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The Bayonne Bridge: The Work of Othmar Ammann, Master Builder (ASCE Manuscript Number: BE/2007/023412

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Abstract

The goal of this paper is to demonstrate the significance of the Bayonne Bridge and to identify it as a work of structural art, because its designer, Othmar Ammann (1879-1965), focused on efficiency, economy, and elegance. To understand Ammann's ideas and his great arch bridge, we will 1) briefly describe his educational background, 2) explore his design concept, 3) explain the behavior of the bridge through a careful structural analysis, 4) include a critical analysis of its design, and 5) reflect on lessons to be learned from Ammann. A full technical study of the Bayonne Bridge has never been published. Since we are very fortunate to have one of the few complete sets of the plans, we will present an independent structural analysis to explain Ammann's design

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concept and to demonstrate its efficiency in the complete form and its safety during construction.

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Introduction

The Bayonne Bridge and its designer, Othmar Ammann, have often been neglected in civil engineering literature. The lack of careful study of the Bayonne Bridge is all the more surprising since in 1931 it received the first award for the most beautiful steel bridge from the American Institute of Steel Construction and in 1985 it was named a National Historic Civil Engineering Landmark [Anon. 1981] [Anon. 1986]. Our goal is to tie Ammann's career to this major bridge by discussing his educational background and by exploring his design concept. We will then present a structural analysis of the bridge to show Ammann's design as efficient in the complete form and its safety during construction. Through this detailed study of both Ammann and the bridge itself, we plan to show lessons to be learned from Ammmann that are applicable to engineers today.

The Port of New York Authority[1] took on the creation of the Bayonne Bridge as a part of the local highway system to improve transportation around the New York area, specifically between Bayonne, New Jersey on the North and Staten Island on the South. The bridge would replace ferry travel which had been the main method of transportation. Even as early as the 1920s, ferry transportation could not meet the demands for this crossing. Though adding ferry connections was a possibility, this would have been expensive and would not necessarily solve problems related to delays and demand. In his 1927 report on the Bayonne

[1]At the time of the design of the Bayonne Bridge, this organization was known as The Port of New York Authority. In 1972, the name of the organization was changed to The Port Authority of New York and New Jersey [Doig 2001]. Hereafter, we will refer to this organization as the Port Authority.

Bridge, Ammann emphasized that a vehicular bridge across the Kill van Kull would be the best way to remedy the traffic problems and that such a bridge would be a great asset to the communities, the Port Authority, and New York and New Jersey [Ammann 1927]. The Bayonne Bridge completes a transportation network of interstate highways by connecting with the Willowbrook Expressway (NY 440), Staten Island Expressway (I-278), the Outerbridge Crossing, the Verrazano Narrows Bridge, and the Goethels Bridge [Anon. 1981].

The Port Authority began planning for the Bayonne Bridge in the 1920s. On March 2, 1925, Congress authorized it to construct and control the bridge. The Port Authority began initial studies for the bridge in April 1926 and submitted plans to the War Department in November 1927. The Chief of Engineers and the Secretary of War approved the plans on December 31, 1927. The states of New Jersey and New York advanced $4 million and the Port Authority sold $12 million in Gold Bonds to fund the bridge [Ammann 1930a]. The Bayonne Bridge ultimately came in $3 million under budget and was opened months ahead of schedule with a dedication ceremony on Nov. 14, 1931. At the time of its opening, it was the longest arch bridge in the world, a record which it held for 46 years [Anon. 1931].

Wilhelm Ritter and Ammann's Education

As a student of Wilhelm Ritter at the Federal Institute of Technology (ETH) in Zurich, Ammann's career and his design of the Bayonne Bridge was largely influenced by his education in the Swiss tradition of structural engineering. This tradition dates back to the creation of the ETH. Founded in 1855, ETH organizers were able to study various established systems of education including the French, which featured an administrative core with individual professors, and the German, which organized professors in departments. The organizers chose the latter approach for ETH and, due to its late start, were able to find experienced candidates for their first faculty. The most important member of this faculty for structural engineering was Carl Culmann (1821-1881) [Oechsli 1905]. He pioneered a systematized, geometric approach to structural analysis that he published in a highly influential text entitled *Die Graphsiche Statik* [Culmann 1866]. His extensive practical experience working for the state railroad of Bavaria and his writings about his travel experience to America and Britain enlivened his work and teachings [Ritter 1903] [Culmann 1851] [Culmann 1852]. This focus on practical experience, professional travel, and research began the Swiss tradition that would be carried on by Culmann's assistant and replacement, Wilhem Ritter(1847-1906).

Ritter graduated from ETH in 1868 and after working for a year he was invited to be one of Culmann's assistants. He earned the qualification of *Privatdozent* within a year, allowing him to teach courses on mechanics and geometry. After working on his own at a polytechnic school in Riga, he eventually came back to ETH where he became a professor in 1881. He taught Graphic Statics and Bridges, with an emphasis on consulting experience, independent research focused on visual study, and professional travel [Meister 1906]. Culmann's tradition thus clearly influenced Ritter's own career path. Ritter, as a part of the larger Swiss tradition, valued full scale load testing and demonstrations of performance over a dependence on mathematical theories and analysis [Ritter 1892]. As a strong proponent of travel, Ritter visited America where he examined many works, analyzed the different choices of forms, and reported on his observations in a text entitled *Der Brückenbau* and in articles in the *Bauzeitung* [Ritter 1895]. Beyond innovative teaching, Ritter had a large impact on the entire careers of his students.

Culmann's Swiss tradition of engineering and Ritter's influence set the foundations for Ammann's career, which began following his graduation from ETH in 1902. Ammann would later travel to the United States and seek the practical experience that Ritter emphasized by working with Gustav Lindenthal on a variety of projects, including being the chief assistant during the construction of the Hell Gate Bridge (1912-1917) [Rastorfer 2000]. Following Ritter's emphasis on load testing and visual analysis of performance, Ammann wrote an article entitled "Present Trends in Structural Design" which emphasizes the importance of testing [Ammann 1940]. During the design and construction of the Bayonne Bridge, a 9 foot brass model was used to study transverse loading, column tests were performed on particular members of the truss, and stress measurements were taken on the actual structure during construction [Ammann 1940]. In addition to these general influences on Ammann's career, Ritter's texts *Der Brückenbau* and *Anwendungen der Graphischen Statik nach Professor Dr. C. Culmann* part 4 *Der Bogen* (on two-hinged trussed arches) undoubtedly informed Ammann's design of the Bayonne Bridge [Ritter 1906] [Ritter 1895] [Billington 2003] [Billington 1980].

