Evaluation of Iron & Steel in Historic Bridges

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ABSTRACT: This paper presents a nondestructive approach for the evaluation of wrought-iron and steel in nineteenth and early twentieth century bridges. Many historic bridges are non-redundant structures, and require complete evaluation of both structural capacity and the condition of the members for continued service. The conventional approach of material characterization in older structures has relied on tensile-testing of coupons removed from a structure to determine strength values. That approach has limitations due to large statistical corrections that are required when using only a few samples, and because the removal of coupons from critical members is rarely feasible, and also because each class of bridge member may have distinct mechanical properties. An approach to in-place materials characterization is presented that is based on screening for low-ductility by examining microstructure, chemistry, and hardness.

1 INTRODUCTION

There are tens of thousands of iron and steel bridges that are considered historically significant and which remain in service as part of our transportation systems. For bridges with structural redundancy that have been in continuous service with minor corrosion damage, a visual examination may be all that is required. But where redundancy is insufficient, significant distress or damage is present, or an increase in loading is required, a complete evaluation of the condition of the members as well as structural capacity may be required for continued service.

Because the geometry and sections of the main members are relatively simple to model, material characterization becomes a key issue in the structural analysis of historic bridges.

The determination of material strengths for historic iron and steel bridges remains problematic, particularly with the need to assure ductile behavior. For members and connections that are critical to the support of the structure, special methods may be needed to qualify their integrity.

A rigorous evaluation is necessary because the materials are of unknown quality, the critical fabrications were never qualified by modern standards, loads have increased, and the effects of decay and fatigue may have reduced the capacity. On the other hand, the importance of historic bridges as significant works of history requires that our evaluation methods be the least invasive.

This paper suggests a nondestructive protocol for the evaluation of nineteenth and early twentieth century bridges built of iron and steel. In addition to visual assessment and structural analysis, the suggested protocol relies primarily on a combination of materials characterization and nondestructive testing. The approach is based largely on available methods; it represents the author's search for a rational basis for evaluating complex structures in which the quality of the materials and their properties are unknown.

Figure 1. Upper chord pin-and-eyebar connection in an 1881 Whipple Phoenix Truss. The eyebars and compression sections are wrought iron, the joint blocks are gray cast iron, and the pins are wrought iron on the upper chord and steel on the lower chord.

It is the thesis of this paper that in the context of historical data and the observed condition of the bridge, microstructure, hardness and chemical analysis are sufficient to characterize the behavior of the material. The goal is to have an approach that in most cases eliminates the need for physical sampling and testing of bridge members, and where sampling is used it can help reduce the ambiguity.

2 DUCTILITY

2.1 *Importance of Ductility*

Modern engineers are accustomed to looking for high values of tensile strength as an indicator of a "good" material. Generally, a high-strength structural steel is viewed as necessarily superior to mild steel. This is because in our advanced system of specification and quality control, the reliability of the material is rarely an issue. Sufficient ductility is assured by the specification and is therefore not a variable to be considered in modern design. When encountering a historic structure, it is common to order tests aimed at finding out the strength, and not much attention is paid to the other properties of the material.

It is important to consider not only the strength of the material, but also the ductility. Ductility is essential in fracture toughness. It assures microscopic crack attenuation, allows the material to tolerate minor internal defects such as inclusions, and permits redistribution of stresses at extreme loads. This results in gradual, rather than catastrophic, failure. The resistance of good wrought iron to brittle fracture can be explained by the ability of the fibrous microstructure to attenuate crack growth by delamination and crack branching. But it is the ductility of the ferrite matrix that enables the fibrous character to be beneficial rather than detrimental (Schindler).

Early steels also exhibit a wide range of ductility. In bridges, a low-strength ductile material is preferred over a high-strength brittle material. In fact, for both wrought iron and early steels, high strength should not be considered an indication of high quality (Kirkaldy 1862). Moreover:

> "… the real strength of a material is less in its capacity to resist than in its ability to yield…The inelasticity of the material determines … its structural performance considerably more than the separation strength." (Freudenthal 1950)

Gordon (1988) showed that wrought iron (e.g. Holley's tests performed in 1877) possessed relatively consistent tensile strength values, while exhibiting a wide range of ductility, as measured by reduction of area (Figure 2). The reduction of area is a better indicator of ductility than elongation (Kirkaldy 1862, Freudenthal 1950). Similar data were found by Buonopane & Kelton (2007) in tests from recovered bridge iron.

