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The Wheeling Custom House of 1859: A study in skeletal iron framing

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In the decade before the outbreak of the American Civil War, The United States government built a series of twenty-one custom houses to provide accommodations for the federal custom service, the postal department, and as the location for a federal court (Guthrie 1860, 8).

Although not a coastal location, Wheeling was selected as one of the sites for a custom house, because it was the confluence of three dominant transportation systems: the head of summer navigation on the 981-mile Ohio River, the terminus of America's first trunk-line railway, the Baltimore and Ohio stretching from Baltimore to the Ohio River and reaching Wheeling in 1852, and the coming of the National Road, 1818, which later crossed over the famous Wheeling Suspension Bridges of 1849.

During the fury of the Civil War, the court-room in the Custom House witnessed the formation of a new state on June 20, 1863, to be called West Virginia. The building is noteworthy in the series of custom houses in the Italianate Renaissance style designed by Ammi B. Young, 1798–1874, the first architect of the U.S. Treasury. The construction manager was Captain Alexander Hamilton Bowman, 1803–1865, who was seconded from the U.S. Army to serve the Department of the Treasury. It was Young and Bowman who introduced the use of skeletal iron framing in response to a concern that these custom houses and other federal buildings would be constructed in a fireproof fashion. Fireproofing, in the minds of architects and engineers of the time, was to construct buildings of noncombustible materials. It was not the use of structural iron, a comparatively new material, which compelled Young and Bowman to develop an interior skeletal frame work together with brick jack-arch floors, but to insure the building was fireproof. The focus of this paper, however, is on the evaluation of the structural significance of the iron framing. The effort to achieve a fireproof structure became a criterion for these federal buildings to be constructed of noncombustible materials both inside and out. Thus, in order to understand the decisions made by the Treasury Department, it is necessary to place the design in the context of what was then considered fireproofing ideas.

Fireproof Structures

The concern to construct "fireproof" buildings arose not in the case of monumental public buildings, but rather in textile mills in England. The so called "slow-burn" construction using heavy timber framing and flooring reduced, but did not eliminate, the fire hazard in textile mills, which were illuminated with open flame lighting and devoid of modern sprinkler systems. Although fire protection was a concern in earlier times, the modern period for such buildings dates from the seminal work of William Strutt, 1756–1830, and Charles Woolley Bage, ca. 1752–1822 (Skempton 2002, 28–29 and 670–72).

William Strutt, long associated with the textile industry, and with Richard Arkwright witnessed, in 1781, the destruction of the family mill in Nottingham, England. When Strutt designed a new mill, and later a warehouse, he was keenly aware of the vulnerability of large industrial buildings to fire, especially following the destruction of the well-known Albion Mill in London, which featured innovative production machinery. Strutt's solution was to use flat brick jack-arch floors supported by large timber beams sheathed in iron plates.

Bage in partnership with the Benyon brothers and the flax spinner John Marshall served as designers for a new cotton mill in Derby completed in 1793. The designed called for the use of cast-iron beams instead of the traditional heavy timber girders used by Strutt, Figure 1 (Swailes 1998, 12–19).

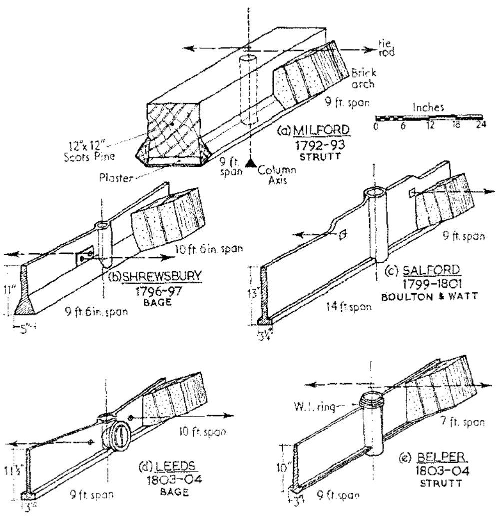

Figure 1
(1958) Evolution of beam design for "fireproof" buildings, 1792–1803 (Singer et al., 477)

The beams of cast-iron supporting 10 foot span brick jack-arch floors are explained by both Swailes and Fitzgerald, Figure 2 (Swailes 1995, 37–47; Fitzgerald 1998, 127–45). The adaptive re-use of such a mill at Huddersfield by Ove Arup and partners considered the load carrying capacity of the cast-iron floor beams supported on a cruciform columns (Robinson and Marsland 1996, 12–13). Such framing systems utilizing cast-iron found widespread use in Britain during the entire first half of the 19th century. While cast-iron beams were largely replaced by mid-century, the use of cast-iron columns persisted into the early decades of the 20th century.

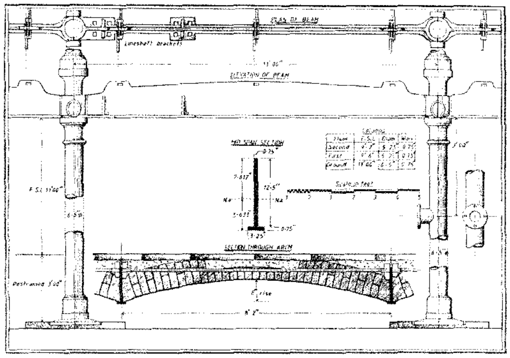

Figure 2
(1998) The Armley Mill, Leeds England (1804–5) featuring cast iron framework and a jack-arch floor system (Swailes, Tom and Joe Marsh, 16)

A notable example of fireproofing occurred across the Atlantic in an attempt by architect Robert Mill's Public Record Office in Charleston, South Carolina. Completed in 1823, the extant structure was erected without benefit of iron framing by using stone columns and walls and brick vaulting (Condit 1960, 26).

