Metallurgical Investigation of an Iron Cable Wire in a Gries-Gendell (Severson) Girder

WAYNE L. ELBAN and MARTHA GOODWAY

Cast-iron girders (c. 1854) tensioned with cable rather than rods were discovered more than 20 years ago in Philadelphia. Metallurgical comparison of this girder cable with the wrought-iron cable of the Wheeling Suspension Bridge (c. 1849) in West Virginia revealed interesting differences in the materials.

Introduction

Wrought iron has little carbon and no added alloying elements, but it contains numerous particles of slag and scale, some visible to the naked eye. It is highly inhomogeneous, and its sources are varied and often uncertain, so knowledge of its properties and their variation is limited. An understanding of the details of historic metallurgical bulk-deformation processes, such as wire drawing, is also incomplete. This paper discusses the investigation of samples of historic iron wire from a cable used in one of four unusual post-tensioned cast-iron girders removed in 1981 from the Farmers' and Mechanics' Bank in Philadelphia.[1] The data is then related to an earlier study on three main cable wires from the Wheeling Suspension Bridge (WSB) in West Virginia, which is closely contemporary (1847–1849) with the girder.[2]

Built in 1854–55, the bank building stands at 427 Chestnut Street, with its massive, ornate iron doors still in place. It is currently the American Philosophical Society's Benjamin Franklin Hall.[3] Sayenga described the discovery and intact recovery of the so-called Gries-Gendell girders (G-G-G) from the building.[4] This designation refers to John M. Gries, the building's architect, and John A. Gendell and Co., the manufacturer of the iron truss castings. These girders, approximately 29 feet long (9 meters), supported the two floors in the rear of the building.[5] Recently, Sara Wermiel provided additional details concerning the origin of the bank girders, as well as similar ones more than twice as long but not accessible, which are still in use in an auditorium at the Peabody Institute in Baltimore, Maryland, which was built in 1858–61.[6] She identified Benjamin Severson as having designed and built the girders based on a number of historic technical articles, many of which he wrote. He had also created a scale model of a railroad bridge (1849) and subsequent full-scale version (1850), which used iron-wire cables positioned parallel to the bottom of the truss.[7]

Sayenga also presented a number of the interesting metallurgical results obtained by researchers at Lehigh University.[8] Their investigation of individual wire samples included bulk chemical analysis, which measured carbon, manganese, phosphorus, sulfur, and silicon contents; tensile testing to obtain yield stress, ultimate tensile strength, and elongation at fracture; Rockwell (B scale) hardness measurements; and microstructural characterization using light microscopy. The purpose of the current work is to build on these results with particular emphasis on diamond-pyramid (Vickers) microindentation hardness testing to obtain hardness profiles across radial and longitudinal wire sections and on inclusion chemistry using energy-dispersive spectrometry (EDS) x-ray analysis.

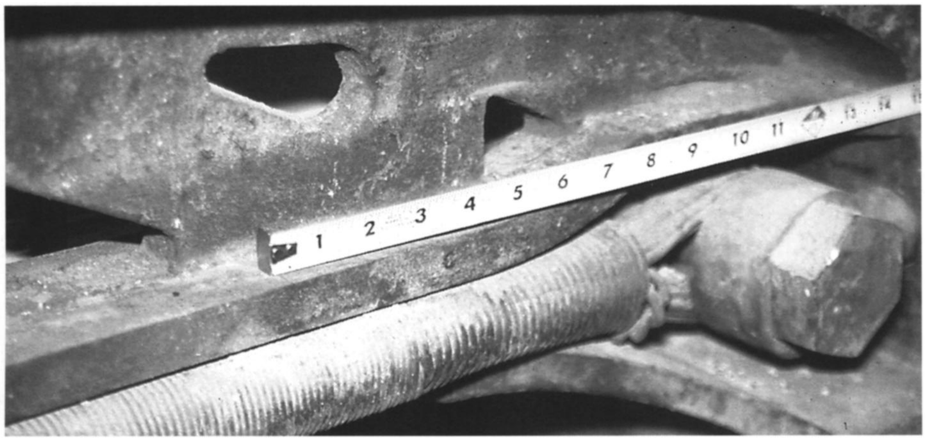

Fig. 1. Continuous wire-wrapped wire cable at one bearing end of Gries-Gendell (Severson) girder in Smithsonian collection. All photographs by the authors.

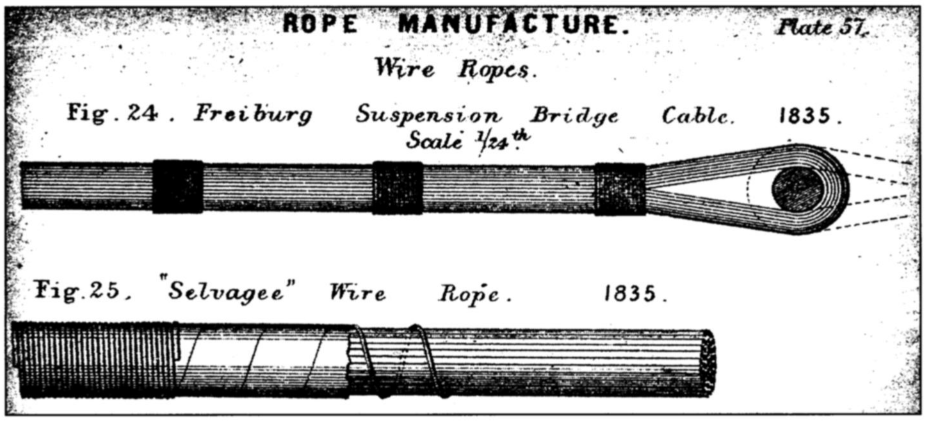

Fig. 2. Types of wire cable construction. Charles P. B. Shelley, "On the Manufacture of Hemp and Wire Rope" in *Proceedings of the Institution of Mechanical Engineers* (1862): 170-209 and Plates 46-62.

Figure 1 shows an end portion of an intact girder with one of its two cables visible. The cable consists of parallel wires that are continuously wire-wrapped or selvaged in a highly uniform fashion that suggests machine rather than hand fabrication; the relatively large diameter of the wire around the girder cable seems to preclude manual processes (Fig. 2).[9] The wrapped configuration represents a significant improvement over the periodic ligatures used on the Wheeling Suspension Bridge main cables, which were assembled only a few years earlier (Fig. 2).[10]

John A. Roebling is credited with introducing the new development in cable assembly in America in 1841 when he attempted to obtain a U.S. patent on a wire-wrapping machine.[11] In an unsuccessful attempt to replace cordage ropes, he employed the device to assemble a cable for the Allegheny Portage. The wrapping wire did not possess sufficient abrasion resistance; once the wrapping wore through, the parallel-laid wires were free to flop about, causing the cable to lose its rigidity. In his proposal Roebling also specified preparing the Wheeling Bridge main cables in this manner.[12] Though his recommendation was not accepted, it would have been a highly appropriate application for this technique. It is used in cable assembly for suspension bridges to this day.