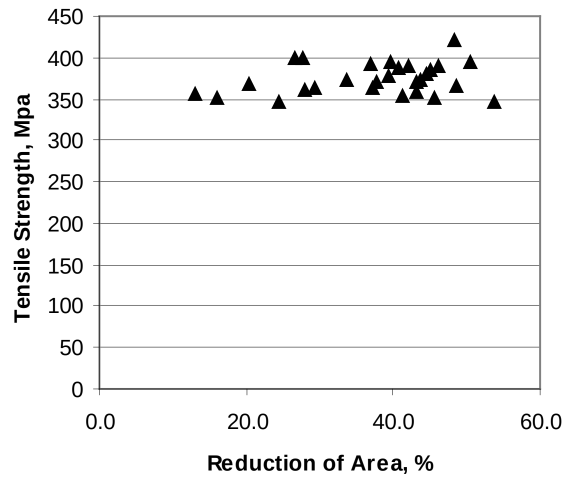

Figure 2. Tests of wrought iron (Holley 1877) based on Gordon 1988. While a lower bound for strength is easily determined, there is a widely scattered range of ductility as represented by reduction of area.

2.2 *The Problem with Coupon Testing*

The conventional approach for evaluating material properties in existing structures has relied on tensile-testing of coupons removed from the structure. In historic truss bridges, however, tests from coupon sampling are not likely to be indicative of the structure as a whole. There are several reasons for this:

1 Samples taken from non-critical members most likely will not be representative of the material in the critical members. A determination of physical properties must be made for each member class. In general, each truss member class (pin, eyebar, rolled section, plate, lacing, rivet) should be assumed to have different material properties. Even if all members are the same species, different grades are likely to have been used in the various members.
2 A small number of samples may not produce meaningful results because of the large statistical corrections that are required to address the uncertainty in the data (SCI 1997).
3 The removal of coupons from critical members like eyebars is usually not possible because of the risk of causing structural damage.
4 Bridges were often moved or rebuilt, resulting in the mixing of metals from different eras.
5 Materials used in past repairs will be of unknown type and quality and will differ from the original materials.

In addition, removal of historic fabric should be avoided. Damage to the original materials or character-defining features could diminish the integrity of the historic structure.

Conservative values for the strength of iron and steel can be found in *AASHTO Manual of Condition Evaluation* (AASHTO 1994) and other references, based on date of construction. These strength values are appropriate for use in preliminary analysis. They are necessarily conservative, and higher values may be justified where indicators of low-ductility are absent. Where low-ductility is suspected or where fatigue is a risk, lower values should be used.

3 HISTORICAL DATA

A wealth of mechanical and chemical data has been obtained over the past century and a half for cast iron, wrought iron, and steel. The work of Kirkaldy, Holley, and others stand out as milestones, and much additional work has been done since. A huge benefit to our understanding can be gained by mining the past data. Currently a survey of wrought iron test data, modern and historic, is being prepared at University of Manchester (O'Sullivan 2007).

4 MATERIALS CHARACTERIZATION

The materials characterization approach relies on microstructure, chemistry, and hardness as proxy data in lieu of tensile test data. No single proxy test is fully diagnostic, but neither is the tensile test for that matter. Given the immense amount of historical data obtained for iron and steel over the years, the proper role for proxy data is not necessarily the direct prediction of tensile strength, per se, but as a screen for bad behavior, i.e. low ductility, and to relate the specific bridge member to existing data for known materials.

This idea is not new. Researchers were attempting to relate chemical analysis and microstructure to material properties in the 19th century. What we need is a set of proxies for which many data can be obtained easily, rather than tensile tests, which are hard to obtain in statistically meaningful numbers.

Microstructure, chemistry, and hardness are all conventional tools for understanding metals, but they developed as laboratory methods for quality control, and their application to field evaluation has never been consistently applied to determining strength and ductility.

4.1 *Microstructure*

There are three species of ferrous metals that may be found in historic bridges--cast iron, wrought iron, and steel--and within each there are several varieties. The first thing is to determine the species and the variety of the metal. This can be done with no damage to the structure by the spark test (Tschorn 1963) to qualitatively distinguish carbon content. The spark test uses a high-speed grinder to produce a stream of sparks, which exhibits specific characteristics depending on chemical composition. For practical field use, it is best to have a set of samples with known material type and chemical analysis. Polishing a small area on each member of interest will reveal the presence or absence of slag.

