebec bridge, followed American practice in its details of fabrication and erection.

These two cantilever bridges and the five bridges over the East River (three wire cable suspension bridges, one cantilever and the Hell Gate arch bridge) are the heaviest and longest-span bridges of the last fifty years. Of these the Hell Gate bridge, carrying four railroad tracks laid in stone ballast, was dimensioned for the heaviest known live-load—four lines of heavy locomotives on two trusses. A long-span wire-cable road bridge is now building over the Delaware River at Philadelphia. It will have the distinction of the heaviest steel wire cables (30 inches). Other long-span suspension bridges are proposed, one at Detroit and another at Nagasaki, Japan. The Sydney bridge in Australia, for which the contract has just been awarded, will be an arch design of 1,650 ft. span, a replica in form of the Hell Gate arch bridge, but for only half its live-load. The largest and heaviest bridge of all is proposed over the Hudson River at New York City, a suspension span of 3,240 ft. for a wide roadway and multiple tracks.

A most important development in bridge construction during the last forty years came through the use of armored or reinforced concrete. At first used only sporadically for small spans, the new material rapidly extended its field to larger and heavier arches. It has put into the hands of the bridge engineer a material with which he can in many cases build structures superior to those of steel in respect to durability, cost of maintenance and architectural appearance. Spans of over 600 ft. and high viaducts are feasible. Bridge architecture has gained much through this material.

WITH increasing skill and knowledge in the testing of materials and of their physical qualities, greater economy in the design of bridges has resulted. This may lead, under the stress of competition, to the temptation to attenuate the dimensions in bridge members, relying on supposedly accurately computed stresses, and upon supposedly sound material, insufficiently inspected and tested. So it will happen that in spite of the fact that modern bridge construction, having a strictly scientific basis, should with certainty avoid error and weakness, failures of important structures have occurred. Such was the collapse of the bridge over the Firth of Tay in Scotland near Dundee, when the loaded part of the bridge with a whole passenger train went down with great loss of life during a gale in December, 1879. The violence of the gale was blamed for it, but as a fact it was faulty design in the cast-iron bridge piers and wind bracing, which gave way, that caused the disaster. The new bridge which replaced it is safe against even more terrific gales. In the winter of 1876 occurred the collapse of the Ashtabula railroad bridge in Ohio during a severe snow storm, with great loss of life. The cause was found also in faulty details of design and faulty maintenance. The largest bridge failure of all was the collapse of the unfinished Quebec bridge in 1907 under its own weight on a clear day without notable wind, with a loss of 85 lives. The real cause was not defective material but defective design and ignorance of the real strength of a form of steel column which had not been tested.

Heavy construction of modern practice
YUMA BRIDGE, SOUTHERN PACIFIC RY., 1923

Such bridge disasters carry a certain lesson to engineers. In construction work there is often the pressure for lower cost. It requires courage of a high order on the part of the engineer to resist it. In this the engineering profession has a duty to perform. Bridges or buildings collapsing, pier foundations settling or washing out and dams going out, should not be laid up to Providence. Engineers are sometimes under the authority of laymen with whom financial considerations may seem more important than safety. If the pressure for cheapness comes from them, then the engineer should decline responsibility for the work. The economics of design that we hear so much about is in the direction of real scientific progress, but it must not be misused for gain and to cover up poor work. Competition of plans for ordinary bridge work under approved and fair rules has produced good results and is to be encouraged. But competition as practiced for many years, particularly for highway work, in charge of corrupt or ignorant public officials, had for years been a byword. Fortunately it is now getting less frequent.

Steel Arch Bridge in the Northern Forests

The progress of bridge construction during the last fifty years is best exemplified on the American railroads. The railroads being responsible for damages had the best reason for having the best designed bridges. American railroad bridges of the last 25 years have not their superior in any country for quality of material and workmanship. Large bridges costing millions of dollars were comparatively few and will probably become less frequent in the next fifty years. The size of bridges never was limited by question of what we could fabricate, but rather by financial considerations.

Turning now from the last half-century to the next half and the future, what may we expect in the way of further progress in this branch of engineering?

It is probable that the zenith of large bridge construction will be reached within the next fifty or hundred years, because of the increasing cost of iron and coal. Their prices have more than doubled in the last ten years. The iron ore beds will become exhausted long before the coal mines. The extent of both in all countries is now pretty well defined. The production of iron in large masses will diminish and become increasingly costly. There is no other metal of the same availability and strength to take its place for long-span bridges. With the exhaustion of the coal mines, the production and use of portland cement (which requires coal for calcination) will also cease. Stone bridges will then again be the only practicable lasting kind, as in the days before iron and concrete were used.

Bridge construction and bridge architecture will be to posterity in a certain sense a surer index of the progress of our present day civilization than houses, temples

Modern Concrete Arch Highway Bridge

or cathedrals appear to us of past ages. This will be so because the economizing of iron, when it becomes costly, will probably begin in bridge and structural construction before it begins in other kinds of construction. The large sources of energy in nature, coal, water power, wind, tides, heat of the sun, etc., can none of them be utilized without large masses of iron for the tools, machinery and power plants necessary for the conversion of these energies into power for the use of man—all of them more necessary than iron bridges, which may be then structures *de luxe*. Surely they would have appeared as such to the armored knights only one thousand years ago, when an iron armor was worth nearly half its weight in silver. Iron bridges, iron ships and railroads will then be curiosities. The colossal consumption of iron will have come to an end. In a span of time much shorter than that from Tut-ankh-amen to the present, steel bridges will probably have disappeared from the face of the earth through corrosion and neglect. Iron is a more perishable material, particularly in northern climates, than stone of which were built the Pyramids and the Greek temples and the wonderful Roman arch aqueducts—all in frostless, benign climates. These could be built again, but not iron bridges.

The creative genius of mankind, which now in this glorious age of iron is ascending to hyperbolic eminence in every branch of technical science, will leave few if any durable iron monuments to distant posterity. Among them should surely be, if possible, substantial large iron bridges that could be made to last several thousand years, if properly cared for in countries with stable, high civilizations. But who can look that far into the future?