Preliminary Characterization

Examining the sample girder wire revealed that much of it still had an amber- or reddish-colored protective coating.[13] The surface of the wire had well-defined draw marks in the form of numerous longitudinal grooves, some quite prominent (Fig. 3). These marks indicate that the die used to draw this wire to its final diameter either was not well honed or had undergone significant irregular wear.[14] The wear could be a result of surface scale from prior heat treatment of the wire or of secondary-phase cementite (Fe_3C) particles being present. The wire shows some surface cracking, predominantly longitudinal (Fig. 4). There are also what appear to be circumferential "tool" marks present, which are attributed to gripping the wire during the drawing operation (Fig. 5).

Method

Metallographic sample preparation. Wrought iron is often anisotropic, meaning that it exhibits properties with different values when measured in different directions. Therefore, both radial and longitudinal (i.e., along cylindrical axis) sections were examined. Sections of bare wire were mounted in phenolic, then fine ground with 240-, 320-, 400-, and 600-grit SiC papers.[15] They were then rough polished with 5.0 and 1.0 µm Al_2O_3/water slurries and final polished with 0.5 µm Al_2O_3/water slurry using standard manual techniques.[16] Etching was accomplished by cotton swabbing the polished surfaces with 1% nital (HNO_3 in ethanol) for 15 seconds.

Indentation hardness testing. Using a Clark model DRM12 tester, Rockwell (B scale) hardness (HRB) was determined for separate radial sections that underwent final polishing with the 1.0 µm Al_2O_3/water slurry. Single indentations were placed approximately in the center of a total of six samples.

Diamond-pyramid (Vickers) microindentation testing was performed on the radial and longitudinal sections using a LECO model M-400 tester.[17] Particular emphasis was given to obtaining ferrite (α-Fe) hardness measurements across the entire diameter at regular intervals to assess the observed variation in microstructure from a mechanical properties viewpoint. All of the impressions were reasonably symmetric, and both diagonals were measured and averaged in the hardness calculations.

Energy-dispersive spectrometry x-ray analysis. Numerous ferrite grains and inclusions were subjected to standardless, semi-quantitative chemical analyses using a ThermoNORAN EDS low–atomic number x-ray detector in a JEOL model JXA-840A scanning electron microscope (SEM).[18] The inclusions were investigated to assess their composition, as well as to profile their frequency and distribution, where an effort was made to obtain spectra for inclusions of varying size and appearance.

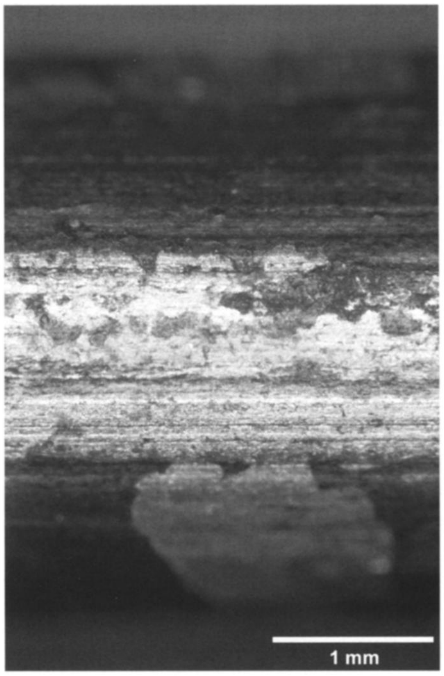

Fig. 3. Photomacrograph of the surface of the as-received girder iron wire partially denuded of coating and showing numerous longitudinal grooves.

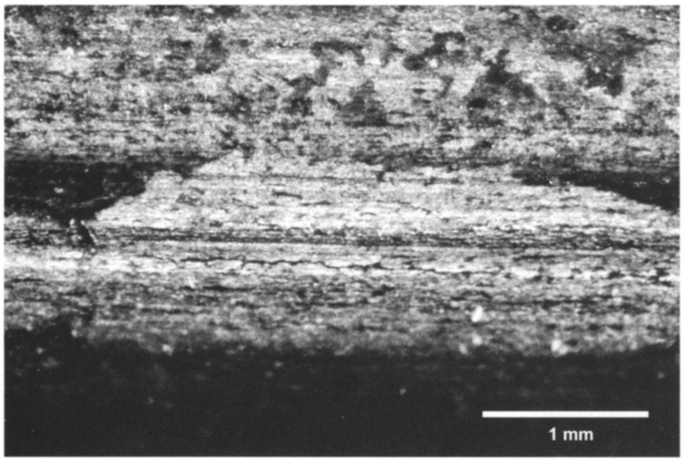

Fig. 4. Photomacrograph of the surface of the as-received girder iron wire partially denuded of coating and showing details of a prominent longitudinal groove with irregular cracking along one edge.

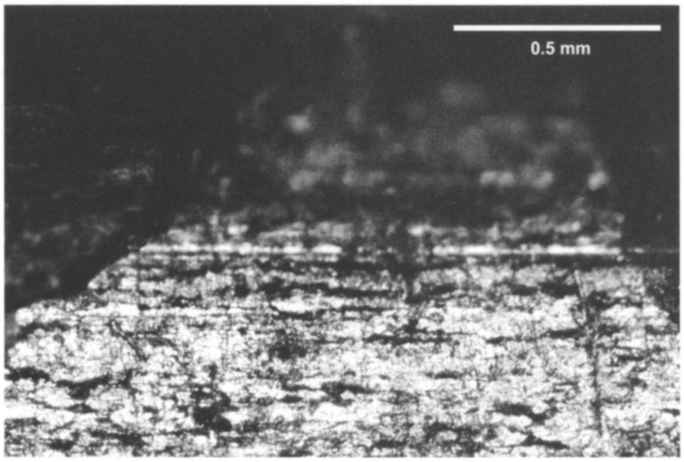

Fig. 5. Brightfield photomicrograph of as-received girder iron wire partially denuded of coating and showing varying size circumferential "tool" marks.

Results

Metallographic examination. In the macrostructure of the radial and longitudinal sections the reflectivity is highly variable, indicating significant inhomogeneity on a coarse scale (Figs. 6 and 7).[19] This differs from the appearance of similar sections of the wrought-iron wires from the Wheeling Suspension Bridge.[20] The radial cross section of the girder wire does not possess radial symmetry as expected nor does it have a deformation flow-line appearance similar to any of the radial sections of the bridge wires. Rather, the girder wire appears to consist of two quite dissimilar materials.

