ABSTRACT: The Hell Gate Arch Bridge of the New York Connecting Railroad was dedicated 100 years ago on March 9, 1917. When constructed, it was the longest arch bridge in the world with a span of 997.5 ft between centers of bearings and 1017 ft between the faces of abutments. The Chief Engineer of this project was Gustav Lindenthal and working under him were Othmar H. Ammann and David B. Steinman, two future giants of long span bridge engineering in the United States. The rivalry developed between them on this project continued for the rest of their careers. This paper describes the development of this project and the design and construction of this monumental bridge.

1 NEW YORK CONNECTING RAILROAD COMPANY

Although the Hell Gate Bridge was opened to traffic in 1917, its idea was conceived in 1892 by the incorporators of the Connecting Railroad Company (Connecting RR), namely, Oliver W. Barnes, Frank M. Clute, Alfred P. Boller, Charles MacDonald, and Thomas S. King. Boller and MacDonald were successful bridge engineers and they needed financiers and people connected with the railroad industry to develop the project. The Hell Gate Bridge would allow the Pennsylvania Rail Company (PennRR) to travel to New England states which was not possible up until then.

In 1900, the PennRR acquired control of the Long Island Railroad (LIRR) and a connection with the LIRR across the East River and with the New England roads via the Connecting RR on the line originally mapped out, became vital along with the plan to enter Manhattan using two tunnels under the Hudson River.

In April 1902, the PennRR completed the purchase of the entire outstanding stock of the Connecting RR and a short time thereafter, as per a prior understanding with the New York, New Haven and Hartford Railroad Company (NY, NH & HRR), sold one-half of the stock to that company.

A map of the PennRR system in New York is shown in Figure 1 along with the route of the acquired Connecting RR.

2 VARIOUS DESIGNS OF THE HELL GATE BRIDGE (AMMANN 1918)

The first design prepared by Alfred P. Boller in 1900 (Figure 2) was a cantilever design with a central span of 840 ft supported on braced steel towers and carrying two tracks with open tie flooring and subjected to Cooper’s E-40 loading.

In 1904, Gustav Lindenthal was selected by the PennRR to prepare different designs considering the ever-increasing weight of locomotives. He developed multiple designs until 1912 when permission was obtained to build the Hell Gate Bridge. Figures 3 through 7 show the evolution of the designs. The spandrel braced arch design developed by Lindenthal with the help of Consulting
Architect Henry Hornbostel is shown in Figure 8. Lindenthal visualized the bridge as a monumental portal for steamers entering New York Harbor from the Long Island Sound. The arch, flanked by massive masonry towers, was selected for construction by the PennRR and the NY, NH & HRR.

This arch span had four railroad tracks between its trusses and two highway tracks on brackets outside. The span distance between centers of skewbacks was 977.5 ft. The distance between near sides of the tower piers at the coping was 1015 ft. The distance between centers of the trusses was 60 ft and the distance between outside railings was 93 ft. The bottom of the floor system would clear the river at high tide by 135 ft and the center of the top chord by 307.5 ft. The span was divided into 23 panels of 42.5 ft each and the arch was of the two-hinged type.

Figure 1. Pennsylvania R.R. System in New York

Figure 2. Cantilever Design (1900)
Figure 3. Suspension Bridge Design (1904)

Figure 4. Continuous Truss Design (1904)

Figure 5. Cantilever Design (1904)

Figure 6. Crescent Arch Design (1905)
3 MATERIAL (AMMANN 1918)

All the material in the steel superstructure of the Hell Gate Bridge and its approaches was rolled, forged, or cast steel made by the open-hearth process. The following four grades of steel were used:

1. Hard steel for all rolled parts and pins of the Hell Gate Arch bridge,
2. Structural steel for all rolled parts and pins of the approaches,
3. Rivet steel for all rivets, and
4. Cast steel for all castings for bearings

The different grades had to conform to the chemical and physical requirements in Table 1.
Table 1. Chemical and physical requirements for steel.

