Cabin John Bridge: Role of Alfred L. Rives, C.E.

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Abstract: The Cabin John Bridge (CJB), located just outside Washington, D.C., is a masonry arch with a central angle of 110°, an intrados radius of 40.9 m (134 ft), and a span of 67 m (220 ft). Construction of the bridge began in 1857 but was not completed until late in 1865 because of suspensions due to lack of appropriations and the Civil War. The CJB is part of the Washington Aqueduct (WA) and is still the longest single-span masonry arch in the United States. The bridge was designated a National Historic Civil Engineering Landmark by the ASCE in 1972. The paper provides context for the bridge design and explains the construction technologies that were used. In the process, French and British influences on American masonry arch design practices at mid-19th century are revealed. The respective roles of Captain Montgomery C. Meigs, the chief engineer of the WA, and Alfred Landon Rives, his assistant engineer, are critically assessed. The paper provides, for the first time, relevant facts on Rives’ education and engineering career. The performance of the bridge over 145 years is reviewed and discussed.

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Introduction

Fig. 1 shows the Cabin John Bridge (CJB), located just outside Washington, D.C. It is a masonry arch with a central angle of 110°, an intrados radius of 40.9 m (134 ft), and a span of 67 m (220 ft). Construction of the bridge began in 1857 but, after suspensions due to lack of funding and the Civil War, was not completed until late in 1865. Although a masonry arch with an estimated span of 72 m (236 ft) existed over the Adda River at Trezzo, Italy, from about 1377–1417 (Baker 1909; Sejourne 1913), the CJB was the longest single-span masonry arch in existence in 1864 and remained so until the 1903 completion of the Adolphe Bridge in Luxembourg. The CJB is part of the Washington Aqueduct (WA) bringing water from the Great Falls of the Potomac River to Georgetown and is still the longest single-span masonry arch in the United States. It carries an aqueduct conduit over the ravine of Cabin John Creek, now supplemented by a second conduit built in the 1920s. Under normal operating conditions, both conduits presently carry water (Gamby, Deputy General Manager, Washington Aqueduct Office, Washington, D.C., personal communication). The original conduit within the spanned area of the CJB has an enviable record of carrying water for over 145 years. The bridge was designated a National Historic Civil Engineering Landmark (NHCEL) by the ASCE in 1972.

Despite the uniqueness, importance, and performance of the CJB, historical literature provides neither explanation nor context for its design. A principal reason for this is the tragic progression in the relationship between the two principals involved in its construction: Montgomery C. Meigs and Alfred L. Rives. Meigs was a West Point graduate, a proud member of the U.S. Army Corps of Engineers, chief engineer of the WA, and future quartermaster general of the Union army. Rives was a graduate of the renowned École des Ponts et Chaussées (EPC), proudly placing C.E. after his name, a civilian "assistant engineer" on the WA, and the future acting chief of the Engineer Bureau of the Confederate States. Meigs and Rives are emblematic of the relationships between military chief engineers and civilian assistant engineers and of the divisive allegiances to Union and Confederate causes. These two issues have clouded historical assessments of the design of the CJB.

Another reason for the lack of historical context for the design of the CJB is that at mid-19th century, masonry arch design was rapidly evolving from geometry-based methods to graphics-based equilibrium methods, largely developed by French theorists. Such methods were used only for a relatively brief period of time, until linear elastic design approaches were formulated in the 1880s. Modern engineers and engineering historians are often not familiar with graphics-based methods, and they are therefore rarely explained.

This paper rigorously examines the roles of Meigs and Rives in the design and construction of the CJB. For the first time, facts are presented on Rives’ education and engineering career. The French method used to analyze the bridge and the British precedent on which the design is based are explained. The long construction timeline and the innovative construction technologies used are discussed. Lastly, the performance of the bridge over 145 years is reviewed.

WA, Montgomery C. Meigs, and Assistant Engineers

Although many ideas for a comprehensive water supply system had been proposed over the years, at mid-19th century, Washington still relied on springs and wells for its water (Macqueen 1934;
Ways 1996). In 1850, Congress authorized funds for a study to determine "an unfalling and abundant supply of good and wholesome water." Colonel George W. Hughes of the Corps of Topographical Engineers performed the study and submitted a report to Congress in March 1851 (Hughes 1851). Col. Hughes identified the two logical sources of water for the city: the Potomac River at Great Falls, Maryland, approximately 15 km (9 1/4 mi) upstream from the city, and Rock Creek, a stream within the city boundaries. Rather than proceeding with Col. Hughes' plan, Congress appropriated funds for additional studies. On November 3, 1852, Lieutenant Montgomery C. Meigs was assigned the task. He began his work by studying the two prominent, recently completed aqueducts in the region: the Croton Aqueduct, finished in 1842 to serve New York City, and the Lake Cochituate Aqueduct, opened in 1848 to serve Boston, Massachusetts. Meigs submitted his final report to Congress after a little more than 4 months. He concluded that the only reliable source of "good and wholesome water" was the Potomac River at Great Falls. Fig. 2 shows a sketch of the Washington water system ca. 1949 (Schmitt and Macqueen 1949). The principal features of the original plan are:

- A dam across the Potomac at Great Falls such that the hydraulic head is approximately 45.7 m (150 ft) above high tide at Washington;
- A rock/masonry conduit from Great Falls toward Washington, following the path of the existing Chesapeake and Ohio (C&O) Canal;
- A "receiving" or "settling" reservoir at Little Falls Branch, now called Dalecarlia; and
- A rock/masonry conduit from the Little Falls Branch reservoir to a "distributing" reservoir at Georgetown.

The plan required approximately 1.4 km (3/4 mi) of rock tunnel and two long-span bridges for crossing Cabin John Creek and Rock Creek. Meigs completed conceptual designs for both a 2.13-m (7-ft) and a 2.74-m (9-ft) diameter conduit. In an effort aimed at economy, Meigs felt his duty was to "devis[e] a work presenting no considerable difficulties, and affording no opportu-
nities for the exhibition of and triumphs of science or skill" (Meigs 1853). In this spirit, his original conceptual design for the aqueduct bridge over Cabin John Creek followed the precedent of the Harlem River crossing of the Croton Aqueduct (Lankton 1978). Meigs proposed “six semi-circular arches of 60 feet span, resting upon piers 7 feet thick by 20 feet long.” In addition to emphasizing the economic feasibility of the entire aqueduct, Meigs repeatedly noted in his report that the hydraulic head at Great Falls would allow a gravity system, without significant pumping, so that the water could be delivered “in the Capitol fourteen feet above the upper floor” (not an insignificant point for Congress). On March 3, 1853, Congress decided to build the larger conduit and appropriated $100,000 to begin construction, effectively providing a unique career opportunity for Meigs.

Montgomery C. Meigs was born on May 3, 1816, in Augusta, Georgia, but grew up in Philadelphia and graduated from West Point in 1836. The following year, he became a member of the elite Corps of Engineers and subsequently helped build fortifications at Detroit, at Rouses Point on Lake Champlain, on the Delaware River, and at other posts. One of his earliest assignments was as an assistant to Lieutenant Robert E. Lee. In 1849 and 1850, he was assigned to the Engineer Bureau in Washington as assistant to General Joseph G. Totten, chief engineer of the army (Ways 1996). It was the success of his report on the WA that began his very public career. Immediately following his March 1853 report, Meigs was promoted to captain and appointed chief engineer of both the WA and the U.S. Capitol Extension. Macqueen (1934) and Ways (1996) chronicled his work on the WA, and Dickinson et al. (2001) discussed his work on the U.S. Capitol. Meigs’ already full portfolio of work expanded in February 1855, when he was made chief engineer of the extension of the General Post Office in Washington. Meigs scrupulously managed the finances of these projects, earning the respect and support from Congress and, understandably, a few powerful political enemies. These enemies were able to “banish” Meigs from the nation’s capital from October 1860 to February 1861 (East 1939). Upon the start of the Civil War in 1861, Meigs was appointed quartermaster general of the Union army. Wegley (1959) described his significant contributions to the Union victory in this vitally important position. Meigs’ formal involvement with the WA ended in 1862, approximately 2 years before the aqueduct was placed permanently in service, when authority for the WA was transferred from the War Department to the Department of the Interior. Meigs was an avid chronicler of his life, work, actions, and thoughts. He wrote shorthand journals (Wolff 2001), kept pocket diaries, and assembled scrapbooks on his projects. Collections of Meigs’ documents exist at the Manuscript Division of the Library of Congress, at the National Archives and Records Administration, at the Office of the Architect of the Capitol, and at the WA Office. Collectively, these documents provide a unique, although naturally one-sided, record of three important public projects in Washington as well as glimpses of political and social milieu.