The microstructures of the radial and longitudinal sections also reveal a high degree of inhomogeneity (Figs. 8 and 9). By comparison, there are significantly fewer inclusions present in either section than in the bridge wire specimens. The girder radial section has only a few inclusions of any significant size. However, in the longitudinal section, one very prominent (wide) inclusion boundary, consisting of multiple stringers, separates the top ferritic iron area, consisting of a ferrite (α-Fe) matrix with relatively large slag inclusions or stringers, from an area containing a duplex structure of a ferrite (α-Fe) matrix with numerous tiny secondary-phase particles, later identified as cementite (Fe_3C).[21] At higher magnification, these particles were found to be equiaxed with surface relief visible before etching, appearing as tiny "plateaus" or protrusions, often having rounded rather

Table 1. Vickers Microindentation Hardness Measurements on Ferrite in Wrought Iron from Farmers' and Mechanics' Bank in Philadelphia, Wheeling Suspension Bridge, Wheeling Custom House, and USS *Monitor*

Description	Min. VHN (kgf/mm^2)	Max. VHN (kgf/mm^2)	Avg. VHN (kgf/mm^2)
Farmers' and Mechanics' Bank Girder (G-G-G-1)			
Radial/ Wire: Ferritic iron	159	197	173 (σ= 13.1)
Radial/ Wire: Ferrite (α-Fe) + Fe_3C	185	234	205 (σ= 16.3)
Longitudinal/ Wire: Ferritic iron	162	188	178 (σ= 9.64)
Longitudinal/ Wire: Ferrite (α -Fe) + Fe_3C	192	213	198 (σ= 6.28)
Wheeling Suspension Bridge (WSB-1) -- Elban and Goodway (2002)			
Radial/ Wire inside "core"	211	254	237 (σ= 12.4)
Radial/ Wire outside "core"	204	238	225 (σ= 12.3)
Longitudinal/ Wire inside "core"	231	247	238 (σ= 5.96)
Longitudinal/ Wire outside "core"	216	236	228 (σ= 6.82)
Wheeling Custom House -- Elban et al. (1997)			
Transverse/ I-beam flange	156	225	189
Transverse/ I-beam flange ("added" material)	142	178	153
Transverse/ I-beam web	155	237	213
Transverse/ I-beam web-flange transition	127	213	168
USS *Monitor* -- Beachem et al. (1979)			
Hull plate	111	164	Not given

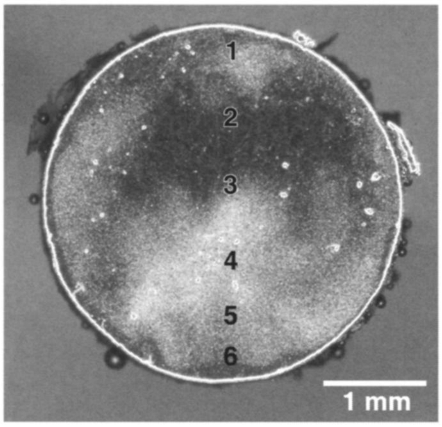

Fig. 6. Photomacrograph of polished radial section (Sample I-1) of girder iron wire showing EDS x-ray analysis locations.

than angular boundaries. Since scratches did not typically cut through these protrusions, they are harder than the alumina (Al_2O_3) abrasive or any inclusion particles that may have become dislodged and scraped across the surface during polishing. Although the transition through the two structures is gradual in the longitudinal section, the radial section shows a more distinct difference in structure as ferritic iron (top) rather abruptly becomes duplex material (Fig. 8).

In a ferritic iron portion of the longitudinal section, the ferrite (α-Fe) grains exhibit the deformation texture derived directly from the cold-drawing operation (Fig. 10). Some areas have an aspect ratio as low as two, indicating that the wire was not very heavily drawn after earlier annealing. In this portion of the wire there is no evidence that recrystallization and grain growth occurred, thus indicating the wire was not subjected to any detectable post-drawing heat treatment. This is consistent with earlier findings on wire from the bridge and similar to the findings of previously published work done at the Smithsonian on early music wire.[22] However, the lower magnification photomicrograph reveals a number of smaller, more equiaxed grains (Fig. 9). This also indicates that the wire drawing was not too severe and that the accompanying plastic deformation occurred primarily in the larger grains in keeping with the Hall-Petch grain-size effect.

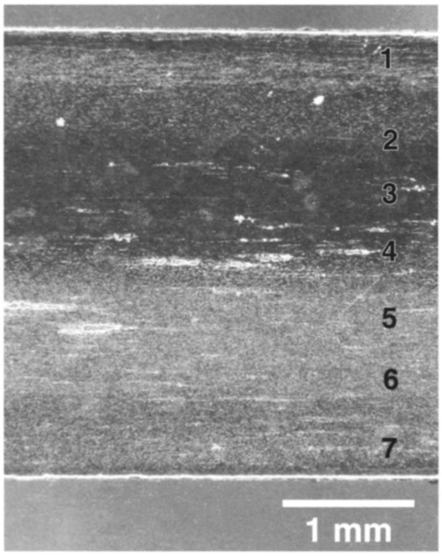

Fig. 7. Photomacrograph of polished longitudinal section (Sample I-2a) of girder iron wire showing EDS x-ray analysis locations.

The ferritic iron is particularly clean with a very low number of small inclusions; those present are often located in the grain interiors (Fig. 10). Examination of numerous small inclusions at 1000X failed to reveal pearlite, indicating the iron was made by the puddling process.[23]

Hardness testing. Microscopic examination of the Rockwell impressions revealed they were radially symmetric. The average value compared with the bridge wire values is:

Wire	HRB
G-G-G-1	81.3 (σ= 0.5)
WSB-1	85.4 (σ= 2.3)
WSB-2	89.1 (σ= 0.3)
WSB-3	82.9 (σ= 0.6)

Table 2. Summary of EDS X-ray Analysis Results for Elements Found in Inclusions in Iron Wire from a Gries-Gendell (Severson) Girder Compared with Those from the Wheeling Suspension Bridge

Wire Number	Sample, Section	Number of Inclusions	Common Elements Detected in All Wires	Elements Detected that Were Missing in at Least One Wire	Number of Elements Detected
G-G-G-1	I-1 Radial	40	Al, C, Ca, Fe, K, Mg, Mn, Mo, Na, O, P, S, Si	Cd, Cl, Nb, Sr, Th, Ti, Tl, Zn	21
	I-2a Longitudinal: lightly repolished	46			
	I-2a Longitudinal: initial study	7	Al, C, Ca, Fe, K, Mg, Na, O, P, S, Si	Ti	12
WSB-1	A Radial	26	Al, C, Ca, Fe, K, Mg, Mn, Mo, Na, O, P, S, Si	Te, U, V	16
	B Longitudinal	33			
WSB-2	S-1 Radial	55*	Same	Os, Pb**, Sm, Ti, Zr, V	19
	II-2a Longitudinal	48***			
WSB-3	L-1 Radial	50****	Same	Cl, Cr, Cu, Pb, Ru, Ta, Tc, Ti, V, W	23
	III-2a Longitudinal	40			

---

* Includes three apparent corrosion products, two "mosaic" regions, and one crack region.