<table>
<thead>
<tr>
<th></th>
<th>Hard Steel</th>
<th>Structural Steel</th>
<th>Rivet Steel</th>
<th>Cast Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus, max. (basic) (acid)</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>0.06</td>
<td>0.06</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Sulphur, max.</td>
<td>0.05</td>
<td>0.05</td>
<td>0.04</td>
<td>0.05</td>
</tr>
<tr>
<td>Ultimate tensile strength [lb/in²] (max.) (desired)</td>
<td>76,000</td>
<td>70,000</td>
<td>58,000</td>
<td></td>
</tr>
<tr>
<td>(min.)</td>
<td>66,000</td>
<td>62,000</td>
<td>50,000</td>
<td>33,000</td>
</tr>
<tr>
<td>Yield point, min.</td>
<td>38,000</td>
<td>35,000</td>
<td>28,000</td>
<td>33,000</td>
</tr>
<tr>
<td>Elongation, min. (2 in for cast steel) (8 in for other steel)</td>
<td>*</td>
<td>22%</td>
<td>28%</td>
<td>20%</td>
</tr>
<tr>
<td>Character of fracture</td>
<td>Silky</td>
<td>Silky</td>
<td>Fine, silky</td>
<td>Silky/fine granular</td>
</tr>
<tr>
<td>Cold bend without fracture</td>
<td>**</td>
<td>180˚ around pin of thickness of test piece</td>
<td>180˚ flat</td>
<td>90˚ around pin of thickness of test piece</td>
</tr>
</tbody>
</table>

*Minimum elongation for “hard steel”: 1,400,000 divided by ultimate strength for thickness up to and including 0.75 in; 1% less for each additional 0.125 in in thickness, with a limit of 16% for thickness up to and including 2 in and 15% for thickness greater than 2 in.

**Cold bend test for “hard steel”: 180˚ around a pin of double the thickness of the test piece for material up to and including 0.75 in, 180˚ around a pin 3 times that thickness for material greater than 0.75 in thick.

4 LOADS AND UNIT STRESSES (AMMANN 1918)

4.1 Dead load

The actual dead load varied from 45,000 lb/ft at the center to 62,000 lb/ft at the ends. The average dead load used for the final calculation was 51,000 lb/ft.

4.2 Live load

The following live loads were considered:

1. Cooper’s E-60 loading was assumed for each of the four tracks, or an alternative three-axle load of 70,000 lb on each axle wherever this caused greater stress.
2. The arch trusses for a uniform load of 6000 lb/ft of track, or 24,000 lb/ft of bridge, placed in the most unfavorable position in either a single stretch or in two separate stretches, when the latter condition gave a greater stress.

4.3 Impact

The impact stresses or vertical dynamic effects of the locomotives and cars were determined according to Lindenthal’s formula. This formula is provided in the paper by Ammann (1918).

4.4 Lateral forces from live load

The lateral force of lateral impact due to the swaying motion of fast-moving trains on tangents or the centrifugal force on curves up to 2 degrees was assumed at 600 lb/ft of single track. For the four-track bridge on tangent, a total lateral force of 1500 lb/ft was used.
4.5 Wind pressure
A wind load of 4600 lb/ft of bridge was considered for the design of the Hell Gate Bridge.

4.6 Longitudinal force from traction and braking
The longitudinal force acting along the rail from traction and braking was utilized either at 5000 lb for each of the eight driving axles of the two locomotives (125% of the load on each driving axle), or at 1000 lb/ft of train (approximately 15% of the average weight of the train), whichever gave the greater results.

4.7 Temperature stresses
The stresses from temperature were determined for a variation of ±72° F from the normal temperature of 60° F.

4.8 Total stresses
Various combinations of stresses were selected to determine the total stress.

4.9 Permissible unit stresses
The permissible unit stresses used for the Hell Gate Bridge are given in Table 2.

4.10 Secondary stresses
Care was taken in designing and detailing all the bridges to avoid large secondary stresses, and where this was not possible, cross-sectional areas of some of the members were increased. It was expected that most of the secondary stresses would be covered by the factor of safety.