Meigs’ appointment as chief engineer for three large projects followed the Congressional custom of entrusting major public works only to members of the elite Corps of Engineers. In practice, military chief engineers hired “assistant engineers” who were generally civilians. These assistants typically had practical experience on other civil projects that often were canals. Sometimes they were graduates of private or state military schools such as Norwich University or Virginia Military Institute (VMI), or graduates of some of the nation’s oldest engineering schools like Union College or Rensselaer Polytechnic Institute (Greene 1855), or graduates of “scientific schools” such as those at Dartmouth, Yale, or Harvard (Lundgreen 1990). But at mid-19th century, these engineering programs were still small and civilian engineering societies were very much in their nascent stages. It is understandable, then, that the established graduates of West Point overshadowed these civilian assistant engineers, men whose roles remain almost completely unexplored. Considering the scope of work under Meigs’ charge, it was not possible for him to personally handle all the required conceptual and detailed design, all the development of construction technologies, and all the construction management. Therefore, much of this work had to be delegated to assistant engineers. Fig. 3 shows a seated Meigs surrounded by his assistant engineers: Alfred L. Rives, Edmund D. T. Myers, Charles G. Talcott, and William R. Hutton. Not shown is his principal assistant engineer, William H. Bryan, a civilian who began working with Meigs on the WA study. In the report to Congress on the study, Meigs gave an unqualified recognition of the role Bryan played.

To Mr. William H. Bryan, civil engineer, who conducted all the explorations for bringing the water from the Potomac, I am under particular obligations. His knowledge of the river, gained during a long experience upon the Chesapeake and Ohio canal, was invaluable. It enabled him to make valuable suggestions, many of which I have adopted; and indeed, we have discussed together the various means of mastering the difficulties of the problem, till it would be difficult to determine which of us many of its features originated: while his zeal and untiring industry in the office have alone enabled me so soon to present the estimates in the complete state in which they now appear (Meigs 1853).

This was no statement of false modesty by a man with a well-known predilection for memorializing his accomplishments in print, stone, and iron. Meigs was clearly making a statement of fact: Meigs and Bryan prepared the overall plan of the WA. In the spirit of historical understanding and objectivity, it is similarly important to examine and assess the role of Alfred L. Rives in the design and construction of the CJB.
Alfred Landon Rives

Alfred Rives' father, William Cabell Rives (pronounced Reeves), was a prominent politician, diplomat, and writer from Albemarle County, Virginia. Beginning in 1822, he served three terms in the U.S. House of Representatives. From 1829 to 1832, he served as minister to France for President Andrew Jackson and was subsequently elected to the U.S. Senate for three terms. He was again minister to France from 1850 to 1853 (Lison 1972). He produced a three-volume History of the Life and Times of James Madison between 1859 and his death in 1868. The Rives and Madison family homes were only about 30 km (18.5 mi) apart, and W. C. Rives was given full access to Madison's manuscripts and papers. Alfred's mother, Judith Page Walker Rives, was also a writer, publishing recollections of her life in France and on other domestic themes.

Alfred Rives was born in Paris, France, on March 25, 1830, while his father was ambassador there. His childhood, however, was spent on the family home, called Castle Hill, in the piedmont region of Virginia, near Charlottesville. He was tutored at home until 14 and attended Concord Academy in Caroline County, Va, for 2 years. Rives then enrolled at the VMI, graduating in 2 years, sixth in a class of 24 but “first in engineering.” He briefly enrolled at the University of Virginia (UVA), receiving a diploma in French language and literature, but left to accompany his parents to France in 1849, when his father was again appointed minister. No doubt Rives wanted to study engineering in France, then the acknowledged leader in the theoretical training of engineers. At this time, Alfred proposed, according to his mother, “to follow the career of the world-renowned Stevenson [Robert Stephenson], whose fame and power were then at their zenith!” (Judith Page Walker Rives 1871). At mid-19th century, training of the elite French corps of engineers normally consisted of theoretical preparation at the École Polytechnique and then additional study at one of the écoles d’application, such as the EPC. Up to 1851, EPC enrolled only Frenchmen; no official register of “international” students prior to 1851 exists (Saquet, “Documentaliste du Fonds Ancien, Ecole Nationale des Ponts et Chaussées,” Paris, personal communication; Lundgreen 1990). Rives' mother recalleed that “With great difficulty his father obtained for him an entrance into the EPC, the highest engineering school in France, I might say, in the world. Foreigners had never been admitted into this sanctuary, and there was no little grumbling when the exception was made in Alfred’s favor” (Judith Page Walker Rives 1871). Rives, in fact, passed a rigorous entrance examination and was formally admitted as an élève externe in July 11, 1851 (Saquet, “Documentaliste du Fonds Ancien, Ecole Nationale des Ponts et Chaussées,” Paris, personal communication). That year's entering class consisted of ten élèves internes, all “top graduates of the École Polytechnique” and two élèves externes, Rives and Polish national Victor Hube (Rives 1876, 1895a). Rives family papers at the Library of Congress, the UVA (Rives 1853b), and at Duke University (Rives 1853a) contain substantial material on Rives' years of study at EPC. After his second year of study, during the summer of 1853, Rives was asked by the French minister of public works to inspect and report on recently completed public works projects in America, a task that was greatly facilitated by his father’s letters of introduction. Rives traveled to Boston, New York City, West Point, Philadelphia, Baltimore, and Washington (ALR to JR, 7/8/53, DU). At West Point, Rives met with Professor Dennis Hart Mahan, who, in turn, wrote a letter of introduction to Col. Sylvanus Thayer of the corps of engineers. Mahan and Thayer were, at the time, two of the most influential engineers in the nation. The UVA collection includes Rives' notebooks on the Cours D'Architecture, Cours de Chemins de Fer, Machines a Vapor, and miscellaneous notes on Mécanique Applique. It also includes a paper by Rives entitled Concours de Grand Pont, a competitive design project/exam for a large bridge. Here Rives remarked on the Grosvenor Bridge over the River Dee at Chester, a record-setting, 61-m (200-ft) span masonry arch that opened to the public in 1834 (ICE Transactions 1842). Rives' paper also contained an explanatory section on the Théorie de M. Méry, which was a graphical analysis method for mas only arches published in the Annales des Ponts et Chaussées (Méry 1840). The UVA collection also includes copies of drawings purchased by Rives. These wonderfully detailed and carefully conserved drawings include the Newark Dyke Bridge and the Newcastle and Berwick Railway High Level Bridge, as well as several suspension bridges.

By his final year in 1853–1854, Rives (1854) had accomplished a remarkable academic feat, rising to the top of his class and besting all his classmates from the École Polytechnique. Rives proudly told his parents, he “had the pleasure at my last examination of being 2nd in steam engines and 3rd in sea ports putting me first in general.” It was an honor he shared with two other classmates (ALR to JR, 4/18/54, DU). “I have succeeded at the Ecole this year beyond my highest expectations,” he continued, “having come out on the studies I followed absolutely first; what you might judge important first in travaux maritimes” [ports and harbors]. In light of his exceptional academic success, the French minister of public works approved a gift of some 150 volumes from the school to Rives with a presentation title printed on the covers in gilt letters (ALR to WCRJ, 7/11/54, LC). The volumes consisted of “1) La Collection des Annales des Ponts et Chaussées (10 volumes); La Collection des Annales des Mines depuis 1822 jusqu’a present, comprenant (Les années antérieures à 1822 n’existent plus an Dépôt) (63 volumes); Lesbros, Expériences Hydrauliques, un volume; et Redgiminaute, Pont de Moulin.” The collection of the Annales des Ponts et Chaussées was an especially valuable one that Rives apparently later kept with him at the WA. Rives, the first American graduate in the register of the EPC, received his diploma on December 21, 1854 (Saquet, “Documentaliste du Fonds Ancien, Ecole Nationale des Ponts et Chaussées,” Paris, personal communication). Unfortunately, Rives had contracted a severe infection in September 1854 that required almost 4 months convalescence. He departed France aboard a steamer on January 13, 1855.