Macro-etching is a method of preparing the surface for visual or low-magnification examination. It is appropriate for field identification of wrought iron and identification of gross characteristics and flaws, such as weld, cracks, etc. Micro-etching is the polishing of the metal with a very fine grit and etching for observation with a microscope. Etching is done with a suitable reagent, such as nital. Oberhoffer's reagent can be used to show phosphorus segregation (the copper in these reagents will deposit on the phosphorus-free areas first) (Gordon 2005).

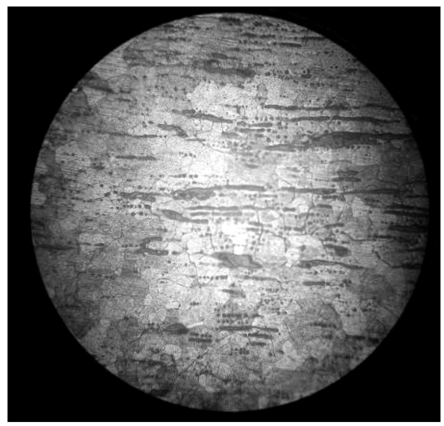

Figure 3. Field metallography (100x, nital etch) of 1881 wrought iron eyebar showing normal ferrite matrix and finely distributed slag.

Field examination of microstructure is an effective way of identifying metal types and screening metal for defects in chemistry or manufacture. It is used to reveal characteristics and flaws, grain size, and type. Wrought iron with satisfactory microstructure (finely distributed slag, fine equiaxed ferrite grains, and near absence of pearlite) and chemistry (limits on C, P, and S) will have adequate ductility to remain in service (Gordon 2005). Steel microstructure is well described in the ASM Handbook (ASM 2004) and cast iron guidance is available in Walton (1971).

4.2 *Chemical Analysis*

Chemical analysis can assist the identification of species and give an indication of quality and consistency in the structure. Chemical constituents strongly influence the strength, ductility, and weldability of metals. In structural steels, the main determinants are carbon (C), manganese (Mn), sulfur (S), and phosphorus (P). Sauveur (1912) correlated carbon content with strength and ductility (elongation) for hypo-eutectoid steels (below 0.84%C). In wrought iron, these same chemicals determine many of the characteristics, but the quantity and distribution of slag inclusions have an equally important role.

In-place chemical analysis is now possible with specialized optical emission spectroscopy instruments, commonly called PMI (Positive Material Identification). One such instrument is the Arc-Met 8000 by Metorex. This instrument is routinely used for accurate in-place analysis of steel and cast iron. Given proper access, it is possible to obtain dozens of field data of chemical analyses in a single day, providing an excellent statistical basis for judging the materials.

For wrought iron, however, the use of the PMI instrument is problematic because of the presence of slag, and the results may not be reliable. The operator must obtain multiple 'burns' at the same spot, which requires steady support for the operator and instrument. Preliminary field results have been obtained using reference samples of known chemical content for comparison. However, further evaluation of the process is required before the method can be considered useful for field analysis of wrought iron structures.

Laboratory chemical analysis can be done on very small samples, such as drilling swarf, but obtaining even a small sample from a critical element is risky. Use of a ball endmill bit will produce a smooth, concave depression, rather than a hole.

It is essential, whether in the field or in the lab, to use a type of instrument that can be calibrated to analyze the lighter elements, especially phosphorus and sulfur, which are the key determinants in screening for low-ductility. For steels, it is possible to make a conservative estimate of fracture toughness based on carbon content and comparison with chemically similar modern metals. As carbon content increases, the ductile-to-brittle transition becomes more dramatic, and occurs at higher temperatures.

One very important parameter for wrought iron is the percentage of phosphorus contained in solid solution. Phosphorus increases hardness, tensile strength, and brittleness at low temperatures. In wrought iron, phosphorus is partitioned between both the ferrite and the slag (Gordon 2005). Chemical tests usually report the total phosphorus in the sample and do not distinguish between the metal and the slag. Some historic tests of wrought iron show phosphorus content about equally distributed between the ferrite matrix and the slag (Higgins 1934), though Aston & Story (1936) give a representative distribution of 0.10% in ferrite vs. 0.02% in the slag. The effects of phosphorus and its real distribution is an area of valuable further research.

Table 1 suggests values for screening wrought iron and steel for ductility-reducing chemical concentrations. Chemical contents above the maximum values shown in the table are not in themselves cause for rejection, but rather indicate the need for further investigation, including metallography and hardness testing.