4.11 Erection stresses
The erection stresses were well within the safe limits allowed for the total stresses in the completed bridge.
Table 2. Permissible unit stresses assumed

<table>
<thead>
<tr>
<th></th>
<th>For Trusses &amp; Bracing of Hell Gate Bridge (Hard steel) in lb/in²</th>
<th>For Approach Spans &amp; Floor System &amp; Suspenders of Hell Gate Bridge (Structural Steel) in lb/in²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial tension, net section</td>
<td>24,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Bending on extreme fiber of beams, girders, and steel castings, net section</td>
<td>-</td>
<td>20,000</td>
</tr>
<tr>
<td>Axial compression, net section:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a) Closed section, or section with two diaphragms, or one diaphragm and two planes of latticing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U/r = 20$</td>
<td>24,000</td>
<td>20,000</td>
</tr>
<tr>
<td>40</td>
<td>23,000</td>
<td>19,000</td>
</tr>
<tr>
<td>60</td>
<td>22,000</td>
<td>17,000</td>
</tr>
<tr>
<td>80</td>
<td>20,000</td>
<td>15,000</td>
</tr>
<tr>
<td>100</td>
<td>18,000</td>
<td>14,000</td>
</tr>
<tr>
<td>120</td>
<td>15,000</td>
<td>12,000</td>
</tr>
<tr>
<td>b) Half-open section with one cover and one latticing, or with one diaphragm without latticing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U/r = 20$</td>
<td>23,000</td>
<td>20,000</td>
</tr>
<tr>
<td>40</td>
<td>22,000</td>
<td>18,000</td>
</tr>
<tr>
<td>60</td>
<td>20,000</td>
<td>16,000</td>
</tr>
<tr>
<td>80</td>
<td>18,000</td>
<td>14,000</td>
</tr>
<tr>
<td>100</td>
<td>16,000</td>
<td>13,000</td>
</tr>
<tr>
<td>120</td>
<td>14,000</td>
<td>11,000</td>
</tr>
<tr>
<td>c) Open section, with two or more planes of latticing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$U/r = 20$</td>
<td>22,000</td>
<td>19,000</td>
</tr>
<tr>
<td>40</td>
<td>20,000</td>
<td>17,000</td>
</tr>
<tr>
<td>60</td>
<td>18,000</td>
<td>15,000</td>
</tr>
<tr>
<td>80</td>
<td>16,000</td>
<td>13,000</td>
</tr>
<tr>
<td>100</td>
<td>14,000</td>
<td>12,000</td>
</tr>
<tr>
<td>120</td>
<td>12,000</td>
<td>10,000</td>
</tr>
<tr>
<td>Shearing stress:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On plate girders, net section</td>
<td>-</td>
<td>15,000</td>
</tr>
<tr>
<td>Shop rivets and pins</td>
<td>15,000</td>
<td>-</td>
</tr>
<tr>
<td>Field rivets and turned bolts</td>
<td>12,000</td>
<td>-</td>
</tr>
<tr>
<td>Bearing stress:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pins</td>
<td>24,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Shop rivets</td>
<td>30,000</td>
<td>-</td>
</tr>
<tr>
<td>Field rivets and turned bolts</td>
<td>24,000</td>
<td>-</td>
</tr>
<tr>
<td>Pressure on:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Expansion rollers per linear inch</td>
<td>Diameter of roller, in inches, X 1000</td>
<td></td>
</tr>
<tr>
<td>Granite masonry</td>
<td>800</td>
<td>800</td>
</tr>
<tr>
<td>Concrete masonry</td>
<td>600</td>
<td>800</td>
</tr>
</tbody>
</table>

5 FABRICATION OF THE HELL GATE BRIDGE

The fabrication of the 977.5 ft steel arch started at the Ambridge, PA plant of the American Bridge Company early in 1914. The fabricating process on this steelwork was unusual because of two specific requirements (Engineering News, 1914):

1. Practically all the holes needed to be drilled because punching was not possible for thicker plates, and
2. The structure had to be assembled in the yard in a horizontal position, with the field connections drilled to match before the parts were shipped to the site.
There were 840,000 shop rivets and 334,000 field rivets, of which 400,000 were 1.25 inches in diameter. Most of the 1 and 1.25-inch shop rivets were driven with hydraulic riveting machines having a pressure capacity of 100 tons (100psi). The points of the long rivets were dipped in water after heating to ensure a more complete upsetting of the shank before the head was formed.