Buildings by Daniel Badger and James Bogardus took the process forward by featuring cast iron facades in the years prior to and just following the American Civil War, 1861–1865. Bogardus's Harper and Brothers building was a landmark, a veritable essay in iron. At his New York foundry, Bogardus cast girders and columns for the iron framing. The partitions were brick, and most importantly, the floors consisted of flat brick jack-arches supported on rolled wrought-iron rail-beams supplied by the Trenton Iron Works. It was this firm which played a leading role in the large federal government building program, and especially the Wheeling Custom House. As a result, it set an important example in the building arts. It should be noted in passing that this was the same period that the great Crystal Palace of 1851 was erected in London. It was so revolutionary, using glass and iron, that architects declared it non-architecture, because it did not use traditional materials. In many ways, it was the most revolutionary and important building of the 19th century. Thus, by mid-century, skeletal iron framing was well established leading to the celebrated sky-scraper.

Recognizing the inherent weakness of cast-iron in tension, the girders supporting the floor system in the Harper and Brothers building were enhanced with wrought-iron tie-rods, Figure 3. Such a system of augmenting the inherent weakness of cast-iron in tension was used earlier in Britain. The wrought-iron floor joists installed were the first 7-inch rail-beam rolled in the United States (Condit 1960, 35–36). Completed in 1854, the Harper building survived until 1920 when it was demolished to be replaced by a newer building.

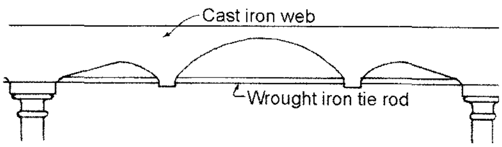

Figure 3.
1960) Composite cast and wrought-iron girder (Condit, 36)

Another memorable building contemporaneous with the Wheeling Custom House was the Cooper Union building under construction from 1854–1859. Founded by Peter Cooper, the Union served as a free school for art and engineering for working class students, both men and women. Again, Trenton Iron Works supplied the wrought-iron joists, their third such project employing rolled wrought-iron members.

The Trenton Iron Works

To many, Peter Cooper's fame rests on his building of the Tom Thumb, a diminutive locomotive for trials on the Baltimore and Ohio, and the subsequent and celebrated race with the grey mare. The Tom Thumb was, in a sense, a plan to secure business for his firm with the Baltimore and Ohio Railroad to supply iron, particularly rails, for this expanding system. Because of the poor grade of iron ore available in the Baltimore area, Cooper decided to sell his Baltimore iron works and relocated in the New York area by acquiring a foundry, which he subsequently upgraded. He pioneered the use of anthracite as the fuel, and also as a powerful reducing agent in the production of pig-iron. It was also used in puddling furnaces to convert pig-iron to wrought-iron. His contribution to the fledgling iron and steel industry included the production of America's wrought-iron "I" cross-section beams. It was his 9-inch "I" beams which were an integral part of the iron framing of the Wheeling Custom House, and a plethora of government buildings under construction at the time.

In an effort to expand his company, he moved again to a location in the Lehigh Valley to have access to anthracite coal and high quality iron ore, both of which could be transported by water, and later by the expanding rail network. For his rolling mill, he relocated to Trenton on the Delaware River. This location was also served by the Delaware and Raritan Canal, and in addition, by railway lines. Phillipsburg, New Jersey, on the Delaware River, was selected for the production of pig-iron since it was close to the raw materials needed.

Peter Cooper planned to establish his son Edward in a managerial position, including product development. Edward responded by suggesting a partnership arrangement with his tutor at Columbia College, Abram S. Hewitt (National Register nomination for the Cooper Union Building). Like partnerships such as Rolls and Royce or Boulton and Watt, the Cooper-Hewitt pair were quite complementary with Hewitt exhibiting a forceful personality, which was essential in the development of the firm, while Cooper, not a decisive decision maker, had highly-developed mechanical skills coupled with an inventive streak. Although the elder Peter Cooper was opposed to the partnership in the beginning, he relented by agreeing to establish the Trenton Iron Company, and a company called Cooper and Hewitt. This latter company served as the manager for the Trenton Iron Company. Both of these organizations were established by 1845.

During the next four years the firm enjoyed a close working relationship with railways, particularly a flourishing market for rails. The economic boom did not last as British firms invaded the home market, and in modern parlance "dumped" rails on the market at half the previous price. The Trenton Iron Works continued to draw wire, which was a hedge against the weak iron rail business, but more important for our concern an interest in the large government public works programs, which necessitated diversification by rolling iron beams for the construction of "fireproof" buildings beginning with the Harper Brothers and Cooper Union buildings.

The first beams resembled railway rails with a bulb top and flat bottom flange. As early as 1847, under the aegis of Peter Cooper, the company attempted to roll 7-inch rail-beams, but was unsuccessful and succeeded in causing the company to invest $30,000 needlessly (Shaw 1960, 18). It was about this time, 1845 and later, that the first "I" beams in Britain were rolled as a substitute for curved cast iron ribs in the monumental Palm House at Kew Gardens near London. (Peterson 1980, 67–70; Peterson 1994, 17–25).