** Detected twice: in crack region and believed associated with exterior lead paint that had penetrated crack and in prominent stringer with large amount of Al.

*** Includes 21 prominent stringers of undetermined size.

**** Includes six apparent corrosion products.

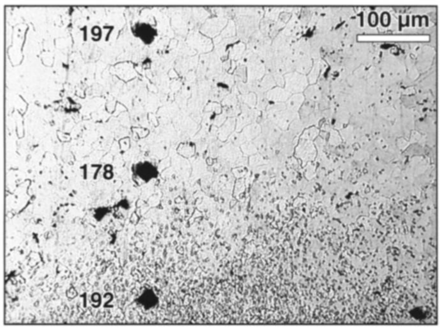

Fig. 8. Brightfield photomicrograph of polished radial section (Sample I-3) of girder iron wire showing transition from ferritic iron (top) to duplex (α-Fe + Fe_3C) material; Vickers hardness numbers are indicated.

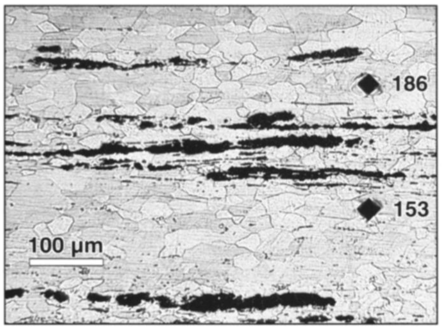

Fig. 9. Brightfield photomicrograph of polished longitudinal section (Sample I-2b) of girder iron wire showing gradual transition from ferritic iron (above wide band of inclusion stringers) to beginning appearance of duplex (α-Fe + Fe_3C) material within what is otherwise ferritic iron; Vickers hardness numbers are indicated.

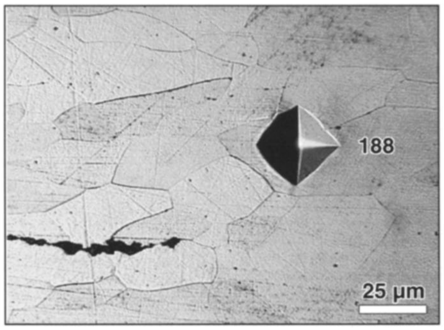

Fig. 10. Interference (Smith) photomicrograph of polished longitudinal section (Sample I-2b) of girder iron wire showing deformation texture of ferritic iron portion; Vickers hardness number is indicated.

where the corresponding standard deviation, σ, is included. The relatively low hardness for the girder wire suggests that it was not as heavily work hardened as the bridge wires. In making this comparison, it should be noted that the girder wire was sectioned from a cable that had been previously tested in tension to failure.[24] The current hardness is somewhat higher than the average value of 73.5 reported by Lehigh researchers.[25]

The average hardness of the ferrite in the duplex structure of ferrite and cementite (α-Fe + Fe_3C), reported as Vickers hardness number (VHN), is significantly higher than in the ferritic iron for both radial and longitudinal sections (Table 1). This indicates that the mechanical state for the matrix throughout the cross section is not uniform. However, for a given type of material, only a very small difference exists in the average values for the radial and longitudinal sections, indicating that plastic anisotropy is minimal.

To relate the girder wire measurements to those obtained for other historic wrought-iron structures, hardness values are also given for the ferrite in wrought iron from the Wheeling Suspension Bridge, the Wheeling Custom House, and the USS *Monitor* (Table 1).[26] Of the four sources, wire from the bridge, having the smallest cross section, has the highest hardness, in keeping with the reported inverse dependence of tensile strength on size for wrought-iron round stock ranging from ¼- to 4-inch diameter.[27] While having essentially the same cross-sectional area, the girder wire is softer than the bridge wire by 13 percent in the case of the duplex material and by 24 percent in the case of the ferritic iron.

Elemental analysis of inclusions. Table 2 lists all of the elements detected in inclusions in the girder wire and, for comparison, in the three Wheeling Bridge wires. The inclusion chemistry for the wires from these two structures is quite disparate. Five elements — cadmium, strontium, thorium, thallium, and zinc — found in the girder samples were not detected in any of the bridge samples, while one element found in samples from all three bridge wires, vanadium, was not detected in the girder samples.

In general, inclusions in the girder wire have a more nearly uniform composition than inclusions analyzed in the bridge wires. The frequency numbers for common elements detected — calcium, potassium, manganese, sodium, phosphorus, sulfur, and silicon — appear in Table 3 for samples from the girder wire

Table 3. Frequency of Various Common Elements from EDS X-ray Analysis of Inclusions in Iron Wire from a Gries-Gendell (Severson) Girder Compared with Those from the Wheeling Suspension Bridge

	Wire G-G-G-1			Wire WSB-1			Wire WSB-2			Wire WSB-3		
Constituent	Radial Section	Longitudinal Section	Frequency	Radial Section	Longitudinal Section	Frequency	Radial Section	Longitudinal Section	Frequency	Radial Section	Longitudinal Section	Frequency
Ca	35	43	(0.91)	5	7	(0.20)	20	12	(0.32)	25	15	(0.48)
K	34	42	(0.88)	1	5	(0.10)	13	nd	(0.13)	17	3	(0.24)
Mn	4	6	(0.12)	2	12	(0.24)	12	5	(0.17)	19	1	(0.24)
Na	15	15	(0.35)	4	nd	(0.07)	2	nd	(0.02)	2	nd	(0.02)
P	13	9	(0.26)	17	10	(0.46)	25	10	(0.35)	28	17	(0.54)
S	9	14	(0.27)	14	4	(0.31)	13	10	(0.23)	14	9	(0.27)
Si	38	44	(0.95)	19	17	(0.61)	41	32	(0.74)	36	32	(0.81)
Total Inclusions Analyzed	40	64		26	33		51*	48		44**	40	

* Does not include analyses for three apparent corrosion products and one crack region.
** Does not include analyses for six apparent corrosion products.
nd = not detected

Table 4. Summary of EDS X-ray Analysis Results by Region for Various Common Elements Found in Inclusions in a Radial Section (Sample I-1) of a Gries-Gendell (Severson) Girder Iron Wire

Region No./ Location		Average, Wt % (Detected in Number of Inclusions)						
	Inclusions Analyzed	Ca	K	Mn	Na	P	S	Si
Ferritic Iron:								
1/ ~10% in from top circumference	7	2 (6)	1 (6)	nd	1 (1)	nd	tr (1)	13 (6)
2/ ~20% in from top circumference	8	2 (7)	1 (7)	tr (1)	tr (2)	tr (6)	tr (1)	11 (8)
3/ Near center	8	2 (7)	1 (6)	nd	nd	1 (6)	tr (5)	9 (7)
Ferrite (α-Fe) + Fe_3C:								
4/ ~67% in from top circumference	7	11 (6)	5 (6)	nd	1 (5)	nd	tr (1)	37 (7)
5/ ~80% in from top circumference: roughly symmetric with region 2	5	8 (4)	4 (4)	1 (2)	1 (4)	nd	nd	30 (5)
6/ ~90% in from top circumference: roughly symmetric with region 1	5	3 (5)	2 (5)	1 (1)	1 (3)	1 (1)	tr (1)	19 (5)

nd = not detected; tr = trace amount

and the three bridge wires. Much higher incidences of calcium, potassium, and sodium, and a somewhat higher incidence of silicon were found in the girder samples. The frequencies of manganese and phosphorus were significantly lower, while the observation of sulfur was essentially the same.