Following a brief employment with the Virginia Midland Railway (Rives 1855a), and no doubt with the help of his father, Rives was hired by Meigs as an assistant engineer in May 1855, shortly after the Post Office extension was added to Meigs' portfolio of projects. Rives' initial responsibilities primarily lay with the Capitol Extension and with the Post Office, but early in June he accompanied Meigs along the C&O canal to the Great Falls and beyond to the Seneca Creek quarry to visit aqueduct works. Shortly after, Meigs visited the Post Office construction site and gave directions to accelerate the work. “Neither this nor the smithery of the roof of the Capitol goes on as fast as I could wish,” he recorded in his journal. So he placed the ironwork under Rives' direction. “He is to see what has been done already,” Meigs noted, “and give such orders as will secure a rapid completion of the whole work so that no part shall be delayed by waiting for winter” (Meigs SJT 6/11/55). In August, Rives cataloged his responsibilities for his brother.
"I am engaged in calculating and estimating the strength and distance apart of the Post Office iron floor girders; in superintending the construction and erection of four large boom derricks for Post Office (70 foot mast and 60 foot beam) together with the trestle work on which they are to rest; in the construction and superintending two derricks for Post Office stone cutting shops, and Rail Road 700 ft long for ditto; in making drawings for suitable truck to receive the stone, and for a bridge to cross a creek over which the R.R. will pass; in superintending, constructing and locating a large derrick to unload stone from R.R. trucks of Baltimore and Washington RR; in superintending and laying off walls, placing bolts and arranging machinery to test the tie beams of the roof of the Capitol Extension (the drawings of a large portion of the machine being my own); in determining the level of floors, courses of stone, &c in Post Office and Capitol Extensions; in calculating and revising beams of iron for Gate House for WA, weighing about 10,000 lbs apiece; in superintending construction of roof of Senate and House of Representatives; in now and then assisting in the adjustment of some nice machinery, such as that lately put up by Capt. Meigs to facilitate the work of the sculptors. In addition to this, the Capt. left yesterday for New York, but before leaving called me up, and told me, if possible, to make all necessary arrangements (for which he gave me full powers) before his return on Wednesday next, for putting up the heavy scaffolding to be used in pulling down the old, and putting up the new, done." (ALR to WCRJr, 8/19/55, LC)

By early September, Rives had established his working relationship with Meigs. "My position is now very agreeable, though laborious one," he wrote his father, "as I have complete control over the works under my charge. Capt. Meigs only now and then making a suggestion, or giving me advice when I call his attention to any delicate point. None of the other assistant engineers or employees of that description in the Capt.'s office or even about the Capitol can say the same" (ALR to WCR, 9/2/55, LC). In mid-November, Rives was placed in charge of a section of the aqueduct construction near Great Falls to temporarily replace another assistant engineer who had taken ill. "This I hope is the dawning of a new era in my professional life," he told his mother, "as I am to have charge of a party, and be division engineer at the most important point of the aqueduct, and the one least subject to supervision from higher authority" (ALR to JR, 11/12/55, UVA). By any standard, Meigs assigned Rives a remarkable variety of tasks, extraordinarily quickly, an indication of Meigs' recognition of the 25-year-old Rives' excellence and ability for independent work. The index to Meigs' shorthand journal contains one full page of citations to Rives, more than for any other individual. There are numerous citations to social visits as well as professional interactions. Meigs and Rives bonded in a relationship with aspects of mentor-protégé, practitioner-theoretician, and father-son interdependence.

CJB—Conceptual Design

In January 1856, perhaps because of the winter slowdown in construction, Meigs and Rives began work on the detailed design of the CJB. The starting point was the conceptual design that Meigs presented in his 1853 report to Congress: "six semicircular arches of 60 feet span." Early in that month, Meigs wrote in his journal: "I saw at the Engineer Department, in the Annales des Ponts et Chaussées, an aqueduct bridge which is almost exactly like that I have designed for the Cabin John" (Meigs SJT, 1/9/56). For a field engineering office to have direct access to these writings on French technology was extraordinary; they were very likely the volumes that Rives received as a graduation gift. On January 16, Meigs wrote: "Today I spent some time with Mr. Rives in looking over his drawing of the CJB arch, investigated by Méry's Geometrical Construction" (Meigs SJT, 1/16/56). Meigs was referring to Rives' analysis of a brick short-span design, which had evolved to one having five rather than six arches. Meigs noted that the estimated maximum normal stress was approximately 2.07 MPa (300 lbs/in.²), only about one-tenth of the strength of commonly-used brick. Meigs' statement indicates that Rives performed the structural analyses using Méry's graphical approach, which Rives learned at EPC.

Meigs mentioned the Grosvenor Bridge in his shorthand journal for the first time on February 7. "I looked over some papers today in the department and wrote to Professor Mahaney [although the transcripts of Meigs' journals contain the name 'Mahaney,' it is almost certain that Meigs contacted West Point professor D. H. Mahan who discussed the Grosvenor Bridge in the 1852 edition of his well-known book (Mahan 1852)] to ask him where he found a detailed description of the Dee or Grosvenor Bridge over the Dee at Chester, England. This is the greatest span now standing, in stone. It is 200 feet. I should very much like to build such a one" (Meigs SJT). The Grosvenor Bridge, a design that Rives was familiar with since his studies at EPC, still stands and is shown in Fig. 4. The architectural design of the bridge was by Thomas Harrison, but George Rennie, son of the prominent John Rennie, changed the dimensions of the voussoirs and the configuration of the abutments making it "a typical Rennie structure." Harrison, then 82 years old, asked to be relieved of the responsibility for the construction, which was subsequently awarded to Jesse Hartley, the engineer of the Liverpool docks (Ruddock 1979). The inroads is a circular arc with a radius of curvature of 42.7 m (140 ft) and an interior angle of 91.2°, giving a span of 61 m (200 ft). It has hollow spandrels, but solid spandrel walls. "The arch stones are four feet deep at the crown and increase to six feet at the springing" (ICE Transactions 1842). Fig. 4 shows that the masonry above the principal arch was also placed with radial bed joints to form a "backing" arch. The first two courses of arch stones are of granite. "The key course with one on each side of it and the quoins all through the arch are of the limestone known as Anglesea marble" (ICE Transactions 1842). The remainder of the structure, including all the other arch stones, is largely of local sandstone. Sheets of lead prevented spalling (from local compression failures) and the opening of cracks as the centering was struck. The ICE article discussed the exceptional centering and the method of striking devised by the contractor, James Trubshaw Jr. (1777-1853). The center was six ribs wide with a lagging, or covering, that was 4 1/2 in. thick. A pair of folding wedges, 15 or 16 inches long by 10 or 12 inches broad that tapered to about 1 1/2 in., supported each rib. Six pairs of striking wedges supported each course of arch stones in the bridge. The wedges allowed for a precisely controlled, slow striking. The article noted that the contractor's method of striking was to "keep up the crown and let the haunches down," and to perform this soon after the arch was finished, while the lime-based mortar was "yet as it were a paste" (ICE Transactions 1842).

Meigs went to the patent office on February 9 to read the article on the Grosvenor Bridge in the ICE Transactions. His "pocket diary" entry for Sunday, February 10 indicated that he
met with Rives, and the February 14 entry contained the note: “Drew CJB project [?] A single arch 220' span. 110'. Rise 57.255 ft.” Meigs’ shorthand journal entry for February 18 contained a sketch of the long-span conceptual design of the CJB. In the same entry, Meigs stated that: “Mr. Rives has worked out the bridge thrust, and finds it to be about 700 pounds per square inch.” Meigs and Rives had obviously agreed to do a structural analysis of the long-span conceptual design some days before February 18. To complete Méry’s graphical structural analysis, Rives needed not only the overall geometry but also an estimate of the dead load distribution, which, in turn, required an estimation of the spandrel openings. The following day, Meigs, in his words, “made great progress. I arranged the interior of the abutments and spandrels [sic]. I think, in a very good way” (Meigs SJT, 2/19/56). Only one day later, on February 20, Meigs recorded that “Mr. Rives handed me today the drawing of the discussion of the bridge of 220 feet span. The results are very satisfactory.” A week later, on March 5, Meigs indicated that Rives had finished a drawing of a five-arch bridge for Cabin John. “He has made a very beautiful drawing of it. He now takes up the center of the large arch design for this bridge.” Rives and Meigs were clearly leaning toward the record-span design, but as responsible engineers, they decided to estimate the costs of it and the less-daring conceptual design. After two weeks of study, “Mr. Rives has made a rough estimate of the cost of the two bridges and finds a difference of a few dollars only between them.” Within a week Meigs wrote: “I hope to put Rives in charge of the bridge” (Meigs SJT, 3/27/56). By the end of March 1856, it is likely that a decision had been made to proceed with the detailed design of the 67-m (220-ft) arch, but the $250,000 allocation made in 1856 for the WA was restricted to “existing liabilities and preservation of work already done from injury.” In April the aqueduct engineers awaited an additional appropriation from the House of Representatives to resume work. Should it come, Rives told his father, “I shall probably set immediately about preparing working drawings for the 220 ft arch. If not, I shall have to wait and pursue my usual hum-drum avocations” (ALR to WCRjR, 4/9/56, LC). By May 7, Rives had given up hope and wrote his brother that: “I shall consequently be engaged in Washington during the summer, principally, I suspect, as photographer” (ALR to WCRjR, 5/7/56, LC). Indeed, work on the aqueduct was suspended in July 1856.

At this time, Congress requested preliminary studies for new bridges over the Potomac River at Washington. Meigs was naturally considered for the work, but he strongly lobbied to have Rives commissioned for the job. He introduced Rives to the Secretary of the Interior on August 28. Early the next week, Meigs “spoke again for Rives.” He tried to introduce Rives to President Franklin Pierce on September 9, but not finding the president at home, left a letter recommending Rives “as a proper person to be placed in charge of the new bridge investigation” (Meigs SJT, 9/6/56). Rives, in fact, received the appointment on September 13, 1856. On the same day, Meigs told the president that Rives was highly pleased with the appointment. “Rives is delighted, full of ambition, and eager to distinguish himself,” Meigs observed in his journal. “He will work very hard upon his subject. . . I have got him this appointment and he ought to do justice to me, to make good work of it.” One of the principal objectives of the study was to conceptualize a replacement for the Long Bridge, a wooden road bridge first opened in 1809 that spanned the Potomac from Maryland Ave. at 14th Street, SW to the Virginia shore. Rives completed the study in under five months; his report, dated February 9, 1857, is printed as Executive Document No. 68, House of Representatives, 34th Congress, 3rd Session. The accompanying drawings prepared by Rives and his assistant, Frank Wolfe, can be found today in the National Archives. Rives completed the conceptual designs for a startling number and variety of bridges: a stone arch replacement for the Long Bridge, a cast-iron replacement for the Long Bridge, wrought-iron plate girder spans, a single-span suspension bridge, and a double-span suspension bridge. Although the report was “well-received,” no funds were allocated for new bridges over the Potomac River.