A second attempt to produce a 7-inch bulb rail-beam occurred in 1852 in connection with Peter Cooper's decision to build the Cooper Union building. This deeper member could be employed for main line track by railways, but even more important was sensibly the shallowest beam, which could be employed as floor joists with reasonable spans, which would provide both the strength and stiffness necessary. The success of this second attempt is credited to William Borrow, a recently landed emigrant in 1851 from the British Isles. He designed a new and much more powerful rolling mill. The following quotation paints a vivid picture of iron production at the Trenton Iron Company:

> They consisted of puddling furnaces, heating furnaces, rolling mill, and wire mill, equipped with machinery that was partly American and partly English. The double puddling furnaces, which steadily increased in number until by 1854 there were twenty-two, converted molten pig-iron, under constant stirring by skilled workmen, into wrought iron or at least a better quality of cast iron. The double heating furnaces, of which there were six in the year named, heated the pigs or ingots for the first rolls–those which crushed them into flat blooms or billets. These billets, taken up white-hot, were then shot forward through a series of other rolls adjusted to turn them into rails, beams, or roods, as desired. As the smaller pieces went forward, hissing whenever they touched any moisture, they rapidly took on the aspect of fiery writhing snakes, struggling in the murky gloom to escape workmen who caught them with pincers and thrust them back and forth with incredible quickness. When the larger rails were ready for final shaping, vises seized them and laborers hammered away deafeningly. As they finished, the rail was pushed under sharp steel saws which cut it to the precise length required. It then passed to a cooling-bed, and when quite cold was thrust into powerful presses, which straightened out bends or other irregularities. There were also foundries and pattern-shops for the production of special casings, and blacksmith shops and machine shops. "No pains or expense have been spared," Hewitt wrote in 1854, "to make the mill perfect in its arrangements."
>
> Power was derived partly from the race of the Trenton Waterpower Company, with three great wheels serving the mills, and partly from steam, for two engines were operated by the waste heat of the furnaces. Anthracite was of course used at both Phillipsburg and Trenton. The whole plant had a capacity by 1854 of more than 35,000 tons of finished iron annually–a spoonful to the gargantuan production of after years, for Hewitt lived to see a single American corporation formed with an annual capacity of 8,000,000 tons of finished steel; but a very satisfactory figure in the early fifties (Nevins 1935, 99–100).

Following the successful rolling of the 7-inch rail-beam, the firm advertised with a broadside featuring the use of their wrought-iron 7-inch rail-beams supported by wrought-iron box girders composed of iron plates, riveted top and bottom with rolled iron channels. This was the system proposed for the Wheeling Custom House, 1856–1859.

The two plants produced the 7-inch rail-beams. The first consisted of three tall blast furnaces at Phillipsburg using New Jersey ore, and some from Pennsylvania, together with anthracite to produce pig-iron, the annual production amounted to more than 25,000 tons. The pig-iron was shipped by water and rail to Trenton.

The Trenton mill consisted of twenty-two double puddling furnaces for converting pig-iron to wrought-iron by reducing the carbon content to nearly zero. The result was wrought-iron as described above. There were six double heading furnaces for heating the wrought-iron so that it could be rolled into billets. The white-hot billets were then rolled into rails,

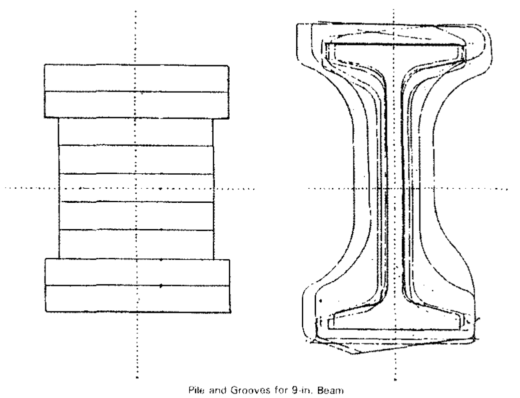

Figure 4
(1998) Transformation of a wrought-iron pile into an "I" section by repeated rolling of hot wrought-iron from Weissenborn 1861 (Elban et al., 38)

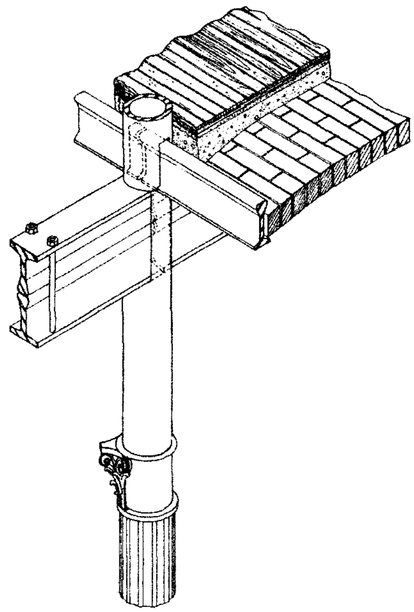

Figure 5
(1980) Detail of the skeletal framing used in the Cooper Union building (Peterson, 18)

beams, angles, channels, and other shapes depending upon the configuration of the rolls. Since the puddling furnaces were unable to produce enough wrought iron to roll a beam, a pile composed of wrought- iron bars was stacked up, heated, and rolled producing a symmetrical "I" beam, which was noticeably more efficient in bending than a rail-beam with a bulb top, but proved to be a difficult proposition to roll since one set of rollers had to fit between the flanges, Figure 4 (Nevins 1935, 116–17).