Analytical results for the common elements obtained by region for a radial and longitudinal section of the girder wire appear in Tables 4 and 5 (Figs. 6 and 7). This wire was very well fluxed compared to the bridge wires, which generally had significantly lower silicon contents. There was a virtual absence of scale (wüstite: FeO) in the girder samples, unlike the WSB-1 samples in particular, which had an abundance of scale. For the girder wire, the most interesting is the difference in inclusion chemistry between the ferritic iron and duplex structure regions. For the radial section, the amounts of calcium, potassium, and silicon are much higher in the duplex structure than in the ferritic iron portion of the sample (Table 4). A similar trend occurs in the longitudinal section for calcium especially, and also potassium (Table 5); however, it is not possible to make an analogous claim regarding silicon because of the large variation in both regions. Nonetheless, it can be asserted that individual inclusions were much more often near the composition of fayalite [71.0% FeO, 29.0% SiO_2, corresponding to 13.6% Si] in ferritic iron than in the duplex structure regions.[28]

Table 6 provides chemical composition as a function of inclusion size for iron, silicon, and aluminum. An overwhelming majority (just over 87 percent) of the inclusions in the girder samples contained a high (≥5%) amount of silicon, whereas the bridge samples had a relatively small number. There was a virtual absence of inclusions with a high (≥15%) amount of aluminum. This is in contrast to the bridge samples, particularly WSB-1, which had a high number of these inclusions attributed to bits of furnace lining becoming incorporated in the iron during smelting or refining. It is conjectured that new or higher quality furnace bricks (i.e., with greater spall resistance) were used in making the iron for the girder wire or perhaps the operational temperature in the furnace was lower, thereby reducing the thermal stress.

An initial EDS study of the same longitudinal section (Sample I-2a) focused primarily on the most prominent inclusion-boundary region (Table 2). In this work seven additional individual inclusions were analyzed and found to have fairly uniform chemical composition notable for high silicon content and titanium presence in each. Away from the inclusions, the ferrite in both the ferritic iron and duplex structure regions has about the same carbon content.[29] In this portion of the sample section, particles in the duplex structure region are often protrusions. Four of these were analyzed and found to have elevated carbon and sometimes to be also rich in silicon and oxygen.

Seven of these protrusions in the radial section (Sample I-1) were also chosen for EDS x-ray analysis. Six contained iron with only varying amounts of carbon that were typically significantly higher than the amount of carbon present in nearby ferrite grains. The remaining protrusion also had a trace amount of thallium. Combining the previous observation regarding the scratch resistance of the protrusions with the EDS results, we conclude that the duplex structure consists of ferrite and cementite (α-Fe + Fe_3C).

Elemental analysis of ferrite. EDS x-ray analyses of ferrite in both ferritic iron and ferrite and cementite (α-Fe + Fe_3C) regions revealed high-purity iron with varying small amounts of carbon present but no phosphorus or sulfur detected. Only one probe out of 26 showed a substitutional element present (strontium at 2%).

Discussion and Conclusions

Consistent with the findings of previous researchers, the microstructure of metallographically-prepared sections of the iron wire used in the girder was not completely ferritic iron as expected, given the era in which it was manufactured.[30] The wire also contained a sizable amount of duplex material, which is concluded to be spheroidized cementite (Fe_3C) in a ferrite (α-Fe) matrix.

Vickers microindentation testing provided a hardness profile of the ferrite across the polished sections, allowing the mechanical properties of both types of iron materials in the girder wire to be probed. The higher hardness of the duplex structure is consistent with the presence of cementite (Fe_3C) particles. The hardness values were much less than those obtained for Wheeling Bridge samples of comparable diameter, indicating the girder wire was significantly less work hardened. Nonetheless, the hardness of the girder samples is high enough to reveal a sizable degree of work hardening and an absence of dynamic recovery that are consistent with the wire being drawn cold. The relative ordering of Vickers hardness for both girder and bridge samples is consistent with the Rockwell B measurements.

One possible explanation for the girder wire not having been as heavily drawn and work hardened as the bridge

Table 5. Summary of EDS X-ray Analysis Results by Region for Various Common Elements Found in Inclusions in a Longitudinal Section (Sample I-2a) of a Gries-Gendell (Severson) Girder Iron Wire

Region No./ Location	Inclusions Analyzed	Average, Wt % (Detected in Number of Inclusions)						
		Ca	K	Mn	Na	P	S	Si
Ferritic Iron and Some [Ferrite (α -Fe) + Fe_3C]:								
1/ ~10% in from top circumference: roughly symmetric with region 1	8	2 (8)	1 (8)	nd	tr (4)	nd	tr (1)	10 (8)
Ferritic Iron:								
2/ ~20% in from top circumference: roughly symmetric with region 2	2	tr (1)	nd	nd	1 (1)	nd	tr (4)	17 (2)
3/ ~33% in from top circumference: symmetric with region 3	4	1 (4)	1 (4)	nd	nd	1 (4)	1 (3)	7 (4)
Prominent Boundary Between Materials:								
4/ Near center	8	4 (8)	1 (8)	1 (1)	tr (4)	1 (4)	tr (4)	16 (8)
Ferrite (α -Fe) + Fe_3C:								
5/ ~67% in from top circumference	8	1 (8)	1 (8)	nd	tr (1)	nd	nd	6 (8)
6/ ~80% in from top circumference	8	5 (7)	2 (7)	1 (4)	1 (4)	nd	tr (1)	25 (8)
7/ ~90% in from top circumference	8	2 (7)	1 (7)	1 (1)	tr (1)	tr (1)	tr (1)	10 (8)

nd = not detected; tr = trace amount

wire is that material containing cementite (Fe_3C) would cause greater die wear and have less ductility. Hence, one would not want or be able to draw this material as much as the bridge wire, thus resulting in a lower Rockwell hardness.

The ferrite is very high purity with only one probe detecting anything other than small amounts of carbon. Although not specifically investigated, it appears that any diffusion of elements from the inclusions into the ferrite during processing could have occurred at most only over limited distances and in very small amounts.