Gustav Lindenthal and Ammann's Education

We can consider Ammann's education to be divided into two stages: the legacy of Ritter and the legacy of Lindenthal. First, in his education at ETH under Wilhelm Ritter, Ammann learned the fundamentals of structural engineering and was influenced by Ritter's methods of analysis. His education then continued from a practical standpoint under Gustav Lindenthal. Working with Lindenthal, Ammann gained experience as the chief assistant on the Hell Gate Bridge (the world's largest arch at the time, completed in April 1917) and the Sciotoville Bridge (the world's longest continues truss bridge of its time, completed in August 1917). He was then offered a partnership with Lindenthal on his design for a Hudson River crossing (which would have been the world's longest suspension bridge if it had been built, proposed in 1888) [Rastorfer 2000] [Lindenthal 1922]. Most importantly for his education, Ammann worked on the Hell Gate Bridge and wrote a paper entitled "The Hell Gate Arch Bridge and

Approaches of the New York Connecting Railroad over the East River in New York City" in the *Transactions of the American Society of Civil Engineers* [Ammann 1918a]. From an educational perspective, this paper served as a dissertation and he was later awarded the Thomas Fitch Rowland Prize for his work [ASCE Register 1985]. This major document allows us to compare the Hell Gate Bridge with the Bayonne Bridge to explore Ammann's concept for his own design. See Fig. 1 for images of these bridges.

Though Alfred Boller first designed the Hell Gate Bridge as a cantilever form in 1900, in 1904 the Pennsylvania Railroad chose Gustav Lindenthal as the designer. Due to site restraints which required that there be no temporary or permanent support in the river and that there be no falsework except close to the abutments, Lindenthal was limited to choosing between a cantilever, continuous truss, suspension, or arch form. After analyzing each of these types with respect to the soil conditions, required length, and clearance, Lindenthal concluded that there was little to no economic advantage of one form [Ammann 1918a]. In Ammann's article on the Hell Gate Bridge, he writes that "Mr. Lindenthal conceived the bridge as a monumental portal for the steamers which enter New York Harbor from Long Island Sound...The arch, flanked by massive masonry towers, was most favorably adapted to that purpose" [Ammann 1918a; see p. 865]. Lindenthal's aesthetic of monumentality thus informed his choice of an arch bridge.

When choosing the shape of the arch, Lindenthal compared two different types of arches: the "Crescent Arch Design" and "Spandrel-Braced Arch Design." His crescent design is modeled after Eiffel's Garabit Viaduct in France and features an arch form that is deep at the crown and narrows to points at the ends. His spandrel design is modeled after Rhine bridges at Dusseldorf and Bonn and features an arch form that is deeper at the ends than at the crown [Ammann 1918a]. See Fig. 2 for images of the Garabit Viaduct and the spandrel form at Bonne and Fig. 3 for Lindenthal's sketches of both of these forms at the Hell Gate

Bridge site.

Lindenthal analyzed the forms from structural, construction, and aesthetic perspectives. Considering the forms from a structural perspective, Lindenthal compared the steelwork necessary for each and found that the crescent arch required slightly less. Taking into account construction considerations, Lindenthal believed that the spandrel design offered advantages in terms of the cantilever construction method which would meet the site constraint that there be no falsework in the river [Ammann 1918a]. However, the Garabit Viaduct was built using this method [Beckett 1969] [Eiffel 1888]. Therefore, the crescent form could likewise be built and Lindenthal's tendency away from the crescent form for this reason was unfounded. From an aesthetic perspective, Lindenthal favored an "expression of rigidity" which he saw in the spandrel form. Ammann writes in his report on the Hell Gate Bridge, "Although both designs are pleasing in appearance, the spandrel arch, owing to its height increasing from the center toward the ends, is more expressive of rigidity than the crescent arch, the ends of which appear to be unnaturally slim in comparison with the great height at the center" [Ammann 1918a; see p. 871]. Based on these considerations, Lindenthal chose the spandrel form for the Hell Gate Bridge. More specifically in his choice of form, Lindenthal designed the lower chord as a parabola. He designed the upper chord to have a small reversal of curvature at the ends in order to provide rigid portals, wind bracing for the upper chord, and to improve, in his view, the aesthetics of the bridge [Ammann 1918a].

One of the key aspects of Lindenthal's aesthetic of monumentality and rigidity is his towers. When he considered both the spandrel and crescent forms, he sketched both with monumental towers. The towers in the crescent form (which do not appear in the Garabit Viaduct) appear extraneous, thereby detracting from the aesthetic appeal of Lindenthal's crescent design. When considering the spandrel design, the towers are more integrated into the form and as Ammann writes, "The massive masonry towers which flank the steel arch greatly enhance the appearance of the bridge and give it its monumental character. They also give expression to the solidity of the abutments to resist the great thrust of the arch" [Ammann 1918a; see p. 882]. Lindenthal's insistence on large towers may have therefore led him away from the crescent form and toward the more integrated spandrel design. Ammann insists that these towers contribute to the structural function of the bridge in terms of the foundation of the abutments. Early testing had shown that the foundations on the Wards Island side would need to go to a large depth. According to Ammann, the weight of the masonry towers would then shift the force resultant toward the middle of the foundation ultimately resulting in a reduction of the edge pressure [Ammann 1918a]. However, in the discussion following his ASCE paper, Ammann admits that the towers are not an economic way of relieving the edge pressure though they do contribute to a cost saving in the masonry needed for the foundations [Ammann 1918b]. Ammann also writes that two of the five rows of caissons below each tower take the entire horizontal reaction from the arch [Ammann 1918a]. This shows that the caissons are the primary structure giving stability to the arch. Even if the towers do relieve the edge pressure, they do not contribute to the stability that Lindenthal sought to express.