With the success of the Harper Brothers building and the work on the Cooper Union building, Figure 5, Young and Bowman decided to use wrought-iron rail-beams in the federal government Assay Office in New York. The required number of beams were rolled, which held up work on the Cooper Union building, but by the end of 1856, the Union building was nearly complete. With the success of these buildings, the Treasury Department adopted the Trenton iron beams and box girders for all of its public buildings.

Although William Borrow, the mill superintendent, installed new heavy machinery, the struggle to produce a 7-inch rail-beam was a costly endeavor amounting to a debt of $150,000 by the company. It, nevertheless, was a success. Borrow's new mill successfully rolled the rail-beam in the spring of 1854, but he died on October 1 of that year before he could undertake to produce a true "I" beam as a replacement for the bulb-tee section. This task was left to Charles Hewitt who modified the rolls to produce an "I" beam with symmetrical flanges. Shortly after Borrow's death and not later than the spring of 1855, the first 8-inch "I" beam was rolled (Shaw 1960, 20). By any evaluation it was a major accomplishment worthy of celebrating, but alas remembered by very few. During the next year, 9-inch "I" beams were delivered to the Wheeling, Virginia (later West Virginia) Custom House, Figure 4 (Shaw 1960, 31; Nevins 1935, 174; Jewett 1969, 390–91).

Wheeling Custom House Beams

The floor joists used throughout the Wheeling Custom House are amongst the earliest "I" beams in existence, having been supplied in 1856 as noted above. During the recent restoration, wrought-iron samples of these beams as part of the assessment of the structural capacity of the floor system were tested. Both chemical and mechanical tests were performed and summarized below, Table 1a and 1b:

Table 1a Results from Destructive Testing of 1856 Iron Specimens

	Young's Mod. (ksi)	Yield Stress	Ultimate Stress	Ultimate Strain
Specimen 1	23,025	34 ksi	48 ksi	0.095
Specimen 2	23,803	42 ksi	48 ksi	0.0087
Specimen 3	25,021	39 ksi	54 ksi	0.11
Average	23,950 (23,743)*	38.3 ksi	50 ksi	0.0712

*The values in parentheses include the results from a static compression test.
N.B. ksi = one thousand pounds per square inch.

Table 1b Composition of Wrought-Iron-Beam Sample From U.S. Custom House, Wheeling, West Virginia, percent.

	C	Mn	P	S	Si	Slag
Beam Sample	<0.005	0.029	0.610	0.039	0.590	7.4*
Typical hand-puddled wrought iron**	0.06	0.045	0.068	0.009	0.101	1.97

*Weight Percentage based on a volume percentage of 12.5 measured with the quantitative television microscope and assumed specific gravities of 4.5 for slag and 7.6 for wrought iron.
**For wrought iron made before 1930. Reference: Metals Handbook, 1948 Edition, page 504, American Society for Metals, Cleveland, Ohio. Tests by United States Steel Corporation, Pittsburgh.

Three tension tests revealed typical values for wrought-iron showing considerable ductility and strength. Sample one, however, failed in the fillet zone as did sample two where a large slag inclusion was present. The third sample failed in a ductile manner and exhibited the highest ultimate stress, Table 1. Earlier the results of a chemical investigation revealed important information on the wrought-iron used in the Custom House. It was found that both phosphorus and sulphur are an order of magnitude higher than traditional values. While the phosphorus adds fluidity to the molten iron, both phosphorus and sulphur embrittle the iron after cooling.

The method of production greatly influences the final behavior of the wrought-iron. It was not possible with the puddling furnaces available to produce a bloom of sufficient size to roll a 9-inch section 20-feet long. The solution employed was for a pile of wrought iron bars to be stacked, heated, and rolled. With sufficient temperature, the successive rolling would weld all of the bars together and produce a final "I" section. In cooperation with Loyola College, a metallurgical assessment of the 9-inch wrought-iron beams was undertaken (Elban 1998, 27–35). The results were published, and the conclusions gave an admonition for those dealing with historic wrought-iron structures that there are wide variations in physical properties. It is necessary for those involved in assessing and / or restoring early wrought-iron structures to deal with this material on a case-by-case basis. The inclusion of large amounts of phosphorus and / or sulphur will significantly reduce the fatigue capacity of wrought-iron.

Equally important, the system of rolling structural sections from a pile of bars can produce well-defined boundaries between the bars if the rolling temperature is below white heat. This is the case in both the bottom and top flanges of the sections tested from the Custom House. This has not, however, resulted in a reduction of flexural capacity, but could lead to delamination under certain loading condition such as the application of repeated loads.

The box girders riveted out of wrought-iron plate and channels support the 9-inch joists. Both the plate and the small channels were much easier sections to roll compared to the 9-inch "I" beams. While the box girders supported the floor joists, they were, in turn, carried at each of the three floors by cast-iron columns. These columns, and indeed all the cast-iron work in the Custom House, represents the handiwork of local foundries. Wheeling was, after all, a leading iron producing center suppling iron products for the boat building enterprise, the nation's leading center for the production of cut nails, steam engine production, together with wire manufacturing (Davis, [1861] 1972).