An important confirmation regarding iron-ore processing was obtained from the EDS x-ray analyses of the inclusions. In general, substantial amounts of sulfur and the manganese routinely added to scavenge it were not present. On the other hand relatively large amounts of potassium were detected and attributed to potash that "comes from wood (charcoal) ash, which is to be expected from either a bloom iron or fining operation."[31] Taken together, these results provide strong evidence for the use of charcoal rather than coke as the fuel in smelting the iron.[32] Charcoal iron was the recommended material at the time for making iron wire.[33]

In examining Table 2, finding titanium in the girder samples is interesting because it is reported to be present in magnetic iron ore (magnetite) from Lake Champlain, New York; Wisconsin; and Missouri. According to Overman, smelting ores containing titanium was quite challenging at the time of the girder-wire manufacture.[34] Titanium does not combine easily with available elements and normally had to be removed with the cinder. To work around this undesirable approach, it was necessary to resort to different furnaces, often ones with no hearth or hearths of granite and gneiss rather than sandstone. Hence, it is probable that the iron for girder wire was smelted differently from the bridge wires.

Table 6. Chemical Composition - Size (δ) Dependence from EDS X-ray Analysis of Selected Elements Found in Eighty-Six Inclusions in a Gries-Gendell (Severson) Girder Iron Wire

Constituent (High Level)	Small (δ ≤ 5μm)	Medium (5 < δ ≤ 10μm)	Large (10 < δ ≤ 40μm)	Very Large (δ > 40μm)	Total	Frequency
≥95% Fe	10	0	0	0	10	(0.12)
≥5% Si	41	31	21	0	75	(0.87)
≥15% Al	0	1	0	0	1	(0.01)

Referring to Table 4 and Figure 8, showing the radial section of girder wire, it is evident that the iron differs in composition and appearance according to its location in the wire section. The large spatial variation in the amounts of various common elements in the inclusions of this wire (ferritic iron versus duplex [α-Fe + Fe_3C] material) provides quantitative indication that piling occurred. This was practiced to obtain a more homogeneous product with improved mechanical properties. It is unknown whether some type of scrap steel (e.g., α-Fe rich in Fe_3C) was used, thus contributing to (and explaining) the chemical inhomogeneity.[35] Given the comments that follow, it seems quite possible that such steel would have been foreign made.[36]

An alternative explanation to piling would be that the bar iron was quite unevenly decarburized. This possibility, however, seems unlikely because of the prominent inclusion boundary (EDS analysis results given in Table 5) that separates the ferritic iron from the duplex material with their different inclusion chemistries. This boundary is conjectured to have been an external (surface) layer at one time.

Significant differences were obtained in the inclusion chemistry for the girder wire when compared with an earlier study of three bridge wires, indicating that the ores for these two types of wires came from different sources and most likely were processed differently. The findings are consistent with the manufacture of the girder wire being subjected to better quality control, particularly regarding proper flux stoichiometry, since scale is virtually absent.

The origin of the duplex material in the girder wire is unknown but deserves consideration, albeit it is somewhat speculative.[37] At the outset, we acknowledge that nineteenth-century steel microstructures can vary widely because of significant quality-control issues that are associated with most, if not all, material processes under development in that era. The duplex material in the wire undoubtedly underwent some type of anneal prior to the final wire-drawing operation because cementite (Fe_3C) particles are often rounded. It is uncertain whether heat treatment occurred prior to wire making or at some intermediate drawing stage. However, the presence of a decarburized circumferential layer, reported by Sayenga and observed in the current work as well, strongly indicates at least one annealing operation occurred at some stage in the wire-drawing process.[38] As concluded earlier, the mildly elongated ferrite grains reveal there was no heat treatment subsequent to final drawing (Fig. 10).

Since the girders predate the Bessemer steelmaking process (1856), it would seem the steel-like material can only be either crucible or blister steel. If the duplex material has an American origin, then crucible steel appears to be the less likely candidate. Developed in England in the 1740s, crucible steel was made by melting blister steel in special ceramic crucibles to improve uniformity; principal uses included springs and tools.[39] English (Sheffield) crucible steel was renown for its high quality, but American steelmakers lagged significantly behind the Sheffield makers in the first half of the nineteenth century. Although cast steel was commercially available from the Adirondack Iron and Steel Company in Jersey City from 1848 to 1853, it had characteristically poor quality; another ten years would pass before this situation improved in America.[40] Pennsylvania was reported to have had the largest number of steelmaking concerns in 1850, with several in the Philadelphia area; the material was low quality cast (and blister) steel.[41]

Blister-steel technology was relatively well established in America by the mid-nineteenth century, although achieving material with reasonably uniform carbon concentration throughout the cross-section was highly problematic, and English steelmakers still provided a superior product.[42] The microstructure of the duplex material is consistent with the sometimes observed absence of non-metallic inclusions in blister steel, but the expected distinct pearlite (alternating, closely-spaced layers of α-Fe and Fe_3C) colonies were not observed.[43] Rather, the carbide appears spheroidized, indicating that the duplex material had undergone some type of heat treatment causing the Fe_3C plates to change morphology.[44] As a result, ductility, and hence drawability, would be greatly improved. Modern steel-making practice has spheroidizing anneals occurring just below the lower critical or eutectoid transformation (A_1) temperature (727° C) for steels having carbon concentrations ranging from 0.6 to 1.0 percent by weight.[45] However, a spheroidal transformation can also occur if the material is austenitized and subsequently slow cooled to slightly below the A_1 temperature.[46]

Severson's use of wire cables in the girder (with the necessary modification to the design of its casting) rather than the expected iron rods was clearly innovative.[47] Whether the duplex material with its different chemistry and properties was intentionally combined with the ferritic iron in an attempt to create an experimental material (i.e., a type of composite) in order to improve strength or for some other reason, such as to improve toughness or ease of wrapping, is unknown.[48] However, it is possible the wire makers were not entirely successful in achieving a desirable product. The Lehigh researchers report a relatively low ultimate tensile strength (average of three determinations 68 ksi [470 MPa]) for the girder wire compared to that of simply wrought-iron wire having nearly the same cross-sectional area that was used in the Wheeling Bridge (80+ ksi [550+ MPa]).[49] Taken together, these measurements are consistent with the girder wire having a relatively low Rockwell hardness along with a lower aspect ratio for grains composing the deformation texture. Thus, it appears that some increase in strength normally obtained from work hardening was forfeited so the wire could be drawn successfully.

WAYNE L. ELBAN has been a professor of engineering science at Loyola College in Maryland since 1985. His research interests include mechanical properties of materials and their microstructural characterization.

MARTHA GOODWAY has been the metallurgist at the Smithsonian Institution since 1970. She has been elected a Fellow of ASM International for her work in archaeometallurgy, including research on early wire and the Wright flyer.