On November 18, 1855, while Rives was still working on his Potomac River bridge study, a fire broke out in the WA engineering department, and all of Rives’ drawings of the CJB were ap-
Fig. 5. Possible normal stress states in a masonry arch, acceptable by Méry (1840)

apparently destroyed. At present, the WA Office has no drawings by Rives dating from February and March 1856. Rives’ colleague, William R. Hutton, the WA division engineer, recreated some of the drawings using Rives’ estimates, including the five-arch design (Drawing 30.8 4-9 in the WA Office). Hutton also redid Rives’ graphical analysis of the 67 m (220 ft) conceptual design (WA Office Drawing 30.12 4-12, dated December 11, 1856).

CJB—Modeling, Analysis, and Detailed Design

Early in 1857, Congress allocated a million dollars to continue the WA and the new dome on the Capitol. In March 1857, Meigs commissioned another engineer named Cammererhoover to analyze the 67-m (220-ft) conceptual design for the CJB using an alternate method of analysis developed by another French theorist, Yvon Villarceau (1854). Villarceau defined a numerical method for determining a thrust line for any dominant load and then advocated using an arch axis that exactly followed the estimated thrust line (Heyman 1969). Meigs’ journal entry for March 13, 1857, noted that Rives thought “nothing can come out of this, that the 110 degree arc is certainly the arch of equilibrium” (Meigs SJT). Nonetheless, perhaps challenged by Meigs’ decision, Rives wrote to his father on March 15, 1857: “The plans I had prepared for CJB having been destroyed by fire, and the reproduction of them, since made, being exceedingly faulty, I have almost my entire work to go over” (ALR to WCR, 3/15/57, LC). After 2 weeks, Cammererhoover brought his analysis of the arch to Meigs (this may be WA Office Drawing 30.8 4-30). The captain acknowledged that “It differs a good deal from the arc of the circle.” But he lacked confidence in Villarceau’s theory, and concluded that: “I shall stick to the arc of the circle.” He noted at the same time, “We have determined to make the voussoirs 6-ft deep at the spring and 4 ft at the key” (Meigs SJT, 3/27/57). Rives and Meigs may simply have decided to use the dimensions of the Grosvenor arch voussoirs or, possibly, Rives performed additional analyses using Méry’s method and concluded that deeper voussoirs were needed near the spring points.

Méry’s method may be explained as follows. The forces on any section of a planar arch may be defined in terms of resultant normal and shear forces acting at a particular point on a radial cross section, as shown in Fig. 5. The set of points at which the resultant forces act define a “line of thrust.” For masonry arches without rotational hinges, it is not possible to determine lines of thrust using only equilibrium since such structures are statically indeterminate. Méry proposed a method for determining thrust lines based on three assumptions and a graphical solution of force equilibrium (Méry 1840). He assumed a symmetric loading con-
dition, which implies that the shear force at midspan is zero, thus eliminating one redundant force. Méry then suggested assuming the position of the line of thrust at two sections; for example, at the two points defined by 1 and 2 in Fig. 5. With these three assumptions, the resultant normal force at midspan and a complete line of thrust may be determined using only equilibrium; thus the distance, I, in Fig. 5 is defined along the entire arc length. Once a thrust line is determined, Méry applied two acceptance criteria. The first, which was well-known prior to Méry, is that the line of thrust must lie between the geometric bounds defined by the extrados and intrados, otherwise one or more rotational hinges would form. The second criterion is that the stone compressive strength must be sufficient to resist the maximum compressive stresses along the arch axis. Navier (1833) had previously derived correct formulas for computing maximum normal stresses and further determined that there would be no tensile stresses at a section at which the resultant force was within the “third points” of the section. Méry did not require that the line of thrust lie within the third points of the section. Rather, he accepted the type of normal stress distribution shown in Fig. 5, which implies limited tensile cracking at any section. From equilibrium of forces normal to a section

\[
N = \sigma_{\text{max}}(3l)/2
\]

In which \(b\) is the width of the arch and \(l\) defines the position of the resultant normal force (and thrust line) from either the extrados or the intrados. Then Méry’s acceptance criterion is that for all sections

\[
\sigma_{\text{allow}} b l \geq 2N/3
\]

The evident issue in Méry’s method is that the thrust line is estimated on the basis of its assumed location at two sections. In this context, Méry states:

“There will be, a priori, an infinite number of statically admissible positions for the line of thrust... and it is only through uncertain assumptions regarding support settlements that one can predict which one will occur; but this search is not necessary... to assure the strength of the arch.” (Méry 1840)

That is, for a given system of loads, if an equilibrium set of forces is found such that the strength criteria are met without the occurrence of a mechanism, then the capacity of the arch must be greater than the system of loads for which equilibrium is satisfied. Méry’s sophisticated, correct insight is now known as the “lower bound” or “safe” theorem of limit state structural analysis (Gvozdev 1936; 1960; Greenberg and Prager 1952). [From studies of unpublished papers of Saint-Venant, Foces (2009) concludes that this insight was in fact made by Saint-Venant in 1838, when he reviewed Méry’s submitted manuscript.]

Rives’ structural analyses by Méry’s method guided decisions on overall geometry, the materials to be used, and the sizes of voussoirs, but detailed structural design required additional engineering judgment and skill. The WA Office has copies of the original specifications for the CJB and three drawings dating from 1857 that provide details of the main arch. These drawings are signed or annotated by Rives and then signed-off on by Meigs. The specified stone for the main arch was granite from Quincy (near Boston) Mass., supplied by Frederick and Field. The decision to order stone from a source approximately 1,200 km (750 mi) away by ship may have been made on the basis of observations of construction details used for the Boston Aqueduct. Moreover, the general superintendent, Charles T. Curtis, had previously
worked with Col. Sylvanus Thayer on the construction of Fort Warren, Boston Harbor, and the Boston Aqueduct (Curtis 1897). Rives detailed an arch with 131 voussoirs in nine distinct sizes. Fig. 6 shows the wedge-shaped voussoir stones, astonishingly dimensioned to 0.025 mm (0.001 in.). Rives specified that the joints between voussoirs should be 3.2 mm (1/8 in.) and that no other joint should be greater than 6.4 mm (1/4 in.). Such thin joints imply that the voussoir stones were finished on rubbing or grinding beds. These machines had flat cast-iron wheels or plates that when moved over the surface of stones, slowly smoothed them by the action of an abrasive medium [A. Olcott, "Rubbing and polishing stone," U.S. Patent No. 7,530 (1850); McKee 1976]. For the masonry mortar and concrete foundations, Rives specified natural hydraulic cement rather than lime. Meigs used natural cement and rubbing beds for both the Capitol Extension and Post Office projects.

A prominent feature of the CJB design is the stepped radial "rubble backing arch" or "radial spandrel." It is of sandstone from the Seneca quarry, approximately 22 km (13 1/2 mi) upstream from the bridge site, and is similar to the masonry above the main arch of the Grosvenor Bridge. While this was a common Rennie feature (Ruddock 1979), it usually was not expressed on the exterior spandrel wall. Its presumed purpose was to increase the principal arch's strength or "stability" (Woodbury 1858), although the backing arch width is only a fraction of the bridge's 6.2-m (20-ft-4-in.) width (around midspan, where the bottom of the brick conduit is very close to the granite voussoirs, the width of the backing arch must be less than half the bridge width). Two "stability of arch" drawings showing four Méry analyses performed by Rives are among those in the WA Office (Drawings 30.8-4-23 and 30.8-4-24). Both were signed-off by Meigs on the same day, February 19, 1858. Two of the analyses are for the granite arch with no backing, one with a full spandrel load and one without. For these analyses, Rives assumed that the line of thrust at the crown and at the spring points is at the center of the granite voussoirs. The other two analyses are for the granite arch with a backing arch. For these analyses Rives assumed that the line of thrust at the crown and at the spring points is at the top edges of the granite voussoirs. The drawings do not contain annotations that reveal Rives' conclusions, but the graphically determined positions of the lines of thrust shown on the drawings imply that a backing arch is not necessary. Nonetheless, a decision was made to use a backing arch, either on the basis of the Grosvenor precedent or on the perception that a backing arch would increase safety. This is very likely true, because a backing arch increases the moments required to cause cracking and rotational hinges in the masonry arch. One practical advantage of the backing arch was that its stepped extrados avoided "sharp points in the horizontal courses" of the spandrel walls (Hutton 1899). As in the Grosvenor Bridge, the external spandrel walls, which were also made of Seneca sandstone, are solid, hiding the spandrel arches. The spandrel walls at CJB are vertical but their extensions in the abutments have a slight batter of 1 in 20. Ruddock (1979) noted that vertical spandrels and battered wing walls were standard for bridges in Scotland after 1800. Solid spandrel walls also allowed use of much more economical brick masonry for the interior spandrel arches and other interior work.