Having made the decision to use the Cooper & Hewitt iron framing system, a flourishing correspondence ensued, beginning in 1854 between the company and the U.S. Treasury Department, Figure 6. In these early letters, the concern was the utilization of the 7.25-inch iron rail-beams. In the original design of the Wheeling Custom House these beams were featured. The rail-beam members were tested in various configurations in an effort to enhance the strength and stiffness of the basic rail-beam. P.G. Washington, writing on behalf of James Guthrie, the Secretary of the Treasury, issued orders to Lieutenant G.B. Alexander which say in part:

> From Philadelphia you will proceed to Trenton, N.J. where experiments are in readiness to test the strength of wrought iron beams and girders which I wish you to witness and report the results with as little delay as possible as very large orders are about being given for both beams and girders which may have to be modified if the results should disappoint expectations (NARA, RG77, Dec. 9, 1854).

On the same day, the Secretary wrote to Cooper & Hewitt in New York City concerning the wrought-iron box girders.

> To: Cooper & Hewitt, New York City
> Dec. 9 1854
> Gentlemen:
> In relative to the thickness of the plate iron for the girders it will to a great extent depend on the length of the girder and on the strength of the form of beam as determined by the experiments now making at your mill. The beams in all cases are to be of your largest size pattern. The plan of making a girder by the union of two beams will not I think be practicable, as it would limit constructors to such sizes as two of your present patterns would produce, whereas various sizes would be required.
> P.G. Washington for the Sec. of the T (NARA, RG77, Dec. 9, 1854).

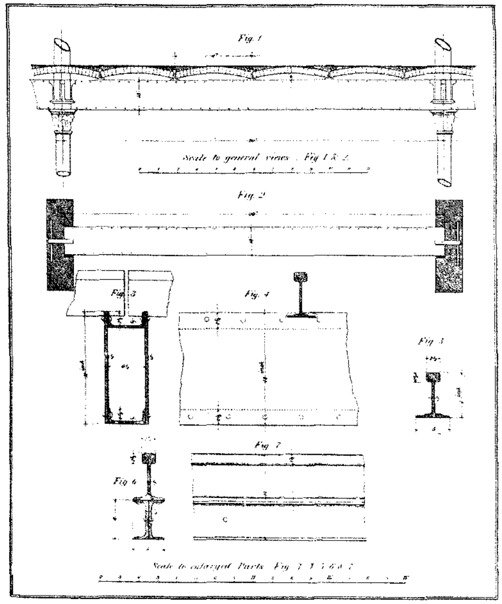

Figure 6
(1980) A Cooper & Hewitt broadside depicting their iron framing system (Peterson, 85)

In a letter to Robert Anderson, U.S. inspecting agent at Trenton, New Jersey, the Secretary authorized the purchase of a testing machine and assigned Anderson to oversee the testing when the testing machine arrived, Figures 7, 8, and 9.

> With regard to the purchase of a machine for testing the beams, I have to state that when Mr. Cooper was here he said that one could be procured for the sum of five hundred dollars. He will be written to today to purchase one, or to have one made as soon as possible. When it shall have reached you, it will be your duty to test each beam and to append a certificate of your having done so to the account of the beams sent in for payment (NARA, RG77, Jan. 25, 1856).

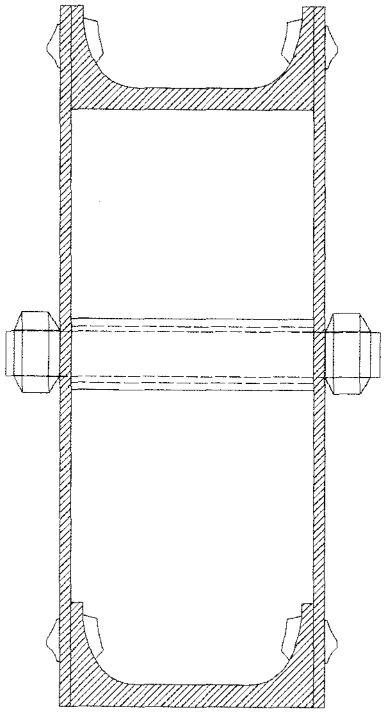

Figure 7
(1855) Iron box girder tested by the Treasury Department (Alexander, 3–5)

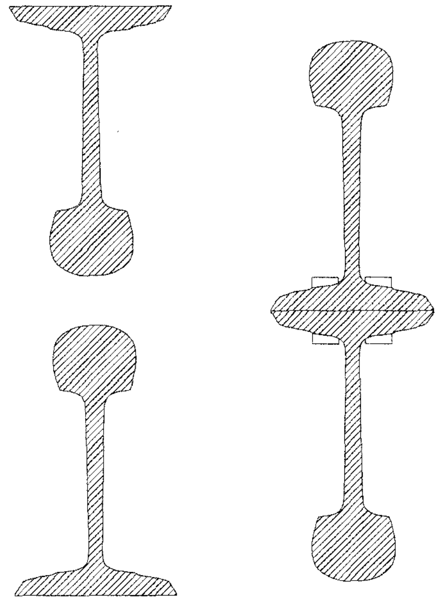

Figure 8
(1855) Various configurations of rail-beams (Alexander, 3–5)

By mid-summer, the Secretary wished to know the "state" of the girders and beams for the Wheeling Custom House.