Though Lindenthal offered some structural reasons regarding the choice of the spandrel design, the large masonry towers, and the curvature of the upper and lower chords, these are not convincing arguments. Rather, the key motivation appears to be the "expression of rigidity" rather than actual structural rigidity. The spandrel design appears to be a hingeless arch that is braced by the towers. However, it is actually a two-hinge arch that has been portrayed to give this false aesthetic of rigidity and monumentality. Though we may disagree with Lindenthal's logic, he chose the spandrel form based on what he considered construction and aesthetic advantages. Lindenthal's design does have aesthetic interest, though its form does not express its structure. Indeed, some such as Carl Condit, believe the Hell Gate

Bridge has superior aesthetic qualities. He wrote that, "Only one American arch bridge exceeds the New York span in clear length, but not one is superior to it in over-all size and weight and in the power and dignity of its form" [Condit 1961].

Ammann officially began working with Lindenthal in April 1912, after Lindenthal had already received authorization to construct the Hell Gate Bridge [Rastorfer 2000]. In his article, Ammann writes that between 1904 and 1912 "the design of the Hell Gate Bridge received almost continuous and thorough study, involving the working out of complete designs of several types of bridges and a number of modifications of the type finally adopted" [Ammann 1918a; see p. 863]. Though Ammann could not have been involved in this phase of the design of the bridge, he does publish a series of calculations in the appendix of his article. These calculations rely heavily on graphical methods of analysis, suggesting Ritter's influence on Ammann's analysis. Several of Ammann's figures are even very similar to the kind published by Ritter himself [Billington 2003; see p. 82-83]. In this respect, Ammann's education in the Swiss tradition of engineering becomes apparent in his work on the Hell Gate Bridge.

The Design Concept

In his design of the Bayonne Bridge, Ammann drew on his experience working on and writing about the Hell Gate Bridge. Through this paper Ammann shows his interest in the aesthetics of structures and reveals his aesthetic motivation. Ammann writes that, "An elaborate stress sheet, worked out on a purely economic and scientific basis, does not make a great bridge. It is only with a broad sense for beauty and harmony, coupled with wide experience in the scientific and technical field, that a monumental bridge can be created" [Ammann 1918a; see p. 863]. He credits Lindenthal's Hell Gate Bridge with being such a monumental bridge [Ammann 1918a]. Although Ammann gained great experience working under Lindenthal, Ammann's aesthetic motivation can be credited to his education in the Swiss tradition under Ritter.

Like Lindenthal, Ammann considered several different forms including the cantilever, suspension, and arch bridges. In the early design stages for the bridge, cost comparisons were made between the 3 forms. Ammann found that cantilever form was the most costly and considered it "aesthetically inferior" [Ammann 1930a; see p. 19]. The arch and suspension forms were closer in cost. However, Ammann chose the arch form based on the logic that the suspension form may have been too flexible for rapid transit trains (initial calculations on a suspension form of the same span showed the arch form deflects 7.5 times less), the arch form would cost 1-1.5 million dollars less, and the bedrock on the each shore provides abutments for the thrust of the arch [Ammann 1930a] [Anon. 1928]. In the *Proceedings of the American Society of Civil Engineers* regarding the bridge, "It was realized that only comparative bids on the various types would determine the actual costs; but the delay incident to this determination was most undesirable, hence the decision in favor of the arch design" [Ammann 1930b; see p. 489]. Though Ammann made these arguments in favor of the arch bridge, they are not solid reasons for selecting an arch over a suspension form. His logic that a suspension form is too flexible for rapid transit is refuted by his own 1923 design of the George Washington Bridge which involved a suspension form with 4 rapid transit lines [Ammann 1933]. Since he was simultaneously building the George Washington Bridge, which would become the longest spanning suspension bridge in the world, Ammann may have been motivated by an emotional drive to simultaneously build the longest spanning arch bridge. However, this motivation does not take away from the design of the bridge or its consideration as a major design in steel arches.

When considering the shape of the arch, Ammann, like Lindenthal, considered adopting a crescent form. However, Ammann too decided against the crescent form citing difficulty with regard to the design of the hinges and because of aesthetic considerations [Ammann 1930b]. As a result, he chose a spandrel-braced form which we can question for its illogical image in two-hinged design. Furthermore, this choice does not eliminate Ammann's need to design hinges at each end.

The form of the Hell Gate Bridge arch can be seen in a modified form in the Bayonne Bridge. Like the Hell Gate Bridge, the Bayonne Bridge has a greater depth (vertical distance between the upper and lower chords) at the ends than at the crown, though this effect is not as pronounced. The depth at Hell Gate Bridge ranges from 140 ft (42.7 m) at the ends to 40.3 ft (12.3 m) at the crown, whereas the depth of the Bayonne Bridge ranges from 67.5ft (20.6 m) to 37.5ft (11.4 m) [Ammann 1918a] [Ammann 1928]. Furthermore, the upper chord of the Bayonne Bridge does not feature a reversal in curvature at the ends like the Hell Gate Bridge.

Though the shape of the Bayonne Bridge follows that of the Hell Gate Bridge, Lindenthal is critical of Ammann's choice of form in the *Proceedings of the American Society of Civil Engineers*. Lindenthal is in favor of a hingeless arch whose width is greater at the hinges and then thins at the center. Lindenthal suggests that, "Viewed from the ends, this bridge would then have conveyed the expression, architecturally satisfying of solid, broad-footed stability" [Lindenthal 1930; see p. 514]. Again Lindenthal is in favor of an "expression of rigidity" and criticizes the Bayonne Bridge for not adhering to his aesthetic of monumentality. However, we consider it a move toward a purer image of structural art. The Bayonne Bridge reduces the change in truss height which was unnecessary structurally in the Hell Gate Bridge and eliminates the reversal in curvature of the upper chord which does not contribute to the structural form. Therefore, Ammann's design strips away the nonessential visual elements of his bridge to reveal more of its true structure.