The main arch trusses were completely assembled on skids in the fabrication shop yard. Due to limited space, for the full length of the bridge the trusses were assembled in four panel sections. The last panel of each section stayed in place for the first panel of the next section, thereby assuring total continuity of construction (Engineering Record, 1914).

All field joints of the trusses were reamed in the yard by four portable electric reamers handled by gantry cranes. The heaviest finished pieces were shipped from the site on special cars of 150,000 lb capacity specifically built for this project.

Figure 10 shows one of the end shoes of the arch. Each shoe built up of steel castings with 4-inch metal thickness weighed 50,000 lb. In as much as it sits on a masonry seat inclined about 45° to the horizontal, provision was made for anchoring it in place until the arch was so far erected that the thrust of the structure would hold the shoe securely to its seat.

The end casting of the arch had a slightly convex cylindrical face to give hinge action. A dowel was connected to the hinge castings to prevent displacement transversely.

Figure 10. Details of Panel Point O and Bearing
6 ERECTION OF HELL GATE BRIDGE

The erection plan was clearly thought out by Lindenthal. The river conditions ruled out the use of falsework except for a very short distance from each abutment. Therefore, erection on the cantilever principal with the use of temporary backstays (acting as counterweights) was adopted by the American Bridge Company. The bridge members planned for the subsequent construction were used as backstays to reduce the material handling twice. The total weight of steel in the backstays for both sides came to 15,500 tons of which about 2300 tons were not utilized in the permanent structure. Figure 11 shows the progress of the erection of the Hell Gate Bridge (Ammann 1918). Adjustment of the arch trusses in height was required at various erection stages. For this purpose, four 3000-ton capacity hydraulic jacks were placed one on top of each of the four erection posts. There were multiple 500-ton capacity local jacks used to assist during the erection process.

Erection of the Hell Gate Arch is covered by Whitney (1915), Parsons (1915), Railway Review (1915), Skinner (1919), and Engineer (1915). The closing of the trusses at the center by jacking transformed the two individual cantilevers into a three-hinged arch. The transformation of the trusses from three-hinged into two-hinged arches required the connection of the top chord and one of the diagonals of the center panel of each truss at $60^\circ$ F. These members were erected immediately after the closing of the arch, but had been left bolted at one end and free to move at the other.

The connection at the free end required drilling the rivet holes from the solid sections and riveting. This took several days. The bottom chords were fully riveted at this third hinge point and from there on the bridge had two hinges, one at each skewback.

The 1907 Quebec bridge disaster was in the minds of each of the 150 workers who erected the Hell Gate Bridge. The total construction cost of the project was about $30 million. The rule of thumb during those days was the loss of one life for every $1 million of construction cost. Although not perfect, the safety record of the Hell Gate Bridge was very good because only five lives were lost during construction.

7 STRESS MEASUREMENTS ON THE HELL GATE BRIDGE

Considering the scale and magnitude of the Hell Gate Bridge, Lindenthal decided to use his own money to measure stresses in the bottom chord at various stages of erection until the bridge was completed. He did this as scientific research. The details of his work are summarized here based on the paper by Steinman (1918).

The instrument used for the stress measurement was a 20-inch strain gage designed by James E. Howard. This instrument was essentially a micrometer caliper with an accuracy of 0.0001 inch.

The bottom chords of the arch had a double rectangular section (Figure 12) consisting of two compartments separated by a horizontal diaphragm. It was decided to take six readings at each cross-section, four at four corners and two at mid-height in the vertical webs. The measurements were taken during the first 12 stages of construction as shown in Figure 13.