> You will please inform the Department of the State of the girders I beams for the Wheeling VA, C.H. and whether you have had the necessary drawings furnished you in filliy them (NARA, RG77, July 19, 1856).

The year 1856 saw the request for bids to construct the Custom House. The official record is somewhat confusing. James Milligan, of Pittsburgh, submitted what appeared to be the low bid of $77,920 with the understanding that the Treasury Department would purchase the ironwork directly from Cooper & Hewitt (NARA, RG77, March 19,1856). Several of Wheeling's well known firms submitted bids amongst them, Sweeney with a total bid of $84,431.69, while James Bodley, well known producer or iron wire, bid $9,002.32 for brickwork. Presumably the brickwork was for the jack-arch floors. Many other firm submitted bids, all higher than James Milligan's quote (NARA, RG77, April 12, 1856; NARA, RG77, May 8, 1856). In March 1856, Captain Bowman wrote to James Guthrie regarding the bids submitted suggesting that the bids lacked sufficient details and the job should be rebid. After receiving a second round of bids, Bowman recommended the contract be awarded to William & J. Steward and Philip Schele & Company in the amount of $80,159.97 (NARA, RG77, March 5, 1856; NARA, RG77, June 2, 1856).

The project superintendent, James Luke, informed Secretary Guthrie on July 14, 1856, that the work had commenced and the excavation almost complete. Later, on October 1, 1856, superintendent Luke informed Secretary Guthrie that the beams and girders for the first floor would be shipped from Trenton on or about October 9 (NARA, RG77, July 14, 1856).

Historians welcome logistical complications which generate much paperwork. Cooper, Hewitt, &

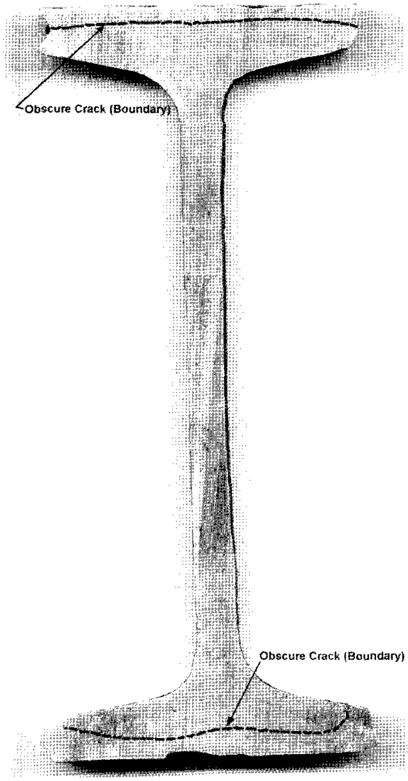

Figure 9
(2002) Cross-section of a 9-inch "I" beam from Wheeling Custom House (Photographed by E. L. Kemp)

Company writing to the Secretary Cobb, the replacement for James Guthrie, explaining the delay in submitting an invoice for the beams made October 28, 1856, arising from the fact that the 9-inch beams were mistaken for the 7-inch rail-beams, which were sent to the branch mint in New Orleans. Since the invoices were also misdirected, it required a reissuing of invoices and appropriate credit given to any payments already made. The story ends happily, however, with the 9-inch beams arriving in Wheeling with white lettering saying Wheeling, Virginia (NARA, RG77, June 5, 1857). Although the building was expected to be completed in 1858, it was in fact a year later that the facilities were opened to the public. Nevertheless, little difficulty was experienced in the construction.

Wheeling Custom House, 1859

The three story building in the Italian Renaissance Palace style measures 85 x 60 feet. The interior columns follow the Greek Doric style in the basement and Corinthian elsewhere, Figure 10. These hollow columns conducted heat to the various floors to provide background heat in each room. Coal fired furnaces supplied the heat from the basement to the various floors. Fireplaces throughout the building supplemented this early central heating system.

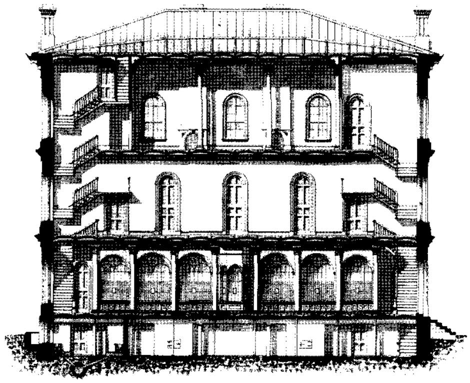

Figure 10.
(ca. 1856) Drawing by Ammi B. Young showing a section through Wheeling Custom House showing the Cooper & Hewitt framing system using 7-inch rail-beams which were replace by the 9-inch "I" beams actually used. (U.S. Treasury Archives, Washington, D.C.)

Beginning at the roof, rail-beams of the 7-inch variety were supplied to support the corrugated metal roofing intended to replicate Italian terra cotta tiles, Figure 11. The only wood in the building was the long leaf southern pine flooring. This wearing surface was secured to wood sleepers imbedded in a light weight concrete matrix used as a leveling course on top of the brick jack-arches. The jack-arches span approximately 5 feet between the 9-inch beams. In the rooms off the corridor, the span is 20 feet whereas the corridor spans are only 15 feet, Figure 12.