We have prepared a sketch of the Bayonne Bridge which modifies the form of the arch to be crescent shaped (see Fig. 4 for a comparison of the Bayonne Bridge as designed by Ammann and as a crescent form). Our sketch features the same depth at the crown as Ammann's design, but it becomes significantly less deep at the ends, thereby more clearly expressing the true structure. This design brings the bridge a step closer to a purer image of structural art. This, however, is only a minor criticism of Ammann's design and is shown here to provide a point of comparison. Ammann could have also chosen a third option which would involve parallel upper and lower chords. However, this option would not necessarily appeal to Ammann's aesthetic intention which was drawn to either the crescent or spandrel form.

Though Ammann originally designed the Bayonne Bridge with masonry blocks as can be seen in Fig. 5, the Port Authority never built them. While Ammann argued that the towers at Hell Gate Bridge served a function in terms of the foundation at the abutments, Ammann's towers at Bayonne Bridge did not serve such a function and were designed only for aesthetic reasons. In the *Proceedings of American Society of Civil Engineers*, Ammann describes that the blocks "are but hollow structures with a steel framework carrying the floor above" [Ammann 1930b; see p. 490]. Ammann therefore carries over the aesthetics of the towers from Lindenthal's Hell Gate Bridge design. However, Ammann's towers are considerably less monumental and barely reach over the bridge deck. Lindenthal actually criticized the design of these towers for lacking bulk [Lindenthal 1930]. Like the form of the arch, the blocks of Bayonne Bridge represent a movement away from Lindenthal's aesthetic of monumentality. The fact that the blocks were never built demonstrates how aesthetic considerations were stripped away when function, efficiency, and economy were not included in the design.

Through this comparative analysis between the Hell Gate Bridge and the Bayonne Bridge, we see two different designer's interpretations of structure and art. While both the bridges are visually impressive, Lindenthal's structures masks its true function while Ammann's moves more toward structural art.

Detailed Analyses and Design

The following technical analyses demonstrate the efficiency of Ammann's design in its complete form and its safety during a phase in construction. See Fig. 6 for a portion of Ammann's design sheet for the Bayonne Bridge. Though we do not have access to Ammann's calculations (only his results are shown on these design sheets), we assume that he used a similar method of analysis to the calculations shown in the appendix of his paper on the Hell Gate Bridge. See [Ammann 1918a; p. 987-999] for these calculations.

Ammann designed the Bayonne Bridge to act as a three hinge arch under the dead loads of the upper and lower chord with the third hinge being a temporary pin connection at the crown of the lower chord (Joint L20 - See Fig. 7). When the last upper chord member is added, the bridge would then act as a two hinge arch under the live load and the dead loads of the posts and hangers, steel floor, and tracks and paving [Ammann 1928]. Since the bridge behaves first as a three hinge and then a two hinge arch under different loadings, we analyzed the systems separately and superimposed the results.

We first performed hand calculations to find the total horizontal and vertical reactions at one support. We used only the dead load panel concentrations as given on Ammmann's plans [Ammann 1928]. See Table 1 for the results of the hand calculations. We confirmed our hand calculations by performing a simplified finite element analysis using a two-dimensional model in Structural Analysis Program (SAP). For a more detailed discussion of these studies, see [Thrall 2007]. Ammann's design sheet lists his results for the horizontal and vertical reactions under dead load in the upper right hand corner (see Fig. 6 and Table 1). When compared with our calculations, we found that there is a .6 percent difference in the vertical reactions and a negligible difference in the horizontal reactions. This gives us confidence that our understanding of the bridge matches Ammann's.

Calculations of the horizontal and vertical reactions can indicate some aspects of the bridge behavior. From Table 1, we see that the horizontal reaction is roughly 30 percent larger than the vertical reaction. The dominance of the horizontal reaction is an indication of the ratio of the rise over the span. If we approximate the entire bridge as three hinge arch, then the horizontal reaction is given by $H = \frac{ql^2}{8d}$ and the vertical reaction is given by $V = \frac{ql}{2}$ where q is the uniformly distributed load, l is the span, and d is the depth. Therefore, $\frac{H}{V} = \frac{l}{4d}$. This relationship has clear implications regarding the form of the bridge. For example by increasing the depth, the horizontal reaction becomes larger with respect to the vertical reaction. In this respect, the ratio of the horizontal to vertical reactions of the Bayonne Bridge is an indication of the ratio of the rise to the span.

Our calculations in Table 1 also show that the three hinge analysis makes up 57 percent of the total vertical reaction and 54 percent of the total horizontal reaction. This shows that while the arch trusses (the dead loads used in the three hinge analysis) are the most visually dominant aspect of the bridge, they contribute to only just over half of the total horizontal and vertical reactions.

To further examine the behavior of the arch, we used our SAP model to calculate the axial forces in each member of the truss. We analyzed our two hinge and three hinge SAP models separately and summed the results to find the total axial forces in each member. For the detailed results of this study, see [Thrall 2007]. We then compared our results with those that Ammann calculated in his design sheets as seen in Fig. 6. We found that our results for the upper and lower chord members match Ammann's values within 1 percent. Our results for the diagonal members were also generally very good (within 7 percent) except for Member 19-20. For this particular member, the axial forces are very low: Ammann found the axial force to be 6 kips, while we found it to be 4.69 kips. This difference of 2 kips can be considered negligible compared to the magnitude of axial forces in other members. Unfortunately we had very poor results for the axial forces in the vertical members. However, the total value for these forces is also relatively small. For instance, the axial force in the vertical member L_0U_0 is just 6 percent of the axial force in the lower chord member L_0L_1. So we will not consider this difference an invalidation of our results.