Acknowledgements

The authors are grateful to Donald Sayenga, The Cardon Management Group, Tucson, Arizona, and historian/archivist for Wire Association International, Inc., for his generous donation of original wire from the Gries-Gendell (Severson) girder and his detailed review of this paper, which provided several enlightening comments; Robert B. Pond Jr., chair, Department of Engineering Science, Loyola College, also for detailed review of the paper and numerous helpful suggestions; Richard Siday, museum specialist, Smithsonian National Museum of American History, for arranging for us to inspect and photograph an intact girder; Roland H. Cunningham, Analytical Support Group, Smithsonian Center for Materials Research and Education (SCMRE), for performing SEM/EDS analyses; Harry Alden, microscopist, SCMRE, for help in obtaining the light microscopy images in Figs. 6-10; Mel J. Wachowiak, senior furniture conservator, SCMRE, for preparing final figures in digital format. Thanks also go to Holly McCluskey, director, and Mary Kay Cox, registrar, at the Museums of Oglebay Institute, Wheeling, West Virginia; Gil Taylor, branch librarian, Smithsonian Museum Support Center; and Peggy Feild, interlibrary loan assistant, Loyola College, for help in obtaining obscure references.

Notes

1. Post-tensioning refers to the process of applying compression to the bottom of a girder by external means prior to application of working loads. This was done in girders made of cast iron to overcome its inherent tensile weakness. Similarly, long-span wooden girders have been strengthened with iron or steel camber rods for many decades, and post-tensioned (pre-stressed) concrete using steel wires or rods is a modern adaptation of this design. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," *APT Bulletin* 25, no. 3/4 (1994): 26-31.

2. Wayne L. Elban and Martha Goodway, "Inclusions in 19th Century American Wrought Iron Structural Cable Wires," *Historical Metallurgy* 37 (2003): 106-120.

3. Henry J. Magaziner and Robert D. Golding, *The Golden Age of Ironwork* (Ocean Pines, Md.: Skipjack Press, 2000), 118.

4. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 26-31. Donald Sayenga, "The 1854(?) Gries-Gendell Cable," *Wire Rope News and Sling Technology* 13 (1991): 16-18.

5. A photograph showing a portion of the floor cut away with the girder in place, as well as measured drawings, are provided by Sayenga in Figs. 1 and 8 in "An Analysis of the Remarkable G-G-G Iron Wire Cables."

6. Sara E. Wermiel, "An Unusual Application of Wire Cables from the 1850s: Benjamin Severson's Wire-tied Iron Girders," *Construction History* 17 (2001): 43-54; also in *Rope Terminations and Fittings*, Organisation Internationale pour l'Étude de l'Endurance des Cables (OIPEEC) Conference Proceedings, ed. by I. M. L. Ridge (2001): 219-230.

7. Wermiel, 46-47.

8. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 26-31. Alan W. Pense, private communication to Donald Sayenga, 1993.

9. Charles P. B. Shelley, "On the Manufacture of Hemp and Wire Rope," *Proceedings of the Institution of Mechanical Engineers* (1862): Fig. 25 of Plate 57.

10. Charles P. B. Shelley, Fig. 24 of Plate 57.

11. Donald Sayenga, "The Birth and Evolution of the American Wire Rope Industry," *First Annual Wire Rope Symposium Proceedings* (Pullman: Engineering Extension Service at Washington State Univ., 1980): 295.

12. John A. Roebling, "Specification of a Wire Suspension Bridge over the Ohio at Wheeling by John A. Roebling," (circa 1847), 12-13. Box No. 1, Wheeling and Belmont Bridge Co. archives, Museums of Oglebay Institute, Burton Center, Olgebay Park, Wheeling, W.V.

13. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 30.

14. Prior to measuring the wire diameter and metallographically mounting sections, the original wire coating was gently removed using SiC paper. The diameter of the bare wire was measured in several locations, the average diameter (3.53 mm [0.139 in.]) being slightly larger than the bridge wires (3.37 mm [0.133 in.] and 3.48 mm [0.137 in.]) and its variation (1.1%) being somewhat larger (0.29 to 0.74%).

15. See previous note.

16. Wayne L. Elban, Mark A. Borst, Natalie M. Roubachewsky, Emory L. Kemp, and Patricia C. Tice, "Metallographic Examination and Vickers Hardness Testing of Historic Wrought Iron from the Wheeling Custom House," *Understanding Microstructure: Key to Advances in Materials, Microstructure Science* 24, ed. by M. G. Burke, E. A. Clark, and E. J. Palmiere (Materials Park, Ohio: ASM International, 1997): 177-183.

17. The operational test parameters (100-gram-force load and 25-second dwell time) were chosen to allow comparison with results from several other historic iron studies. An effort was made to avoid areas where inclusions or grain boundaries were present.

18. The SEM operated at 110,000X magnifications and 60-second counting times. The embedded samples were prepared by being surrounded (i.e., framed) with silver paint, so that no carbon need be deposited on the surface. Micrographs were taken of six or seven areas containing prominent inclusions across the section, and inclusions chosen for analysis were labeled so they could be identified for future reference or re-analysis as necessary. Up to eight inclusions each in a minimum of six representative regions across both radial and longitudinal sections were analyzed. Standardless analyses involve comparisons with internal theoretical elemental standards. In literature provided by ThermoNORAN, the minimum detection limit ranges between 0.1 to 1 percent by weight. However, a number of factors, such as background and number of counts, can significantly influence this assessment. While spectra peaks are identified automatically, careful manual inspection, as prescribed by the manufacturer, was performed to sort out ambiguities in overlapping peaks.

19. Obtaining high-quality metallographically prepared sections was a challenge because of the ease of scratch formation attributed to inclusion particles raking across the relatively soft ferrite matrix during the polishing steps. While this was encountered in earlier wrought-iron studies on the Wheeling Custom House and the Wheeling Suspension Bridge, the problem was particularly acute for the girder wire, possibly due to the lower hardness of the matrix and the presence of cementite (Fe_3C) particles.

20. Elban and Goodway, 106-120.

21. The girder wire consists of two types of iron-based materials both of which were wrought processed (drawn) together to make the wire. One material, which we have designated "ferritic iron," is the familiar wrought iron described in the opening paragraph of the introduction. Distinguished from this is what we have termed "duplex structure (or material)" that additionally contains cementite (Fe_3C) particles.

22. Martha Goodway and Jay S. Odell, *The Metallurgy of 17th- and 18th-Century Music Wire, The Historical Harpsichord*, 2nd ed. (Stuyvesant, N.Y.: Pendragon Press, 1987), 65.

23. Albert Sauveur, *The Metallurgy and Heat Treatment of Iron and Steel*, 3rd ed. (Cambridge, Mass.: The University Press, 1926), 41-46.

24. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 28-29.

25. Alan W. Pense, private communication to Donald Sayenga, 1993.

26. Wayne L. Elban and Martha Goodway, "Wrought Iron Wire from the Wheeling Suspension Bridge: A Metallurgical Assessment," in *Materials Issues in Art and Archaeology VI*, Materials Research Society Symposium Proceedings 712, ed. by P. B. Vandiver, M. Goodway, and J. L. Mass (Warrendale, Pa.: Materials Research Society, 2002), 511-523. Elban, Borst, Roubachewsky, Kemp, and Tice, "Metallographic Examination and Vickers Hardness Testing of Historic Wrought Iron from the Wheeling Custom House," 177-183. Cedric D. Beachem, Dale A. Meyn, and Robert A. Bayles, "Mechanical Properties of Wrought Iron from USS *Monitor*," NRL Memorandum Report 4123, November 20, 1979. Washington D.C.: Naval Research Laboratory.