In the beginning of the restoration work, in the 1970s, there was an urgent need to establish a safe load capacity for each floor. The initial analysis assumed the load path for the dead and life loads, which passed from

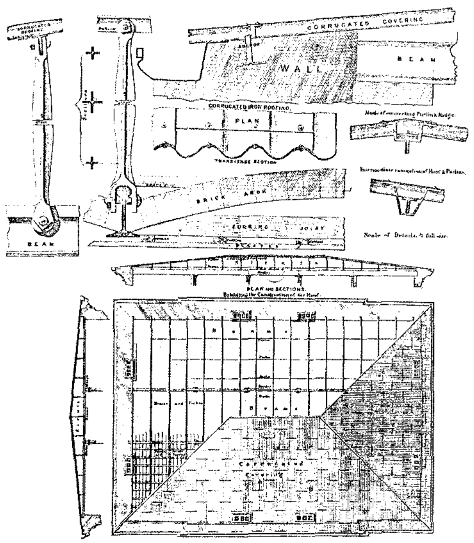

Figure 11
(ca. 1856) Drawing by Ammi B. Young showing the roof iron framing system utilizing 7-inch rail-beams (U.S. Treasury Archives, Washington, D.C.)

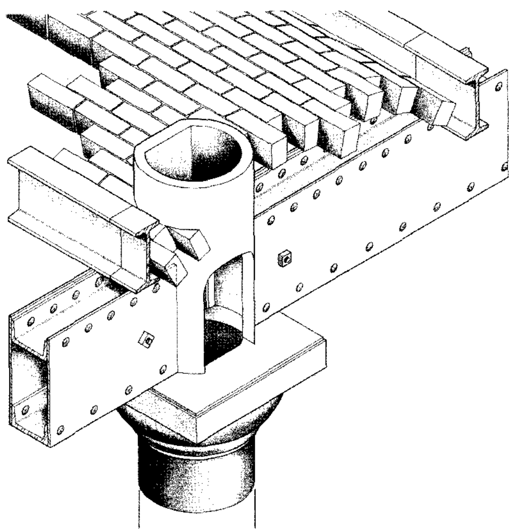

Figure 12
(2002) Drawing by Paul Boxley of the Wheeling Custom House iron framing system (Institute for the History of Technology and Industrial Archaeology Archives, Morgantown, WV, USA)

the floor to the jack-arches, which in turn transferred their loads to the 9-inch "I" beams. This meant that the floor capacity was beholden to the flexural capacity of the 9-inch beams. This study, Table 2, found all the floors associated with rooms having a 20 foot span had a limited capacity of 74.4 pounds per square foot (psf), which would prohibit their use for public assembly. On the other hand, the corridor capacity was estimated at 184 psf, which was more than adequate. One object of the restoration then was to raise the floor capacity to a minimum of 100 psf for public assembly in any room, based on a more elaborate analysis of the floor system. Clearly the 9-inch beams were critical with all the other components exceeding the necessary live load capacity. With larger factors of safety, typically eight used for cast-iron columns, it was not surprising to find the compressive stress in the cast iron at a low 1,100,000 pounds per square inch (psi).

The wrought-iron box girders were estimated to be able to sustain a uniformly distributed floor load of 114 psf, which is in excess of the required 100 psf needed for public assembly. In the absence of test results, modern mortar specifications for an equivalent mortar indicate a value of 1,800 psi. This value appears to quite conservative since the mortar is restrained between the bricks and appears to be of a high quality as a result of extensive examination of the exposed jack-arch floors. This value was then used in evaluating the load carrying capacity of the floor system.

This analysis of the floor system appears to be the correct for the dead loads involved because of the construction method. Although not explicitly stated, it appears that the jack-arch floors were built in the following manner. First, 9-inch beams were placed on the box girders and exterior walls at a nominal spacing of 5 feet throughout the length of the building. The top flanges of the beams were linked at several locations with transfer straps hooked over the flange. These extended from beam to beam throughout the length of the building in an effort to prevent the thrust from the brick jack-arches from overturning the beams, since the jack-arches were build one at a time beginning at one end of the building. It should be noted that the floor joists simply rest on the box girders without any connection to prevent overturning. When the entire floor system was complete, the thrusts on each side of the joists compensated each other, and provide a significant clamping action against the beam webs. Centering for the brickwork was supported on the

Table 2 Summary of Preliminary Structural Analysis

Load Factors (no resistance factors applied): Dead Load: Ultimate Strength (assumed):	1.9 Dead Load, 2.3 Live Load 400 lb/ft of length 35 ksi k=1000 lb
Iron I-beams: Moment of Inertia (I): Span, outer rooms: Maximum Shear Force (DL only): Maximum Shear Stress (DL only): Maximum DL Moment: Allowable Live Load: Live Load deflection: Span, Interior rooms: Maximum DL Moment: Allowable Live Load:	 125 in^4 20 ft 4000 lb 0.91 ksi 20 k-ft 74.4 psf 0.38 in (L / 630) 15 ft 11.2 k-ft 184 psf
Box Girders: Area: Moment of Inertia (I): Shear stress (DL): Allowable Live Load:	 18.37 in^2 559 in^4 0.91 ksi 114 psf
Columns: Applied Load: Compressive stress: Allowable stress:	 22.3 kip 1.1 ksi 80.0 ksi

The load factors correspond to a ϕ factor of 0.68 for a DL/LL ration of 0.4 using the normal 1.2 DL factor and 1.6 LL factor. In addition, the 35 ksi yield stress assumed for the previous analysis is less than the 38 ksi average yield stress obtained by test.

bottom flange of the floor joist. Undoubtably, the centering was not supported by staging, thus before the mortar set, the floor beams were subjected to the dead-load of the brickwork. Whether or not staging was used, it is prudent to assume that the dead load of the brickwork is carried entirely by the floor joist. Thus, the preliminary analysis serves to establish stress levels in the beams before the infill, flooring, or any live load is applied. The possible structural contribution of the brick vault is restricted to the weight of the light infill leveling course and the wooden floor, and of course, the applied live load.