**CJB—Construction**

On March 14, 1857, Meigs created a new division of the WA, less than 1-km (0.6-mi) long and centered on the CJB, and named the 27-year-old Rives division engineer in charge of constructing the bridge. Rives' immediate tasks included recreating the drawings lost in the fire, making detailed working drawings, and developing construction techniques. About three weeks later, when Meigs returned home one evening, he "found a couple of drawings of the center of CJB by Rives, which he left for my signature in order to set the carpenters to work to make patterns" (Meigs SJT, 4/7/56). Two weeks later, Rives wrote to his brother that: "The work at my big bridge is already underway. Most of the drawings are prepared, and my centre, of which I am very proud, is underway" (ALR to WCRJR, 4/21/57, LC). Rives' center is shown in Fig. 7, a drawing delineated by Frank Wolfe, signed by Rives, and signed-off on by Meigs. Fig. 6 shows that four or five voussoir stones formed the 6.2-m (20-ft-4-in.) width of the arch. Therefore Rives designed a center consisting of four parallel frames with flamed timbers to form circular arcs. The critical center details that allowed adjustments as the center deformed under load and that facilitated striking are shown in Fig. 8. In a design similar to the Grosvenor Bridge, Rives used four pairs of wedges, one pair over each frame, at every voussoir location. Rives proudly announced on July 23, 1857, that "The center for my grand arch is finished" (ALR to JR, 7/23/57, UVA). After the center was completed, a boiler plant and smokestack were erected for a steam engine. Three drawings (30.8-4-13, 4-14, and 4-42) at the WA Office detail the steam engine and its foundations. The use of a steam engine was practical for the CJB because the entire bridge could be serviced from a single location, which was not possible for the Capitol and Post Office sites (Vogel 1976). Fig. 7 shows that Rives used one centrally located steam hoist with a pulley...
system to lift the voussoir stones to a pair of high-level platforms. The stones were then placed in position using three traveling platforms with (man-powered) winches. Rives used wire ropes supplied by John A. Roebling's Sons of Trenton, New Jersey. The drawing also shows two inclined planes that may have been used later for transporting lighter masonry units and/or for waste disposal.

At this time, Rives was not only designing the stone details and the centering for the CIB, but was assigned by Meigs to plan "a splendid roof to cover the new Post Office court yard" using iron and plate glass. Rives asserted that the Captain, "was kind enough to remark the other evening, speaking of another assistant—'Why can't he present plans as you do which I have only to approve without altering.' I am almost complete master of my work, neither the Capt. nor Principal Assistant having changed or modified any of my plans for months" (ALR to JR, 9/13/57, DU).

The Quincy granite stones came by ship to the Georgetown docks and then by C&O canal to within a short distance of the bridge. To transport the stones to the actual site, Rives spent the summer damming Cabin John Creek to create a small pond and constructing a lock and lateral canal to connect to the C&O. That fall, his new canal had not been watered more than an hour when Meigs and the Secretary of War rode up. "Both seemed pleased with the work," he wrote to his sister Amelia, "especially the Capt. who was kind enough to compliment me most warmly to the Sec. of War and before 'tou le monde'" (ALR to AR, 10/12/57, UVA).

By March 1858, however, Meigs was dissatisfied with Rives' progress on the CIB. "I do not find that Mr. Rives shows as much energy in pushing his work as I could wish," he complained in his journal. "He does not know how to push work ahead" (Meigs STT, 4/3/58). Meigs felt compelled to take matters into his own hands on April 3, when, in the presence of Senator James A. Pearce of Maryland, Meigs himself supervised the setting of an arch stone. While Meigs spread the mortar, Pearce "gave the block two or three taps with a hammer. . . we pronounced the stone well and truly laid, and the bridge was begun." It is amusing to imagine the effects of the "two or three taps" on a block of granite that probably weighed close to 5 t. Notwithstanding Meigs' peevishness, Rives oversaw the placement of nearly 600 large granite stones during the summer of 1858 and proudly "keyed" the main granite arch on December 4, 1858. Rives' pride in his accomplishment is evident in the letter he wrote to his brother on December 6, 1858: "the Grand Arch was keyed on Saturday the 4th. . . at 2 o'clock" (ALR to WCR Jr, LC).

Early in 1859, Rives took a major step in his private life that would have a profound impact on his professional career. For several years he had been maintaining a long-distance romance with a Richmond, Va., socialite named Sarah Catherine "Sadie" MacMurdo. Because Rives' work kept them separated, it was, at times, a stormy relationship, especially because Rives was himself not a faithful correspondent. Alfred asked for Sadie's hand in marriage early in April 1857, but the engagement was broken off within the month, in large part because of the separation. The despondent suitor hoped to lose himself in the fieldwork of his "great work" as he worked "like a forty horsepower steam engine" (ALR to WCR Jr, 4/21/57, LC; ALR to JR, 4/27/57, DU). Late in 1858, the courtship was officially renewed. With the arch keyed and, undoubtedly, with an eye toward the uncertainty of congressional funding, Rives must have felt the time was right for getting married. The ceremony was held in Richmond on February 1, 1859, and the newlyweds set up housekeeping in Georgetown, a few kilometers from the CIB construction site.

The completion of the main arch of the CIB at the end of 1858 was followed by 4 1/2 years of sporadic construction due to funding interruptions, changes in leadership, and civil strife that changed the lives of both Rives and Meigs. These events delayed
the finishing of the WA and the start of its operation until July 1864. “You are doubtless aware there was no appropriation this year for the Aqueduct,” Rives wrote to his brother, “and consequently there is a very great prospect of my labors in Washington coming to an early close but not however I hope before the centre is removed from CJB. I will thus have been associated with the bridge as long as there was any difficulty or danger in the undertaking and I am not anxious to stay any longer employed on uninteresting and listless work” (ALR to WCR Jr., 5/18/59, LC). In July 1859, Rives and “every engineer employed on the Aqueduct” were laid off “for want of the necessary funds.” However Rives added that: “At the same time, but unofficially, I received from Capt. Meigs a letter requesting me to remain connected with the work... in that event the Captain promises to exert himself to secure for me compensation hereafter. I have thought it but fair to the Captain to accept this state of affairs for a while longer... I may be able to secure other occupation in the mean time” (ALR to WCR, 7/8/59, LC). In fact, Rives explored two professional opportunities: a professorship in applied mechanics at VMI and a position with Richard Morris Hunt, the soon-to-be-famous New York City architect whom he befriended during their time in Paris (Hunt attended the École des Beaux-Arts at the same time as Rives attended EPC). Rives, however, chose to remain largely in Washington. Documents show that throughout 1859, Rives approved payment for work completed by the CJB contractor, Robert McIntyre. In fact, in October 1859, Meigs commissioned photographic portraits of Rives and the artist Constantino Brumidi who painted the frescoes in the U.S. Capitol. In 1860 Meigs himself became a target of Secretary of War John B. Floyd, per- versely because of Meigs’ zealously ethical management of congressional appropriations. On July 17, 1860, Floyd appointed Captain Henry H. W. Benham as chief engineer of the WA and, in October, banished Meigs to Fort Jefferson, on Garden Key of the Dry Tortugas, about 110 km (69 mi) west of Key West, Florida (East 1939). Benham attempted to hire Rives in July 1860 after appropriations were made but was prevented from doing so by Secretary Floyd. Perhaps because of his actions on behalf of Rives, Benham was replaced by Lieutenant James Morton as chief engineer. But when Secretary Floyd was himself replaced, Meigs was ordered to return to Washington. Meigs was reappointed chief engineer on February 21, 1861, with approximately $321,000 of the appropriations remaining. A last brief period of professional collaboration between Meigs and Rives ensued until the start of the Civil War. On March 18, 1861, Meigs issued Rives order Number 13, which prescribed two “inscriptions to be cut on Bridge No. 4” (the CJB). One inscription was to read:

Union Bridge

Chief Engineer, Montgomery C. Meigs

U.S. Corps of Engineers

Assistant Engineer, Alfred L. Rives, C.E.