In steels, manganese should normally be at least six times the sulfur content. In wrought iron, the manganese content is usually less than 0.10% by weight, though it does not seem to have an adverse effect on ductility.

Table 1. Suggested screening values for chemical analysis of wrought iron and steel.

	C	P	S
Wrought Iron*	0.10	0.30	0.04
Steel			
Pins**	0.20	0.05	0.04
Eyebars***	0.30	0.08	0.05

* Aston and Story 1936; and Gordon 2004
** Campbell 1896
*** Gayler 1889; Oberg and Jones 1918.

Using these criteria, the author screened historical data from 37 laboratory tests of wrought iron for which chemical analysis and reduction of area were available (Holley 1877, Kaufman & Roberts 1990, Frank 1974, Sparks & Badoux 1998). Of the ten samples with reduction of area below 25% (low ductility), seven (70%) were caught by the screen. This was done on chemistry alone without the aid of microstructure or hardness data. Taking reported high levels of slag as a measure of poor microstructure, the screen would have rejected 90% of the low ductility samples. Of the remaining samples having sufficient ductility the screen only rejected about 10%

4.3 *Hardness*

The field hardness survey is an inexpensive, rapid test that serves several purposes in a structural evaluation:

- To screen for insufficient ductility
- To indicate the variability of the material within an individual member
- To correlate the properties of one class of members with another
- To estimate the tensile strength of the materials

Quoting Freudenthal (1950, p.539):

"The statistical information concerning the uniformity of the 'ultimate tensile strength' of the material obtainable from a large number of simple and rapidly performed hardness tests is usually more relevant…than the limited information supplied by a small number of tension tests."

Currently, several field hardness methods are available for field use on bridges including the Ultrasonic Contact Impedance (UCI) method, used in instruments such as the Krautkramer MIC10. Regardless of the instrument used, the results should be presented in Brinell Hardness Number (BHN), which is closely correlated with strength in carbon steels. As a rule, hardness values should be obtained at the same locations as the chemical testing and metallography.

The following table suggests guidance for evaluating hardness survey results, showing typical and maximum values for wrought iron and steel. Hardness numbers somewhat above the maximum values shown in the table are not in themselves cause for rejection, but rather indicate the need for further investigation, including chemical analysis and metallography. For example, higher values may indicate that alloy or high-strength steels may have been used, which could be verified by chemical analysis. It is important to repeat that in the case of historic metals, high strength is not necessarily an indicator of quality per se and is to be considered suspect.

Table 2. Suggested screening values of Brinell Hardness Number (BHN) for different materials.

	Typical Range	High Range
Wrought Iron	95-120	130*
Steel		
Pins	120-140	145
Eyebars	100-120	140

Average of three tests on an area of the same member.
*Local values in areas of phosphorus segregation may reach 160 BHN

5 FLAW DETECTION

5.1 *Critical flaw size*

Inspection and nondestructive flaw detection is necessary on critical bridge members for two reasons: the original materials were never tested to modern standards for flaws, and cracks (from corrosion, ductile failure, or fatigue) may have developed over time.

Knowledge of the critical flaw size (size of crack which will propagate without an increase in the applied stresses) is important when inspecting tensile-load carrying members. Critical flaw sizes can be derived for various defects, and this information can be used to set detection limits for inspection and to develop a fracture control plan. The available inspection methods must be capable of detecting the critical flaw size.

A simplified fracture mechanics analysis can be used to estimate the critical flaw size to establish detection limits for inspection. To estimate the fracture toughness, K_{Ic}, a correlation to relate CVN (Charpy V-notch impact toughness) to fracture toughness K_{Ic} (Rolfe and Barsom 1977, ASCE 1979, Norris 1981). In such an analysis, the stress intensity factor, K, due to an applied stress at a hypothetical crack is compared with the fracture toughness K_{Ic} of the material. This approach is accepted for evaluating the fracture toughness and critical flaw sizes in iron and steel truss bridges (ASCE 1979). Frank (1974) examined the fracture toughness of wrought iron as compared to selected steels to estimate the approximate scale of critical flaws and found that the critical flaw size for wrought iron is often larger than that of older structural steels. The same approach has been used for pins and eyebars using ultrasonic testing as the primary inspection technique. (Sparks & Badoux 1998) and for riveted connections (Keller 1995). Brühwiler (1990), Keller (1995), Grundy (2004), and Schindler (1995) examined fracture toughness and fatigue in riveted wrought iron construction

For both low-carbon steels and wrought iron with sufficient ductility, the critical flaw sizes in bridge members are usually large enough to permit visual inspection and detection with ultrasonic flaw-detection equipment (Sparks 1998 2004). Where a material does not pass the screening for low ductility, then the assumed critical flaw size must be adjusted downward.