27. William H. Burr, *The Elasticity and Resistance of the Materials of Engineering*, 7th ed. (New York: John Wiley and Sons, 1915), 295-303.

28. Robert B. Gordon, "English Iron for American Arms: Laboratory Evidence on the Iron Used at the Springfield Armoury in 1860," *Journal of the Historical Metallurgy Society* 17 (1983): 97.

29. No actual carbon concentration values were obtained because carbon contamination of samples placed in an SEM is expected.

30. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 26-31. Alan W. Pense, private communication to Donald Sayenga, 1993.

31. William Rostoker and James Dvorak, "Blister Steel = Clean Steel" *Archeomaterials* 2 (1988): 185.

32. Robert B. Gordon, *American Iron, 1607-1900* (Baltimore: The Johns Hopkins University Press, 1996): 135-36. Initially, pig iron made in charcoal-fired blast furnaces was used in American puddling operations; conversion to coal was well along in eastern Pennsylvania during the 1830s–1840s. However, there is virtual absence of FeS inclusions in the girder wire, whereas the prominence of FeS is characteristic of iron made in coal-fired puddling furnaces. The ratio of these inclusions to the total sulfur-containing inclusions is 0/9 and 2/14 in the radial and longitudinal sections, respectively.

33. Frederick Overman, *A Treatise on Metallurgy* (New York: D. Appleton and Co., 1852), 551.

34. Frederick Overman, *The Manufacture of Iron in All Its Various Branches* (Philadelphia: Henry C. Baird, 1850), 235-236.

35. Daniel Eylon and Hirowo G. Suzuki, "On the Use of Lamination in the Making of Iron and Steel Swords," *Proceedings of the 5th International Conference on the Beginnings of the Use of Metals and Alloys (BUMA-V)*, Korean Institute of Metals and Alloys (2002): 217-223.

36. Donald Sayenga, "Swedish Billet Marks," *Wire Journal International* 33 (2000): 108-115, provided a detailed study of the reliance on Scandinavian iron as the starting material for much of American wire making before circa 1850. Described is John Roebling's dissatisfaction with iron from domestic suppliers and search for an agent to supply Swedish and Norwegian billets in order to make high quality wire. Robert B. Gordon and David J. Killick "The Metallurgy of the American Bloomery Process," *Archeomaterials* 6 (1992): 146, 157, showed that Lake Champlain bloomery forges made wrought iron highly comparable to the highest quality Swedish steel by 1865. This conclusion is based on their determination of very similar mechanical properties (tensile strength, elongation, and Vickers hardness) and P contents (typically 0.04%) for materials from the two sources. They also reported that the P level in Adirondack iron averaged 0.025%, while the concentration in Swedish iron was somewhat lower (0.009-0.017%). The earlier date for the girder wire with its low overall P content (0.022% as reported by Alan W. Pense, private communication to Donald Sayenga, 1993) would seem to argue for a foreign steel source.

37. Although Severson provided considerable detail about his girders in his articles cited by Wermiel, "An Unusual Application of Wire Cables from the 1850s: Benjamin Severson's Wire-tied Iron Girders," he did not discuss the metallurgy of the iron in the cable wires.

38. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 30.

39. Jack Chard, *Making Iron and Steel: the Historic Processes 1700-1900*, 2nd ed. (Ringwood, N.J.: North Jersey Highlands Historical Society, 1995), 10. While initially unspecified, American crucible steel was eventually used for the main cable wires (c. 1876) in the Brooklyn Suspension Bridge and reported to have been specified earlier by John A. Roebling in steel ropes. David McCullough, *The Great Bridge: The Epic Story of the Building of the Brooklyn Bridge* (New York: Simon and Schuster, 2001): 359 and 368-369.

40. Gordon, *American Iron, 1607-1900*, 89 and 178.

41. James M. Swank, *Introduction to a History of Ironmaking and Coal Mining in Pennsylvania: Contributed to the Final Report of the Pennsylvania Board of Centennial Managers* (Philadelphia: James A. Swank, 1878), 80.

42. Chard, 10. Rostoker and Dvorak, 182-183. Gordon, *American Iron, 1607-1900*, 176.

43. Rostoker and Dvorak, 175-188.

44. Leonard E. Samuels, *Optical Microscopy of Carbon Steels* (Metals Park, Ohio: American Society for Metals, 1980), 225-246.

45. James A. Jacobs and Thomas F. Kilduff, *Engineering Materials Technology: Structures, Processing, Properties, and Selection*, 4th ed. (Upper Saddle River, N.J.: Prentice Hall, 2001), 234-235.

46. Samuels, 231.

47. Donald Sayenga, "An Analysis of the Remarkable G-G-G Iron Wire Cables," 27.

48. Eylon and Suzuki, "On the Use of Lamination in the Making of Iron and Steel Swords," 221.

49. Alan W. Pense, private communication to Donald Sayenga, 1993. Emory L. Kemp, private communication to Wayne L. Elban, 1996.

Virginia Capitol
Richmond, Virginia
Historic Restoration and Renovation
Construction Managers: The Christman Company
in Association with Gilbane Building Company
Architect: Hillier - Washington D.C.

The Christman Company
National Historic Preservation Services
Specialists in the Planning and Management of Complex Restoration Projects
- Cost Estimating
- Phasing/Scheduling
- Construction Management
- Program Management

CHRISTMAN
Historic Preservation Group
SINCE 1894

Corporate Office:
408 Kalamazoo Plaza
Lansing, MI 48933-1990
Phone 517-482-1488 Fax 517-482-3520

Mid-Atlantic Office:
901 N. Pitt Street, Suite 180
Alexandria, VA 22314-1594
Phone 703-836-2486 Fax 703-836-0746

E-mail ronald.staley@christmanco.com

Clem Labine's
TRADITIONAL BUILDING
The Professional's Resource for Public Architecture

THE WEBSITE
ONLINE DATA & LINKS FOR OVER 570 SUPPLIERS
OF PRODUCTS & SERVICES FOR RESTORATION & PRESERVATION
www.traditional-building.com

THE MAGAZINE
OVER 500 HARD-TO-FIND SOURCES IN EVERY ISSUE.
BY SUBSCRIPTION ONLY; $21.95/YEAR

69A SEVENTH AVENUE, BROOKLYN, NEW YORK 11217 FAX (718) 636-0750

This content downloaded from 160.111.254.17 on Wed, 19 Sep 2018 18:36:11 UTC
All use subject to https://about.jstor.org/terms