This order, unfortunately, was never carried out. By the second month of 1861, seven states had seceded from the Union, and Meigs had grown nervous about the long-term loyalty of his civilian assistant engineers, especially those from Virginia. Early in March and standing before a justice of the peace, Rives swore an oath of allegiance to the U.S. Constitution, obviously at Meigs’ behest. As slave-owners, the Rives family was deeply entrenched in the South’s unique agricultural economy. But they felt alienated from the “cotton states” of the Deep South and believed that Virginia, as a border state, had the most to lose if the political conflict ended up in war. Alfred was himself not optimistic that “moderate” Northerners with open minds about Southern interpretations of states rights could ultimately prevent the situation from deteriorating further (ALR to JR, 1/8/61, LC; Liston 1972). The opening of hostilities at Fort Sumter on April 12 galvanized radicals on both sides. An earlier Virginia-based reconciliation effort, in which Alfred’s father was active, was pushed aside when the state became the eighth state to secede on April 17. This alone undoubtedly strongly influenced Rives, but he had yet another factor to consider: his wife was pregnant and his family had long viewed the nation’s capital as an undesirable place to raise children (JR to ALR, 4/19/58, DU). So given these political and personal reasons, Rives resigned from the WA, and later joined the Engineer Bureau of the Confederate States of America (assistant engineers E. D. T. Myers and C. G. Talcott also resigned and joined the Confederacy). Shortly thereafter, Meigs was promoted to brigadier general and appointed quartermaster general of the Union Army, serving with distinction until 1882. Meigs’ formal responsibility for the WA ended on June 18, 1862, when Congress transferred jurisdiction over it to the Department of the Interior. William R. Hutton was chief engineer during 1862–1863, and Silas Seymour served from 1863–1864. The CJB was essentially completed under their leadership.
CJB—Performance

Despite the trauma of the Civil War, by December 1863 the WA was complete enough to allow two trial water flows. A 2-week trial began on December 3, and a second began on January 14, 1864, and ran for 5 weeks. Leaks in the conduit within the CJB required purging the lower half of the conduit for the entire length of the bridge, probably with a natural cement mortar. This repair was effective, for after being placed in service on July 29, 1864, the conduit served continuously without modifications until September 1891, a period of 27 years (Macqueen 1934). The only significant alteration during this time was to convert the top surface, or “platform” of the bridge into a roadway. This required the addition of sandstone parapets and asphalt pavement between 1872 and 1875 (Macqueen 1934). The aqueduct was drained in 1891–1892 to repair “a large leak of about 40,000 gallons per day near the west abutment.” The leak was “in the invert of the conduit about 40 feet west of the bridge but the water was flowing under the conduit and washing out the abutment” (Macqueen 1934). The earlier mortar purging had not completely halted leaks. Macqueen noted that winter weather disintegrated the mortar and allowed enormous icicles, “in some cases fifty feet long,” to form on the sides of the bridge. Leaks increased over time, and in 1911–1912 approximately 152 m (500 ft) of metal lining was installed in the bridge conduit. The lining was placed in 0.9-m (3-ft) lengths, each formed by six cast iron, flanged plates bolted together to create 2.44-m (8-ft) diameter rings. The space between the cast-iron lining and the original brick conduit was filled with Portland cement grout. Such lining and grouting techniques were commonly used in subsurface tunneling. The cast-iron plates had 76-mm (3-in.) flanges, so the inside was lined with an additional 76 mm (3 in.) of portland cement concrete. Macqueen (1934) noted that the metal lining stopped all leakage, and “further repairs have not been necessary.”

Growth of the city of Washington led to a 1921 recommendation (“Increase in the water supply” 1921) to expand the capacity of the WA by constructing a parallel conduit. Construction began in 1922 and was completed in 1928. It crosses the Cabin John Creek Valley with an inverted siphon. This “new” second conduit facilitates the draining, inspection, and repair of the original conduit. Over the years, the WA made extensive improvements in water treatment, storage, and distribution facilities (Ways 1996), but the CJB has remained largely as-built. No detectable support motions or structural failures have occurred. The principal issues relative to the bridge have focused on accommodating and controlling traffic, “posting” of load and speed limits, drainage, deicing operations, and, importantly, issues of stone conservation: washes, sealants, mortars, consolidants, and replacements.

WA files contain reports of several assessment studies and rehabilitation efforts that have been completed since the early 1970s. Diver Brothers—Consulting Engineers and Professor S. Z. Lewin of New York University performed assessment studies of the bridge in response to an incident that occurred in February 1975. A large parapet stone fell from the bridge onto the pavement of the Cabin John Parkway running through the valley underneath the bridge. Their studies concluded that, in general, the arch, spandrel, and abutment stones were in very good condition. However, the ledge, parapet, and coping stones, which were not “positively anchored” to the bridge, had deteriorated and had become misaligned. Their reports led to a rehabilitation of the parapet and changing the bridge roadway to one-lane-only. Aside from the metal lining of the conduit, this 1970s work on the parapet was apparently the first significant repair in the history of the CJB. After the parapet incident, inspections have been performed regularly once every two years, in keeping with Federal Highway Administration mandates. Inspection reports over the years have consistently noted wetness inside the spandrel chambers, perhaps a negative consequence of the closed spandrel walls. By 1981, the bridge was posted for “no salting” and a load limit of 6 t. This limit is not based on structural analysis but the judgment that it protects the conduit lying just beneath the roadway surface. In the early 1980s, the WA retained Neal FitzSimons as a consultant on the CJB. FitzSimons’s first report, submitted on December 31, 1982, again found the arch, spandrel, and abutment stones in good condition, although he noted some areas of exfoliation in the sandstone. FitzSimons noted wetness, leaching, and mortar loss in the spandrel chambers. He recommended a condition monitoring system and development of a mathematical structural analysis model (FitzSimons 1982). FitzSimons submitted another report in June 1985 that included a preliminary analytical model of the CJB.

The 1986 inspection report noted cracking and mortar loss on the northwest abutment/approach walls. Following this inspection, the bridge was posted for a 3-t load limit and a 15-mpg speed limit. As part of normal maintenance, the conduit within the CJB was relined in 1987. The 1988 inspection again emphasized stone deterioration in the north approach wall, prompting a special inspection by a geologist and a civil engineer in March 1989. Their report confirmed the deterioration of the north approach walls, which “have gone through many more freeze-thaw cycles due to the lack of drying by direct sunlight” (Bereznak and Stefano 1989). Their recommendations included cleaning, replacement of stones, and the use of a stone consolidant. Harry C. Ways, chief of the WA Division, met with FitzSimons for advice regarding the stone restoration recommendations. FitzSimons strongly advised against air, water, or sand blasting for cleaning and against using coatings or consolidants (FitzSimons, May 4, 1989 letter at WA Office). An in-depth inspection was performed in March 1990. The main arch was again determined to be in good condition but drainage from the roadway had damaged the stone work on the north wall of the west approach. To assess the local deterioration further, the WA hired Baker Engineers, who recommended replacement of selected stones by a “natural stone facing” or natural stones with a thickness of 15.3 cm (6 in.). This work was completed in 1991, and the 1992 inspection noted that the repairs remained in good condition. The 1992 inspection report also noted completion of a monitoring system, primarily intended for measuring abutment movements. However, over the years no movements have been detected, and the monitoring program is currently inactive (Cole, Washington Aqueduct Office, Washington, D.C., personal communication). Inspection reports of 1994, 1996, 1998, and 2000 document changes in stone conditions leading to significant rehabilitation work in 2001. The sandstone parapets were replaced, the granite arch was cleaned, all the masonry was pointed, and erosion control gabions were put in place. There have been no major changes in the bridge condition over the last few years and the next significant rehabilitation work is scheduled for fiscal year 2014 (Cole, Washington Aqueduct Office, Washington, D.C., personal communication).

In summary, the principal causes of deterioration of the CJB appear to have been drainage from the roadway, the closed spandrel chambers, possibly leakage from the conduit, and freeze-thaw cycles on the northern exposure. There are no significant settlements and damage from overloads, although potential damage from traffic remains an unresolved concern. There have been recurring recommendations for removing debris from the spandrel
chambers and for an indexing system for individual stones, but these have yet to be carried out. At present, the CJB is performing the same function as when first commissioned in 1864, in essentially an as-built condition.

CJB—Historical Assessment

The CJB is unique in the United States, and its performance over 145 years has been exceptional. This necessitates a rigorous and insightful historical assessment of its conceptual design, the modeling used, its detailed design, and its construction. The rather complicated history of the project and Meigs' shunning of Rives during and after the Civil War make assessments more difficult. The difficulty began with Meigs' direction to inscribe his name in two places on the bridge. The inscription on the plaque on the cast abutment reads:

Union Bridge
Chief Engineer, Montgomery C. Meigs
U.S. Corps of Engineers
Esto Perpetua

As noted earlier, the above inscription was to contain Rives' name as the assistant engineer but "Esto Perpetua" was substituted after Rives resigned and joined the Confederacy. Meigs also had his name carved in one of the voussoirs on the southeast side of the bridge. In fact, Ways (1996, Appendix A) provides startling evidence of Meigs' renowned ego, listing thirteen locations along the WA at which Meigs' name appeared on permanent inscriptions. In addition, Meigs had his name cast on "the riser on each of the 39 steps of the cast-iron circular staircase" at the Georgetown reservoir, "on many of the brass and iron parts of the derricks and other machinery and on the valves and sluice gates," and "on many of the hydrants throughout the city" (Ways 1996).