5.2 *Visual inspection*

Visual inspection should be the primary method used to assess the overall integrity of the bridge and to identify loss of section, physical damage, and previous repairs. The visual inspection serves to integrate the findings of the detailed inspections and testing. All elements should be inspected visually. However, critical zones are often concealed due to the joint configuration and the presence of spacing collars, bearing plates, etc., making it necessary to use nondestructive test methods. Knowing the extent to which the critical zones will or will not be visible is essential to planning the assessment.

Depending on the type of bridge, the configuration of the connections, and the material characteristics, the following techniques may be appropriate.

5.3 *Ultrasonic Testing*

5.3.1 *Eyebars*

Because the faces of the eyebar ends are generally not accessible for visual inspection, it is necessary to use a technique for circumferential scanning of the eyebar head for cracks (Sparks & Badoux 1998). The neck area of eyebars is a potential zone of failure due to the possible presence of laps or welds, the stress concentration at the neck-to-bar transition, and strains imposed during manufacture.

An actual eyebar head of the same method of manufacture and material type is the best way to calibrate the testing technique. Known flaws (side-drilled holes and notches) can be introduced into these calibration pieces. In wrought iron, special techniques are required due to inclusions (Sparks & Badoux 1998). Steel can also contain laminations, inclusions, and coarse grain size that can disturb the ultrasonic signal. Prior knowledge of the microstructure is essential to obtaining good results. Field trials are necessary to determine the actual level of attenuation. The transducers should generally have 2.25 MHz or higher frequency to be able to resolve the necessary discontinuities.

Figure 3. Circumferential ultrasonic testing of critical eyebar on 1896 Steel Truss Bridge

5.3.2 *Pins*

Whether pins are critical and require ultrasonic testing should be determined by analysis. Nondestructive testing of pins is best accomplished using longitudinal wave ultrasonic transducers. In most steels and occasionally in wrought iron, valid results can be obtained by scanning from one end only. In wrought iron pins or those with shoulders or significant wear grooves, scanning may be necessary from both ends. Test several of the pins from both ends to determine whether valid results can be obtained from testing from one end only.

Calibration standards can ideally be made from actual salvaged bridge pins if available. This is particularly helpful for wrought iron, so that the attenuation properties can be included in the calibration. Also, a standard having actual wear grooves or loss of section can assist in distinguishing these characteristics from cracks. Alternatively, it is also sometimes possible to field calibrate for pin inspection by introducing a side drilled hole or notch in the non-stressed area beyond the nut.

5.4 *Dye Penetrant and Magnetic Particle testing*

Dye penetrant and Magnetic Particle testing are established test methods and are both well suited for revealing cracks in beam webs and flanges, around rivet holes, and for qualifying eyebars. It is advisable to examine at least one representative eyebar head by macro-etching, die penetrant, and by magnetic particle testing. This detailed examination will reveal signs of lap-weld or other anomaly in the eyebar.

6 EXAMPLE: 1896 STEEL TRUSS

Although it is 'conventional wisdom' that older materials were highly variable, more so than modern metals, the author has found very consistent data within member classes for bridges built in 1896, 1881, and 1887. Bridge builders were apparently selective in material choices, which were based on the function of the member in the bridge. The following discussion is for a twelve-panel Parker through-truss bridge spanning 71m (234ft), originally constructed in 1896.

The initial material identification was based on visual observations, a simple spark test, and limited field metallography. Using the spark test, the relative carbon content of the bridge elements were estimated in the following order, from lower to higher carbon content: eyebars, rolled sections, and pins. The spark patterns for the eyebars were similar to wrought iron or very low carbon steel (<0.08% C). The pins showed carbon indications similar to medium carbon steel.

The eyebars showed a visible weathering pattern on the top edges resembling longitudinal ridges, similar to what is often seen on wrought iron, where the ridges are a result of the presence of slag filaments. Under field metallographic examination, the eyebar metal consisted mostly of equiaxed grains. Almost no slag fibers were visible on the wide face, but very fine stringers could be seen on the edges of the eyebars where there appeared to be approximately twelve laminations. This laminated character is indicative of wrought iron; however, subsequent metallurgical testing, as described below, revealed that this was actually laminated steel.