The measurements were limited to dead load only, and were stopped by Lindenthal due to lack of funding. At the end of his paper, Steinman provided a 10-point summary which compared the calculated and measured stresses. He considered the stress measurement a success because in most cases the calculated secondary stresses were lower than the measured ones, and where they exceeded, they were covered by the safety factor. This was the first major bridge where the stress measurements were experimentally carried out and, in most cases, the calculated and the measured stresses differed by less than ten percent.

8 GUSTAV LINDENTHAL, 1850-1936 (FRANKLAND, 1940)

Gustav Lindenthal (Figure 14) was born in Brunn, Austria on May 21, 1850. He was educated at Politechnicum College in Dresden, Germany and received practical training from 1866 to 1870. He came to the U.S. in 1874. Lindenthal worked at the 1876 World’s Fair in Philadelphia as a laborer and then as a designer. In 1878 he joined the Atlantic Great Western Railroad as a bridge engineer. In 1881, Lindenthal started his own engineering practice in Pittsburgh and found assignments in the design and construction of important bridges for railroads and bridge companies.
Figure 12. Bottom Chord Member (Ammann 1918)

Figure 13. Extensometer Measurements of Stresses in Bottom Chord Members (Steinman 1918)
He received recognition and very good publicity for replacing the Smithfield Street suspension bridge, originally built by John A. Roebling, with a 350 ft (106.7 m) span double-elliptical steel truss in 1882. This, and several other projects in Pittsburgh, brought him to the attention of Samuel Rae of the Pennsylvania Railroad who later supported Lindenthal in the proposal for the Hudson River Bridge. It was Lindenthal’s paper in 1888 presented at the American Society of Civil Engineers convention, “The North River Bridge Problem, with a Discussion on Long Span Bridges,” that excited not only the engineering community, but the general public as well.

Lindenthal spent his entire career in private practice except for a controversial two-year period (1902-1903) when he was appointed the Bridge Commissioner of New York City by Mayor Seth Low (Gandhi 2013). The most notable project of his professional practice was the Hell Gate Bridge in New York. On the Hell Gate arch project, Lindenthal hired Othmar H. Ammann, David B. Steinman, and Charles S. Whitney, who would later become world-renowned engineers in their own right.

He combined his love of beauty in engineering works with his search for a structural solution. In his search for aesthetic design, he did not hesitate to consult architects whenever he had to deal with an important bridge project, such as the Hell Gate Bridge. Lindenthal died on July 31, 1935 at age 86.

![Figure 14. Gustav Lindenthal (Wildman 1921)](image)

9 RELATIONSHIP BETWEEN AMMANN AND STEINMAN

Ammann and his wife Lilly met Mr. and Mrs. Lindenthal at a social event in Philadelphia in 1910 (Rastorfer 2000). The Ammanns and the Lindenthals become friends over the next two years, even though there was an age difference of about 30 years between the two men. During that period, Lindenthal was designing the Hell Gate Bridge for the PennRR.

Lindenthal was authorized with construction of the Hell Gate Bridge in early 1912 and Ammann joined him as his assistant in June 1912. As the second in command, Ammann was responsible for about 2.5 miles of bridges, viaducts, trestles, embankment structures, and the Hell Gate Bridge which carried four tracks and connected Queens to Wards Island.

Ammann was reliable, meticulous, and took his responsibilities seriously. He also kept the project on track and within budget. Lindenthal depended on Ammann, with whom he had a good working relationship due to their similar backgrounds and natural chemistry, for the success of the Hell Gate Bridge construction.
In August of 1914, Ammann was still a Swiss citizen and a reserve officer of the Swiss army. The news that the German army had taken position on the banks of the Rhine River across from Basel worried Ammann as his oldest son Werner, parents, and a brother were living in Basel at that time. Ammann left for Switzerland on August 6, 1914.