Meigs' shunning of anyone who joined the Confederacy deepened when rebel partisans killed his son, John Rodgers Meigs, a new graduate of West Point, in October 1864. When his former assistant engineers Myers and Rives attempted to visit Meigs after the war, he refused to "see any of those gentlemen who had deserted their country and joined the party who murdered my son" (Weighly 1959). For his part, Rives had a very different perception: "He feels I suppose that in placing his name alone on Cabin John Arch, and leaving mine off he has done me an unjustifiable injury," Rives wrote his father on August 18, 1865, "and it is easier to forgive our enemies than those we have injured or sought to injure" (ALR to WCR, LC).

Unfortunately, many subsequent reports uncritically accepted Meigs' viewpoint. An article on the WA in Harper's Weekly on May 14, 1864 (Washington Aqueduct 1864), included an illustration of "the bridge over Cabin John Run;" Rives was not mentioned. An article in Engineering (1867) on the CJB lists "Quartermaster-General Montgomery C. Meigs" as the designer, and Rives was mentioned only in the last line as the assistant engineer. In 1870, Emile Malezieux, a French engineer from EPC, came to the United States for an inspection tour of new public works. His observations were compiled in a book published in France in 1873-1874. Malezieux (1870) visited Washington and wrote on the WA and, specifically, on the CJB. He concluded his description of the bridge by stating: Ce pont a été étudié dans tous ses détails et construit (de 1859 à 1861) par M. Alfred L. Rives, ancien élève externe de L'École des Ponts et Chaussées, qui exécuta comme ingénieur ordinaire, sous la direction de Général Meigs. The key issue is the meaning of étudié dans tous ses détails, which is literally translated as "studied in all its details." Twice, Meigs was compelled to address Malezieux's statement, once in 1877 in the midst of a disagreement with Colonel Orville E. Babcock, then chief engineer of the WA, and then, in 1883 (Meigs 1883), following an article by Frank D. Y. Carpenter in Lippincott's Magazine. The dispute with Babcock centered on whether the Rock Creek cast-iron arch bridge of the WA was safely able to continue carrying both the aqueduct conduits and road traffic. Babcock believed that a separate bridge should be built to remove road traffic from the cast-iron arch; Meigs vehemently disagreed. Babcock noted Malezieux's statement, thereby questioning Meigs' role in the design and construction of the CJB. Meigs objected strongly, annotating Babcock's report with comments (Ways 1996). In 1883, Carpenter wrote a confrontational article on "government engineers." He argued that civilian engineers often had central, pivotal roles, but were often unjustly viewed merely as "assistants," while chief engineers, who were generally members of the U.S. Corps of Engineers, received the credit and honors. Carpenter cited the CJB and Malezieux's statement (which he may have learned from Babcock) as an example. Carpenter further commented: "It is in the study of the details that tests the engineer. Any child can conceive the idea of an arch across the Amazon, but it would take an able engineer to construct it." Meigs forcefully replied in a letter published in Lippincott's on September, 1883. The letter is very carefully crafted, not specifically naming Rives, but insinuating that Rives was a mere "draughtsman who, under the eye and direction of his chief, puts upon paper and studies the details of a design," and that Rives was an assistant who superintended the construction "under the same vigilant and constant observation and direction." As shown here, Meigs' insinuations about Rives were not true, and Meigs knew they were false. Regarding the long-span conceptual design, Meigs claimed: "I did this before any of my assistants or draughtsmen, of whom I employed many, saw or knew of my intention to substitute a single-arch bridge for the many-arched bridge." Meigs further asserted that he fixed the span, height, and thicknesses of the arch which he "then committed to an assistant engineer...the application to this design of a then recently published French geometrical method of constructing the lines of pressure." With the exception of providing a literal English translation of Malezieux's words, Meigs never mentioned Rives in the body of his letter. At this time, Meigs also returned to his shorthand journal entry for February 18, 1856, and added notation as evidence of his authorship of the design.

Meigs donated several large scrapbooks of photographs and documents to the WA Office before his death on January 2, 1892. Rives died in 1903, leaving two brief autobiographical statements written in 1876 and in 1885 (Rives 1895a,b). Regarding his work on the CJB, Rives stated: I accepted from Capt. Meigs the position of Division Engineer of the WA and was by him selected to make careful studies, calculations, plans, and estimates for the CJB, which was subsequently constructed under my personal supervision" (Rives 1895a). In 1897, William T. S. Curtis, the son of the superintendent on the CJB, wrote an extensive article on the bridge in which he recalled conversations with his father and with William R. Hutton (Curtis 1897). The bridge will "remain in the eyes of generations yet unborn a monument to the genius and inspiration of its engineer, Montgomery C. Meigs," he concluded. Curtis noted, however, that "The working plans and drawings of CJB, as well as much of the detail work of that character up to the spring of 1861...appear to have been prepared and performed.
mainly by Mr. Alfred L. Rives, who was a graduate of the École des Ponts et Chaussées.” Curtis also recounted the story of Meigs’ intention to place Rives’ name on the commemorative tablet “in recognition of the engineering genius of his assistant engineer.” William R. Hutton wrote an extensive article on the WA for Engineering Record in 1899. Hutton worked in the engineering department in the winter and spring of 1856, when the conceptual design of the CJB evolved to a single long-span arch. Hutton is explicit in his identification of proper credit for the bridge. “The present single span of 220 feet was suggested by Mr. Alfred L. Rives, then employed as assistant to Captain Meigs on the U.S. Capitol Extension, taken up by Captain Meigs, and the details afterwards worked up by Mr. Rives, whose graphical analysis by Meigy’s method is shown in one of the accompanying cuts. A year or two later, when money was obtained, a short division, half a mile long, was made covering the site of the bridge, and Rives was appointed Division Engineer.” Illustrations for the article include Rives’ centering and scaffold for the traveling winches, Rives’ details for the centering, and Rives’ graphical analysis by Meigy’s method.

In 1932, Charles T. Motherseed, an undergraduate at the University of Maryland, wrote a paper on the CJB as part of his initiation into the Maryland Chapter of Tau Beta Pi. “Although General Meigs was the Chief Engineer, most of the working plans and drawings of CJB were prepared by Mr. Alfred L. Rives, the assistant engineer,” Motherseed (1932) wrote. Macqueen, a civil engineer at the WA, echoed these comments. “Plans for the bridge were prepared by Mr. Alfred L. Rives and approved by Capt. Meigs. Mr. Rives was a graduate of a University in Paris and a very capable designer” (Macqueen 1932). Both statements were likely based on an examination of the existing drawings at the WA office. The misdirection Macqueen provided regarding Rives’ alma mater was repeated as the University of Paris in the ASCE-NHCEC nomination, and by (Mrs. Neil) FitzSimons (1973), Myer (1974), and Schodek (1987).

More recent engineering historians have offered little or no additional insight on Rives’ work. Condit (1990) discussed the CJB but did not mention Rives. Myer (1974) did state that “Alfred L. Rives... prepared the actual designs” of the CJB. Importantly, Myer (1974) reproduced most of Rives’ beautiful drawings prepared in conjunction with his study of Potomac River bridges. These drawings show the remarkable variety of forms for which Rives performed preliminary designs. In his book on the contributions of the Corps of Engineers to the development of Washington, Cowdrey (1979) stated that at Cabin John, Meigs "adopted a design prepared by his gifted assistant, Alfred L. Rives." This statement is echoed by Scott (2007) in her recent update of Cowdrey’s book. Schodek (1987) simply stated that the CJB “was designed by Meigs and his assistant, Alfred L. Rives.” Schodek (1987) speculated that “Rives was undoubtedly familiar with the work of Perronet, the brilliant French engineer whose experimentation in the direction of longer and flatter arches anticipated design features used later extensively in concrete.” Condit (1960) made a similar allusion to Perronet, but no contemporary documents have been found to indicate any Perronet influence.

Chapter 6 of Ways (1996) provided an extensive description of the design and construction of the CJB and, in a later chapter, the writer devoted a paragraph to Rives. Ways concluded that: “while Rives’ contribution was significant, the single-arch concept was Meigs’ own” and that “the case for giving Meigs sole credit for the single-arch concept remains a strong one.” After a much more thorough study of Rives’ papers, Herrin (Dickinson et al. 2001) concluded that: “Rives’ contributions to the design and construction of the CJB were immense. It was probably Rives who suggested using Méry’s method to calculate the strains on the bridge, since he had just been taught the procedure... After examining all the records carefully, ample evidence exists to conclude that Meigs did originally design the CJB.” Ways’ and Herrin’s judgments are almost solely based on Meigs’ entries in his journals and diary and on Meigs’ vehement defense after the Carpenter (1883) article. Both writers focused principally on the “single arch concept,” not on the structural analysis, detailed design, working drawings, and construction. Neither examined the Grosvenor Bridge precedent, and neither cited and discussed William R. Hutton’s statement (Hutton 1899).