Table 3 Steel properties in 1896 Parker Truss bridge.

Member	BHN	C %	Mn %	P %	S %
Rolled Sections					
Floor Beam	104	0.14	0.44	0.01	0.03
Chord Channel	105	0.15	0.48	0.01	0.04
Post Channel	94	0.12	0.44	0.01	0.03
Post Channel	100	0.14	0.47	0.02	0.02
Average	*101*	*0.14*	*0.46*	*0.01*	*0.03*
AISI 1012		.10-.15	.30-.60	0.04	0.05
Lower Chord Eyebars					
T10W	101	0.11	0.72	0.05	0.02
T4E	121	0.09	0.70	0.02	0.04
T5E	108	0.13	0.74	0.04	0.04
Average	*110*	*0.11*	*0.72*	*0.04*	*0.04*
AISI 1010		.08-.13	.30-.60	0.04	0.05
Pins					
L12W	146	0.19	0.50	0.02	0.03
L1E	143	0.15	0.46	0.02	0.04
L3E	140	0.18	0.45	0.03	0.04
L4E	135	0.18	0.48	0.03	0.04
Average	*141*	*0.18*	*0.47*	*0.02*	*0.04*
AISI 1020		.15-.20	.30-.60	0.04	0.05

Chemical analysis is from field metallurgy using an ArcMet 930. BHN is Brinnell Hardness Number. AISI numbered steel standards are shown for comparison.

Based on their carbon contents, the example materials should exhibit distinct ductile-to-brittle transition as a function of temperature. For the eyebars, which are the most critical elements, this transition temperature should be about –20-deg C (impact basis) (ASM 2004). The sulfur and phosphorus contents of all the steel elements were below the maximum values allowed for mild structural steels. As such, good ductility is expected with no significant reduction in upper-shelf fracture toughness. Furthermore, the Mn/S ratio is sufficient to fully convert the sulfur to manganese sulfide, a potential ductility reducer.

The pin material generally meets the specifications for pins proposed near the turn of the century by Cunningham (1896). These include limitations on sulfur and phosphorus and a tensile strength between 60-ksi and 70-ksi. The field hardness numbers indicate that the pins have a tensile strength of approximately 70-ksi. Furthermore, the pins showed a fine grain structure without gross segregation.

For structural analysis purposes, the following yield strengths were used (Table 4). By comparison, the prescribed AASHTO allowable for pre-1905 steel is 179 MPa (26-ksi).

Table 4. Estimated values for assessment: 1896 Steel Truss Bridge.

	Yield Stress MPa	(ksi)
Eyebars:	220	(32)
Loop Rods	207	(30)
Pins:	317	(46)
Rolled Sections	220	(32)

The eyebar, plate, and rolled sections are easily weldable due to the low carbon content and absence of contaminants.

7 CONCLUSIONS

There is a clear need for a nondestructive approach for historic iron and steel bridge evaluation. In most cases, it is not feasible or appropriate to remove sufficient material to rigorously quantify the yield stress, tensile strength, and ductility of the material. The aim of this paper has been to illustrate an approach that can be used to screen metals for low ductility based on the following key indicators: microstructure, chemical analysis, and hardness. New tools make obtaining this data much more efficient. When informed by historical test data and in combination with detailed analysis, this approach lends confidence to the evaluation. However, a good deal of work is needed to make such an approach widely useful. A number of further research goals are evident:

1 A program of trials to qualify the ductility screening method proposed here.
2 Improve portable metals identification equipment and calibration procedures to accurately obtain chemical analysis of wrought iron, in situ.
3 Develop an online catalogue of wrought iron, early steels, and cast iron micrographs with associated tensile, ductility (reduction of area), hardness, and chemistry
4 Expand the range of code-allowed notional strength values to include member classes (pins, eyebars, rivets).
5 Develop a nondestructive in-place ductility measurement
6 Research possible NDT methods for characterizing slag distribution quantitatively.
7 Establish a library of typical bridge details, along with proper methods of stress analysis, modes of failure, and guidance for determining stress concentration factors and critical flaw sizes.
8 Study the effect of phosphorus content in wrought iron and steel on ductility and fracture toughness at low temperatures.
9 Determine the typical range of phosphorus partitioning between ferrite and slag, and establish a means of determining this in the field.

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