The magnitudes of the axial forces of each member give an indication of the overall behavior of the arch. The lower chord is the primary load bearing aspect of the bridge under dead load. When comparing the axial forces due to dead load only, the upper chord carries just 33 percent of the axial force of the lower chord at the crown (between joints 19 and 20) and 3 percent at the hinge (between joints 0 and 1). Though we did not perform calculations involving the live load, Ammann's calculations for the axial forces can be seen in Fig. 6. The upper and lower chords carry roughly the same live load at the crown, but at the hinge the upper chord carries just 19 percent of the value of the lower chord. Therefore under both the dead and live load, the upper chord becomes progressively less important as a load-bearing member as it reaches the hinges. This shows that there is no structural advantage to increasing the depth of the truss at the hinge and suggests that the upper chord could have been brought down to the hinge like the crescent form at Garabit. Though this is a mild criticism of Ammann's design, it is important to note that his choice of form is an improvement over Hell Gate Bridge which featured a reversal of curvature of the upper chord at the hinges.

We examined the stresses in the members of the lower chord under both the dead load and the design stress load to consider the efficiency of Ammann's design. When looking at the dead load, we considered the full dead load of the truss, posts and hangers, tracks and paving, and deck. Ammann defined the design stress load as the "most unfavorable" of the following group load cases:

A = D + L + I + T "permissible basic unit stresses"

B = D + T + W "permissible basic unit stresses"

C = D + L + I + T + .5W "permissible basic unit stresses +10%"

E = D + .5(L + I) + T + W "permissible basic unit stresses +10%" [Ammann 1928]

where D is the dead load, L is the live load, I is impact, T is temperature, and W is wind. Ammann calculated the axial force under the dead load and what he determined to be the design stress load for each member. We used these calculations and his values for the cross-sectional areas of each lower chord member to calculate axial stresses. For detailed results of the stress in each member, see [Thrall 2007]. We found the stress under dead load to range from 17.74 ksi (122.3 MN/m^2) to 21.26 ksi (146.6 MN/m^2) and the stress under design load to range from 24.56 ksi (169.3 MN/m^2) to 30.01 ksi (206.9 MN/m^2). The values of the stress in the lower chord are similar among members, suggesting that Ammann designed the bridge to use the material uniformly throughout. The lower chord is made of Carbon-manganese steel with an allowable stress of 28 ksi (193.1 MN/m^2) in compression [Dana 1930]. Most of the stresses under the design load are very close, but just below this value of allowable stress, suggesting excellent efficiency in these members. The efficiency ranges from 0.88 to 1.07 with an average efficiency of 0.98. However, several members actually exceed the allowable stress. The two members with the highest stress are member 3-4 (29.22 ksi (201.5 MN/m^2)) and member 4-5 (30.01 ksi (206.9 MN/m^2)). These represent load cases E and C, respectively, and therefore are permitted stresses 10 percent above the allowable (30.8ksi (212.4 MN/m^2)) which places both members within permissible range. The remaining members which exceed a stress of 28 ksi (193.1 MN/m^2) (members 8-9, 9-10, 11-12, 13-14, 14-15, and 15-16) do so by a negligible amount (at most 1 percent). We can then conclude that Ammann designed very efficient members throughout the lower chord and that he did not waste material.

Considerations regarding feasibility and safety of erection were also taken into account. The American Bridge Company, the company in charge of the erection of the arch, cited two possible methods of erection: 1) anchoring the arch at each bank and cantilevering out each side of the bridge until they meet or 2) using falsework in the river to support the arch until closure. The first method would have required expensive anchorages and towers with ties at each shore. While the second would take advantage of the bedrock at the bottom of the river on which falsework could be built. Furthermore, the falsework could be constructed out of the materials which would eventually be used in the final form of the structure. The second method was ultimately chosen. Ammann's original design with the hinge at the crown of the bridge (the design that we have thus far analyzed) would have required falsework close to the Staten Island side, interfering with shipping. The design was then changed to include an asymmetrical construction with the closure of the arch at Joint L14 South. When construction of both sides of the truss was complete (except one member of the upper chord) both sides were lowered onto a pin in the lower chord at Joint L14, thus forming a three hinge arch (See Fig. 7). The falsework was removed and the remaining member was added to the upper chord, thereby converting it into a two hinge arch [Troelsch 1931].

Though changes to the original design of the bridge were made for construction reasons, Ammann still clearly considered the construction of the bridge in his design. His design of the bridge first as a three-hinge arch under the dead load of the upper and lower chords and then as a two-hinge arch in its final form, shows that he planned to construct the bridge using falsework until the lower chord was closed. This shows that in his design Ammann had a true builder's mentality.

The American Bridge Company cites that the erection of the arch using the falsework method puts members under stresses for which they were not originally designed. For example, at the phase of construction shown in Fig. 8, several panels are cantilevered beyond falsework at Joint L10 and therefore the top chord is put into tension where in its final form it would only see compression. Several modifications to the original design of the arch were made in order to account for these stresses. See [Troelsch 1931] for a complete review of these modifications. For the purpose of this study, we considered one phase of construction as represented in Fig. 8. We based our study on the calculations shown in one stress sheet [Ammann 1930c]. We assumed that the piece of falsework at Joint L11 was pin connected on both ends. The drawings suggest that it was also connected at a right angle to Joint L10, but we chose to ignore this in order to simplify the analysis. We used our SAP model to calculate the stresses in the members for which we have the original calculations, applying only the dead load panel concentrations of the upper and lower chords. The results of this analysis can be seen in Table 2. We found that our results were in good agreement with the original calculations, most much less than 15 percent different. There was one fluctuation for member $U_{11}L_{12}$ which was 33 percent different. We can most likely attribute this difference to several factors, including: 1) our assumptions in modeling the construction phase and 2) our neglect of the additional load of the traveler. Overall our results were in good agreement with the original calculations.