Ammann’s abrupt departure created a major problem for Lindenthal who needed to fill his position with a suitable candidate who would be familiar with the project and equally capable as Ammann. Lindenthal promoted David B. Steinman to the position of First Assistant. Steinman was a brilliant engineer and mathematician and had earned his Ph. D. in Civil Engineering from Columbia University at the age of 24.

As it turned out, the war did not start on the Swiss border, and Ammann was released from the Swiss army in three months. Ammann returned to the U.S. with his son Werner in December 1914. Lindenthal immediately reinstated Ammann as his First Assistant, and demoted Steinman to his former title. This did not sit well with Steinman and a bitter rivalry between the two brilliant engineers continued for the rest of their professional careers. According to Rastorfer, “the mention of Steinman’s name was strictly forbidden in the Ammann household.”

Figure 15 shows Lindenthal with his staff during the construction of the Hell Gate Bridge. Ammann is standing to right of Lindenthal wearing a felt hat and sporting a mustache. Steinman is fourth from the left in this photo.

After the completion of the Hell Gate Bridge, Ammann wrote a paper on the design and construction of the Hell Gate Bridge and Steinman wrote a complementary paper on the stress measurements carried out by him on the project. Both papers were published in 1918 in the Transactions of the ASCE Volume 82.

Steinman acknowledges in his paper the help he received from Ammann “for suggestions during the prosecution of the investigation.” It seems odd that Ammann, who was the supervisor of Steinman, would comment on Steinman’s work in public by saying that in his opinion, the conclusion reached by Steinman “relative to secondary stresses were somewhat too far reaching,” or in other words, “speculative.”
Steinman, in his response to Ammann’s criticism, politely asked Mr. Ammann “to point out anything in the summary of conclusions which can possibly be regarded as too far reaching from the results of the investigations.”

10 RELATIONSHIP BETWEEN AMMANN AND WHITNEY

On the Hell Gate Bridge project, Ammann was Assistant Chief Engineer under Lindenthal and was in direct charge of the office, field, and inspection work. He had a staff of 95. Charles S. Whitney was one of the engineers who had received a Master’s degree in Civil Engineering from Cornell University in 1914 and had joined the Hell Gate Bridge project as an inspector.

In 1942, Whitney wrote a paper on “Plastic Theory in Reinforced Concrete Design,” which was published in Vol. 107 of the Transactions of the ASCE. His paper was well received as it simplified the ultimate strength design of reinforced concrete. To most engineers, he is well known for his “Whitney Stress block” which was adopted by the American Concrete Institute in 1963.

In 1946, Ammann formed a partnership with Whitney and the firm became known as Ammann and Whitney with a worldwide reputation in the design of suspension bridges, concrete shell structures, and special structural engineering projects.

11 CONCLUSIONS

From an engineering point of view, the Hell Gate Bridge project was a great success because it was the longest arch bridge in the world when completed. This was also the first time stresses were measured and compared with the calculated values for a major bridge. The agreement between the two within the permissible limits of experiments (±10%) gave confidence in the design approach adopted by Lindenthal and his assistants, Ammann and Steinman.

From a financial point of view, the New York Connecting Railroad, with its Hell Gate Bridge and few miles of track in Queens, was a disaster. It had cost $100 million to build. With the decline of railroad traffic and the increase in roadway traffic, it was certain even in 1917 that the net earnings from the passenger and freight business over the Hell Gate Bridge would never pay even a fraction of the interest charges on its cost (Railway Age Gazette 1917).

The author believes that with the experience and confidence gained, the rivalry developed between Ammann and Steinman on this project brought out the creativity in both of them during their professional careers and expanded the limits of long span bridges beyond most of the engineers’ imagination.

12 ACKNOWLEDGEMENTS

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REFERENCES

Ammann, O.H. 1918. The Hell Gate Arch Bridge and Approaches of the New York Connecting Railroad over the East River in New York City. Transactions, American Society of Civil Engineers. V82: 852-1039


*Engineering News* 1914. The Hell Gate Bridge in the shop. 72(23): 1116-1118.