Conclusions

Alfred Rives performed brilliantly at the Ecole des Ponts et Chaussées and became its first American graduate. The preeminence of French engineering education at the time was well-recognized worldwide and, indeed, served as the principal model for U.S. engineering education. The engineering curriculum at West Point was strongly influenced by Claudius Crozet, a French engineering officer who began teaching mathematics at West Point in 1816. This influence was continued by the French-trained West Point professor, D.H. Mahan. In the introduction to his seminal 1837 book, An Elementary Course of Civil Engineering, Mahan remarked on the “best of mathematical schools, the French” and noted that the “best counsel that the writer could give to every young engineer, is to place in his library every work of science to which M. Navier’s name is in any way attached” (Mahan 1837). This French influence also included the U.S. Army Corps of Engineers and extended back to the American Revolution when the American army’s engineers were led by the French general Louis Lebègue Duportail and largely consisted of French engineering officers (Buzzard 1958). Indeed, the Corps of Engineers chose the French word Essaions (“We will try”) as its motto. Thus Meigs, a graduate of West Point and proud member of the Corps of Engineers, had to recognize the exceptional talent revealed by Rives’ performance at the EPC.

Rives was hired by Meigs as an “assistant engineer” in the spring of 1855. Meigs’ and Rives’ writings prove that the young engineer worked independently with an extraordinary breadth of activities and at an exceptional performance level. He was asked to conduct structural calculations, create mechanical and structural designs, devise materials testing procedures, and supervise construction at multiple sites. As a consequence of that performance, Meigs was willing to stake his own reputation by strongly recommending Rives for a congressionally mandated study of Potomac River bridges. This he completed in an astounding five months. His report to Congress and the accompanying drawings in the National Archives reveal the breadth and quality of Rives’ conceptual bridge designs.

Despite his renowned ego, Meigs had earlier demonstrated a willingness to acknowledge the debt he owed to his assistants, specifically in the case of the civilian William H. Bryan and the overall design of the WA. Evidence suggests that Meigs would have also recognized Rives’ role in the CJB had not circumstances intervened.

The conceptual design of the CJB evolved in the winter of 1855–1856. In his initial report to Congress on the WA, Meigs proposed to cross Cabin John Creek with a six-arch viaduct. This conceptual design was never developed further, although Rives
completed analysis and detailed design of a five-arch viaduct. The inspiration for the conceptual design of a single 67-m (220-ft) span for the CJB was the Grosvenor Bridge over the River Dee, which Rives had learned of during his studies at EPC. While a cross section of the bridge was published in the 1852 edition of Mahan’s civil engineering book, it was not until after Rives’ arrival that Meigs wrote of an interest in the Grosvenor Bridge. Without doubt Rives and Meigs discussed the Grosvenor Bridge. Meigs’ journals and diary from February 7 to 18 contain several entries related to the CJB. Herrin (Dickinson et al. 2001) and other scholars have previously noted a sketch of the CJB in Meigs’ journal on February 18, 1856 as evidence of his authorship of the conceptual design. Even Meigs himself self-consciously returned to his journals long after the fact and added annotations in an attempt to establish his design priority. But Meigs’ own journal states that Rives presented his results of the structural analysis of the long-span CJB design to Meigs on the same day that the sketch appears. William R. Hutton, who was in the engineering department in the winter of 1855–1856, provided the only independent statement known to the writers on the conceptual design of the CJB. He stated that: “The present single-span of 220 ft was suggested by Mr. Alfred L. Rives, then employed as an assistant to Captain Meigs on the U.S. Capitol Extension, taken up by Captain Meigs.” Also relevant is that in spring 1857, Meigs commissioned yet another engineer named Camerhoover to check the long-span conceptual design, a very unlikely decision if the conceptual design had, indeed, been his own.

Existing documents and drawings show that Rives completed the analysis and detailed design of the 67-m (220-ft) arch span using a combination of French theory and British detailing. Rives used Mbry’s method for analysis and design details from the Grosvenor Bridge. The two bridges have almost identical voussoir sizes and both utilize radial masonry to form “backing arches” or “radial spandrels.” In addition, both designs have interior spandrel arches to decrease dead load on the arch.

Rives’ drawings for the centering demonstrate that he used features of the Grosvenor Bridge centering, specifically “folding wedges” to allow adjustments and controlled, gradual striking. Rives designed and built a slackwater canal to float the stones to the construction site. He installed a centrally located steam engine to power the construction to a degree uncommon in America up to that time and lifted the stones to high-level platforms with Roebling wire ropes, successfully “keying” the main arch on December 4, 1858.

On the basis of existing documents and drawings, and with the understanding that structural design consists of conceptual design, structural analysis, and detailed design, it can be concluded that the CJB was not only built by, but also designed by Alfred L. Rives, C.E., ancien eleve externe of the EPC, the top graduate of the class of 1854.

The story of Rives, Meigs, and the CJB exemplifies the tragedy of the Civil War. Meigs lost his son and, as a former Confederate, Rives was shunned by Meigs, thereby affecting the professional life of a promising, brilliant engineer. Meigs’ journals and his prominence had an overwhelming influence on the scholarship on the CJB, while Rives’ writings and work remained, until now, largely unexplored.

Epilogue

Rives wrote two brief autobiographical statements that survive in archives, one as part of a 1876 letter written to Col. J. Wilcox Brown in connection with a possible position as a professor of engineering (Rives 1876), and another in 1895, at the end of his tenure as general superintendent of the Panama Railroad, of which there are two versions (Rives 1895a,b).

Three days after resigning his position with the WA, Rives received a commission as captain of engineers for the State of Virginia and was assigned to build defensive earthworks in the lower Virginia peninsula, between the York and James rivers. He was quickly recalled to Richmond, Va., and made acting chief engineer of the state. Within a short time, he was appointed acting chief of the Engineer Bureau of the Confederate States, a position that he held until the end of the war in 1865. During the war, he was promoted to major, lieutenant colonel, and colonel of engineers, “which last rank I held for 18 months until the end of hostilities” (Rives 1895a). After the war, he was offered an architectural position with the U.S. government and engineering professorships at the UVA, Washington and Lee, VMI, and University of Georgia (Rives 1895a, 1876). But Rives chose to open an architectural and engineering practice in Richmond. In 1868, he accepted the position of division engineer with the C&O RR and built the railroad through the Allegheny Mountains, “the thirty probably heaviest continuous miles of railroad work in the United States” (Rives 1895a). He became chief engineer of the Mobile and Alabama RR, “locating 230 miles and constructing 50” in 1870 (Rives 1895a). In 1872, through the recommendaation of General W. T. Sherman, commander of the U.S. Army, Rives was offered the position of chief engineer of the civil works of Egypt, but he declined for family reasons. He accepted the combined positions of chief engineer and general superintendent of the Mobile and Ohio RR, “length—527 miles” in 1873 (Rives 1895a) and was later promoted to general manager and vice president. Rives resigned in April 1883 to become vice president and general manager of the Richmond and Danville RR, “2,300 miles in length” (Rives 1895a).

At age 57 in July 1887, Rives accepted the position of general superintendent of the Panama Railroad. It is little wonder! The French began the Panama Canal in 1880 and Panama was surely “teeming with” ancien élèves of EFC, working on what was considered the greatest project in the world. It must have been a truly rejuvenating position for Rives, despite the oppressive tropical climate. As a representative of the Panama Railroad Company, Rives later recalled that in February 1888, “I was sent to Paris to conclude a traffic agreement with the Canal Company” (Rives 1895a). He was back in Paris after 34 years!

Although the French Canal Company had decided to build a locked canal by November 1887, none of the alternate locked designs were implemented, and the canal company was liquidated surving in February 1889 (McCullough 1977). In the same year, the U.S. Isthmian Canal Commission was formed, charged with evaluating alternate canal routes and designs through Nicaragua and Panama. In November 1889, Rives “ventured to present to the Canal Commission a plan for the completion of the Panama Canal, in which I have taken the greatest interest ever since my arrival on the isthmus” (Rives 1895a). Copies of Rives’ plan, one written in English and another in French, can be found in the UVA archives. His report, complete with drawings showing locations of the dams and the locks, proposed a principal dam at Bohio (or Bujio) and six locks. The formal report of the Isthmian Canal Commission (“Report of the Isthmian Canal Commission 1899–1901” 1904) presented an overall plan for the Panama route that is very similar to Rives’, using six locks and a dam at Bohio, very close to where Rives proposed. Rives’ plan, however, is not cited within the final commission report, so its influence remains
unknown. Rives left Panama in 1895, after 8 years of service to the Panama Railroad.

In February 1902, Rives added some notes to his 1895 autobiographical sketch. He stated that he was then "Chief Engineer of the Cape Cod Canal, of which recent surveys and plans have been carefully made, and am also Vice-President specifically charged with the construction of the Vera Cruz and Pacific RR in Mexico." Alfred Landon Rives died at his home, Castle Hill, near Cobham, Va., on February 5, 1903.

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