Table 2 also compares the stresses with the allowable stress for each member, considering the type of steel and whether it is in compression or tension. See [Dana 1930] for a review of the steel used in each member. Each member is well within the allowable stress, except for one diagonal member ($U_{10}L_{11}$). The diagonal members are made of carbon steel with an allowable stress of 17 ksi (117.2 MN/m^2) in compression [Dana 1930]. Though this value exceeds the allowable stress for carbon steel, the company allowed an increase of 20 percent over the allowable stress during the construction process, bringing the permissable stress for the diagonal members up to 20.4 ksi (140.7 MN/m^2). Though this still does not bring this specific member into the permissible range, the American Bridge Company does note that some of the web members of the truss were strengthened for construction stresses [Troelsch 1931]. A diagram in [Troelsch 1931] indicates that this diagonal member was indeed strengthened to resist erection stresses. Table 2 also shows that when panels 12, 13, 14, and 15 are cantilevered over the end of the falsework, member $U_{10}U_{11}$ is put under tension which it would not see in the final form. However, it only reaches a stress of 7.1 ksi (48.95 MN/m^2) which is well within the allowable tensile stress and therefore does not pose a problem.

This study suggests that Ammann designed the Bayonne Bridge for efficiency in its final complete form, but that the members were also checked for safety under construction. Through these analyses, we have been able to replicate Ammann's calculations with very good accuracy. This close correlation allows us to explain Ammann's design with some confidence in his choice of members and of overall form.

Conclusion

Othmar Ammann's education in the Swiss tradition of structural engineering and his experience working under Lindenthal were highly influential to his career and crucial to his success as the designer of the Bayonne Bridge. Through the technical analysis in this paper, we can conclude that his design was efficient and used minimal materials. From this minimal use of material and the fact that the bridge came in well under budget, we can conclude that his design was economical. It is this simultaneous attention to economy and efficiency, in both design and construction, that allows us to define him as a master builder. Furthermore, from his own powerful writing regarding the Hell Gate Bridge, we have a sense of his aesthetic considerations and the elegance which he sought. With this evidence that Ammann considered efficiency which is the central ethos of engineering (not to waste natural resources) economy which is the primary ethic of engineering (not to waste public money), and elegance which arises from the engineer's aesthetic motivation, we can conclude that the Bayonne Bridge is a work of structural art. Indeed the bridge is a great work of structural art but it is not above criticism which we have identified through the spandrel form of the arch and the plan for useless masonry facaded blocks at each end. We do not pretend to be designers but rather as scholars it is crucial to the profession to engage in careful historical context, detailed structural analysis, and only then careful criticism. Ammann was after all the best American bridge designer in steel and his works are worthy of the closest attention. Ammann himself was aware of criticism as essential to development as is clear through his implied self criticism in the development of his suspension bridge designs from the George Washington to the Bronx-Whitestone culminating in his spectacular Verrazano-Narrows Bridge.

Aside from making this qualification of the Bayonne Bridge, we can also see that there are many valuable lessons to be learned from Ammann which have implications for bridge design today. Ammann's article "The Hell Gate Arch Bridge and Approaches of the New York Connecting Railroad Over the East River in New York City" was essential to this study and shows both the importance of reflecting on precedents in bridge design and of writing scholarly work on current designs. By reading his discussion of the precedents to the Hell Gate Bridge form, including the spandrel form at Bonne and the crescent form at Garabit, one can gain an idea of the designer's motivations. This is highly valuable for young engineers today as they can learn from great engineers of the past and serves as encouragement for current engineers to write scholarly works about their own structures for the benefit of future generations. In this article Ammann also stresses the aesthetics of bridge design within his disciplined plans for efficiency and construction economy, a quality which is becoming increasingly important today. Another lesson to be learned is the value of performing hand calculations. As we have shown in this study, Ammann's hand calculations can be reproduced and are accurate compared with finite element models of today. While computer modeling has grown in popularity, especially with young engineers, it is always important to perform hand calculations to verify results. These calculations can be quick and yield accurate results, thereby allowing engineers to explore a variety of forms before settling on a design. Our study has also shown the safety of the bridge during a phase in construction. After the collapse of the I-35 bridge in Minnesota, whose design was simply copied from a series of standard forms, it is clear that each bridge needs to receive individual care and special design attnetion that was characteristic of Ammann's designs. Such considerations are crucial to engineers today. Through these lessons, studying the Bayonne Bridge and the motivations of its designer can have implications for bridge engineers today.

The Bayonne Bridge, aside from being a piece of structural art, is also a historic landmark. Though much has changed since 1931, the Bayonne Bridge remains an outstanding piece of structural art and a monument to both Othmar Ammann and the Port Authority.

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The writers would like to thank Professor Ted Zoli for his help regarding the geometry and modeling of the bridge. Frank Lombardi and Tom Wagner of the Port Authority of New York and New Jersey have generously spent time and energy to provide access to the plans and documents about the Bayonne Bridge. Also, we would like to thank Ted Segal, Powell Draper, and Katie Kelly for their help with the computer analysis. We are also very grateful for financial support from the National Science Foundation Grant No. 0095010.

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Figure 1: The Bayonne Bridge and the Hell Gate Bridge. *These figures show the Bayonne Bridge (top) and the Hell Gate Bridge (bottom) (courtesy of the Structurae Website, Source: Library of Congress - Historic American Engineering Record [Janberg 2007a], [Janberg 2007b]).*

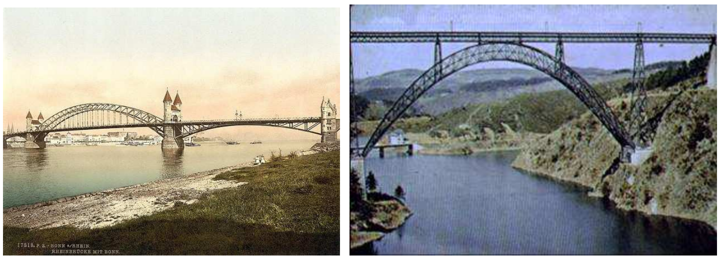

Figure 2: Precedents for Arch Bridges. *The left image is a picture of the Rheinbrcke Bonn-Beuel Bridge (courtesy of the Structurae Website, Source: Library of Congress [Janberg 2007c]) and the right image is picture of the Garabit Viaduct (photograph by David P. Billington).*