Having studied the architect Robert Mills earlier structure in Charleston, South Carolina, it appeared that a reconsideration of the function of the joist-arch system under live load was in order. If one considers the longitudinal structure as a curved surface with the iron beams acting in tension as edge beams, and the jack-arches supplying the necessary compressive forces would such an analysis reveal a safe live load capacity of more than 100 psf?

All earlier examinations of the Custom House interior skeletal frame focused upon the cast and wrought-iron components assuming the massive exterior load-bearing stonework was more than adequate. In like manner, the jack-arch floors were assumed to carry their load transversely to the iron floor beams and not be heavily stressed. If, however, the brickwork supplied the compressive resistance to floor loads in the longitudinal direction, the compressive strength of the brick was needed to confirm the analysis. Test revealed a compression strength of 6,050 psi and with an assumed deviation of 1,500 psi, the brickwork appeared to be more than adequate (Tice 1995, 44–45). The jack-arches were laid up with natural cement-sand mortar as required in the original specifications.

If the brick vault spanning longitudinally with the iron joist providing the necessary tensile strength, one must assume that the bond between the mortar at the base of the arch and the web of the 9-inch beam is adequate. According to early concrete specifications, a value of 240 pounds psi is an appropriate working stress. The light fill was assumed at 50 pounds per cubic foot (pcf), and the southern pine floors at 50 pcf, including sleepers used to attach the floors to the fill (Hool et al. 1918, 265–68).

With the material properties of the structural components in hand, an analysis using Algon's 20 node solid system, as depicted in the illustration, served as the basis for the analysis. With a live load of 100 psf, the results revealed a deflection of 0.56 inches and stresses in both the longitudinal and radial directions, which were quite acceptable and well below working stress levels. The sheer stress at the interface of the iron web and the mortar was found to be 142 psi, well below the 240 psi thought to be a safe value. At a value of 124 psf live load, the analysis reveals that the structure can sustain the desired 100 psf throughout the building. Such a result will allow increased flexibility in utilizing the public space within the Custom House, Table 3.

Table 3 Summary of Finite Element Analysis

Material properties for the brick will be assumed as:	
f'm 1800 psi	
v=0.11	
Modulus of Elasticity	1800000 psi
Modulus of Rigidity	720000psi
f't	320 psi
Material properties for the iron will be:	
Young's Modulus	24000 ksi
Yield Stress	38000 psi
Ultimate Stress	50000 psi
Design Shear Strength (v_n)[10] full x-section	90000 lbs
Design Shear Strength (v_n) cut section	34500 lbs
Model:	
644 nodes	
648 elements can divided into shell elements and beam elements	
Arch span 5 ft = 60 inches	
Thickness of arch 4 inches	
Beam elements use iron properties	
Length of beam 10 ft = 240 inches	
I Beam section:	
Height of Iron Beam	9.0625 inches
Width of top I beam	4 inches
Width of bottom I beam	4 inches
Thickness of flange	0.5 inches
Thickness of I beam	0.432 inches
Load:	
Z axis: Load / area 100 pounds per ft^2 = 0.694 lbs / in^2	
Constraint:	
Pin support in X axis and Z axis at 4 corners	

Note: Model by Femap700 Out put by CSA/Nastran Unit: force (lb) : length (inch)

The results also indicated that the jack-arch floor system supported with iron edge beams can sustain loads by composite action providing there is sufficient bond strength between the iron joists and the brick arches, Figure 13.

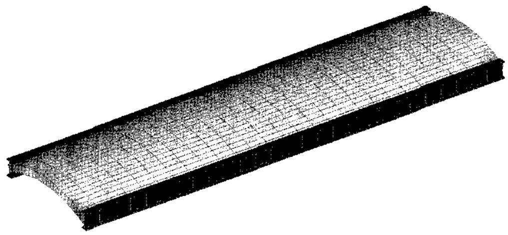

Figure 13
(2002) Three dimensional mathematical model of one bay of the floor system used by the author (Institute for the History of Technology and Industrial Archaeology Archives, Morgantown, WV, USA)

A more sophisticated analysis considering cracking of the brickwork in tension may reveal new insights into the behavior of the arch floor system whether it be constructed in brick or concrete. With the present analysis, however, a load test on the Custom House floor would be the most important means of confirming the structural analysis, and provide insights into other buildings using this system.

Together with other mid-century skeletal framed iron structures, the Wheeling Custom House stands as an important landmark in the history of 19th century building. By the end of the century, the skeletal framed high-rise building became the hallmark of American engineers and architects, and transformed the appearance of American cities.

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