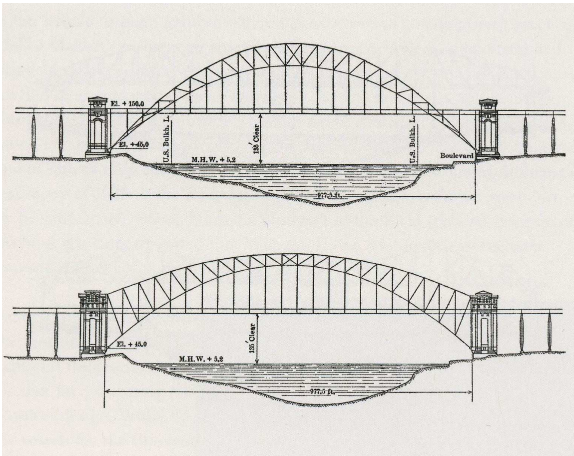

Figure 3: Lindenthal's Arch Designs. *These images are Lindenthal's sketches for the crescent form (top) and the spandrel form (bottom) (courtesy of the ASCE, Source: "The Hell Gate Arch Bridge and Approaches of the New York Connecting Railroad Over the East River in New York City," [Ammann 1918a]).*

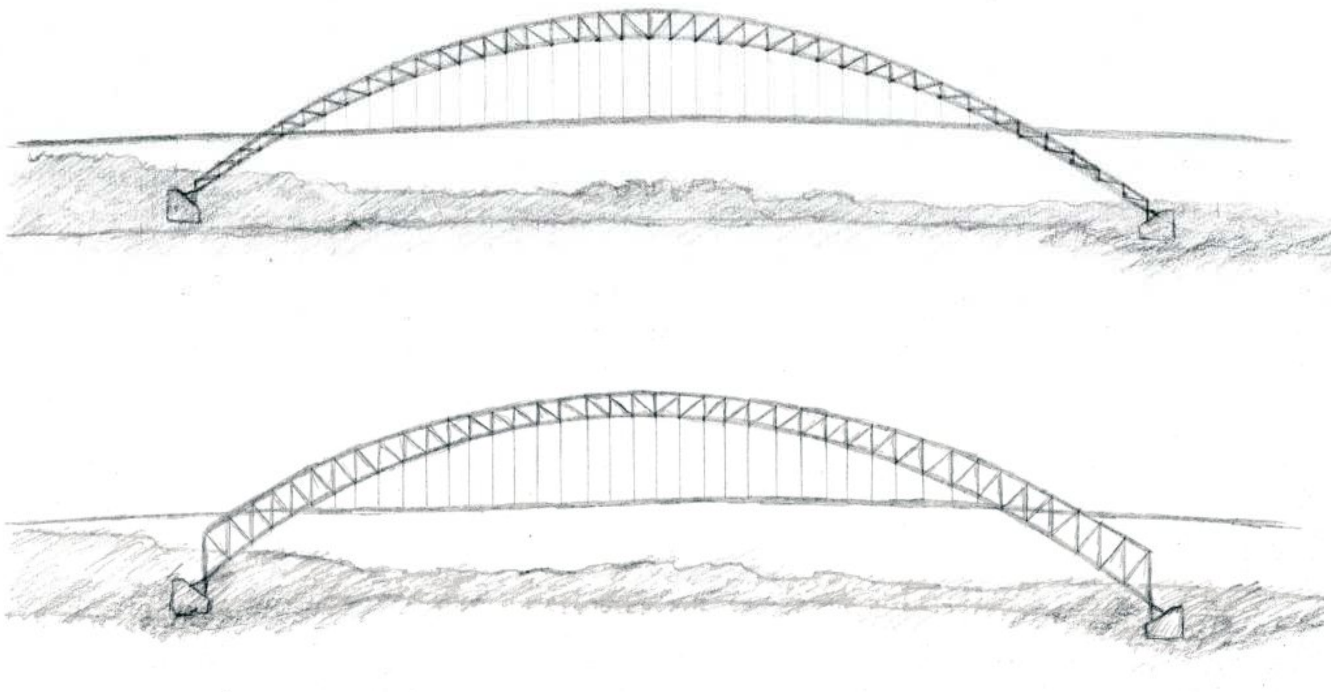

Figure 4: Sketch of Bayonne as a Crescent Form. *The top sketch is of the Bayonne Bridge as designed by Ammann. The bottom sketch is our sketch of the Bayonne Bridge if designed as a crescent arch (Source: sketches by Marilyn Parkinson Thrall and Ashley Thrall).*

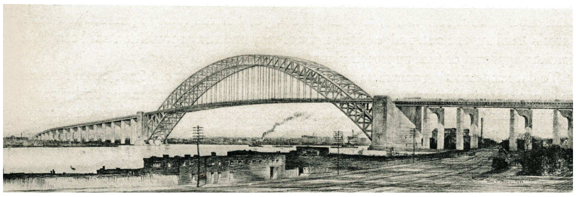

Figure 5: Original Design of the Bayonne Bridge. *This is a sketch of the original design of the Bayonne Bridge with its towers (courtesy of the Port Authority of New York and New Jersey, Source: "First Progress Report on Kill van Kull Bridge" [Ammann 1930a]).*

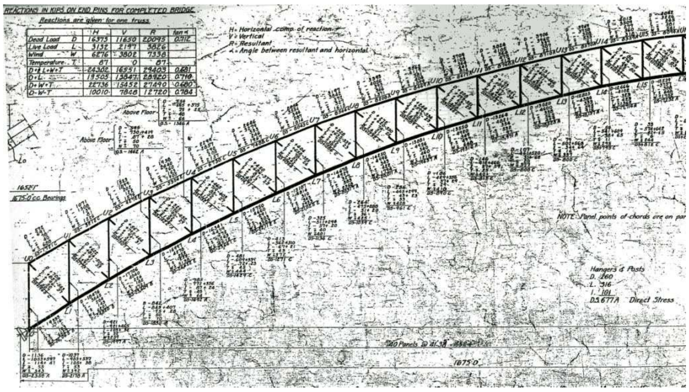

Figure 6: Ammann's Design Sheet. *This image shows a portion of Ammann's design sheet (courtesy of the Princeton University Ammann Archive [Ammann 1928]).*

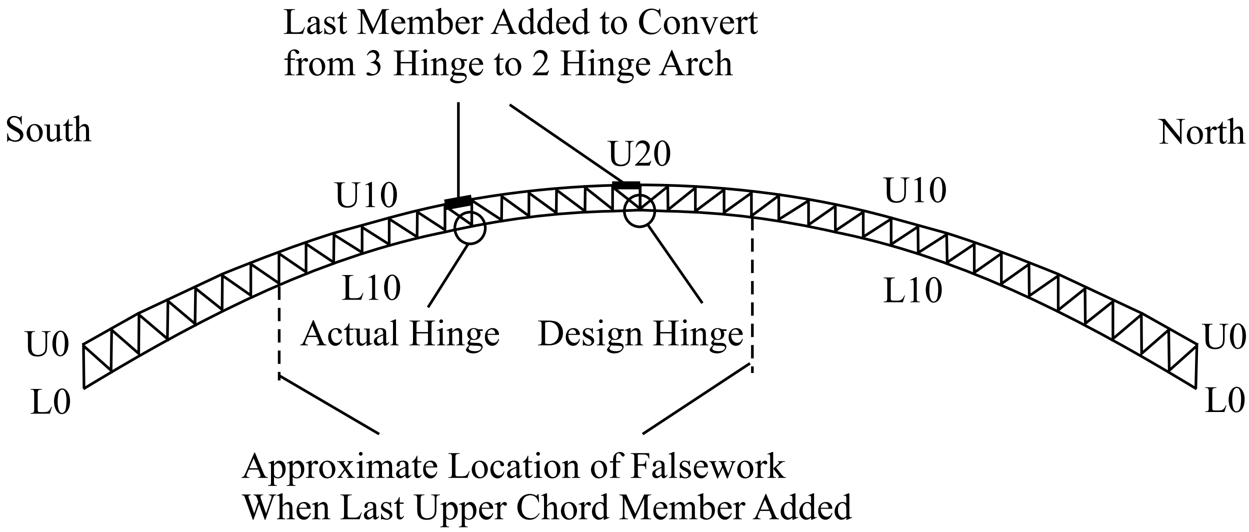

Figure 7: Joint Labeling Scheme. *This figure shows Ammann's labeling system for the joints of chords. U refers to the upper chord and L refers to the lower chord. Joint 20 is at the crown and Joints 0 are at the hinges. The joints have been individually labeled at intervals of 10. Key members and the location of the design and actual hinges have been highlighted [Troelsch 1931].*

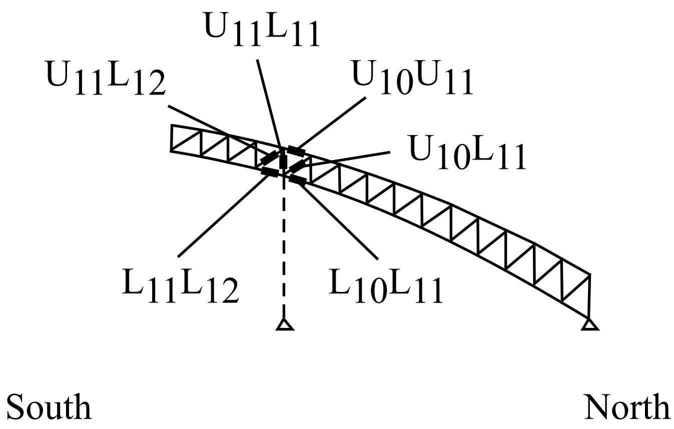

Figure 8: Construction Sketch. *This sketch represents a phase of the construction where the falsework is the column (marked by dashed lines) which is connected at Joint L11. The members for which original calculations were available are labeled [Ammann 1930c].*

	$V(k(MN))$	$H(k(MN))$
Three Hinge Analysis	6570 (29.2)	8820 (39.2)
Two Hinge Analysis	5010 (22.3)	7550 (33.6)
Sum of Hand Calculations	11580 (51.5)	16370 (72.8)
Ammann's Calculations	11650 (51.8)	16373 (72.8)

Table 1: Study of Support Reactions. *This table summarizes the results of our hand calculations for the total horizontal reaction (H) and the total vertical reaction (V). The first row shows the results of our three hinge hand analysis, the second row shows the results of our two hinge hand analysis, and the third row shows the sums of these two analyses. The fourth row shows Ammann's results [Ammann 1928].*

$Member$	$Given$ $(ksi(MN/m^2))$	SAP $(ksi(MN/m^2))$	%	$Allowable$ $(ksi(MN/m^2))$
$L_{10}L_{11}$	-1.2 (8.3)	-1.05(7.2)	13	-28 (193)
$L_{11}L_{12}$	-4.0 (27.6)	-3.96 (27.3)	.96	-28 (193)
$U_{10}U_{11}$	+7.1 (49.0)	+6.90 (47.6)	2.9	+27 (186)
$U_{10}L_{11}$	-23.2 (160)	-25.2 (173)	8.7	-17 (117)
$U_{11}L_{11}$	-12.2 (84.1)	-12.4 (85.5)	1.6	-17 (117)
$U_{11}L_{12}$	+10 (69.0)	+13.4(92.4)	34	+20 (138)

Table 2: Construction Stresses. *This tables compares the stress given on the construction stress sheet with our SAP analysis for a particular phase of construction. The first column refers to the member (see Fig. 8). The second column shows the axial stress given on the construction stress sheet [Ammann 1930c]. The third column gives the stresses as calculated in our SAP model. The fourth column presents the percent difference between our SAP value and that of construction sheet. The fifth column gives the allowable stress for each member [Dana 1930].*

Below are the captions for each figure:

The Bayonne Bridge and the Hell Gate Bridge. *These figures show the Bayonne Bridge (top) and the Hell Gate Bridge (bottom) (courtesy of the Structurae Website, Source: Library of Congress - Historic American Engineering Record [Janberg 2007a], [Janberg 2007b]).*

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Construction Sketch. *This sketch represents a phase of the construction where the falsework is the column (marked by dashed lines) which is connected at Joint L11. The members for which original calculations were available are labeled [Ammann 1930c].*