Non-Destructive Evaluation of a Historic Wrought-Iron Truss Bridge in New Braunfels, Texas

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Ultrasonic testing methods and structural analysis ensured that the 1887 Faust Street Bridge could be rehabilitated for pedestrian use.

Introduction

The development of metal-truss bridges in the mid-nineteenth century was a significant technological advance that lengthened spans and lowered construction costs. In general these bridges served well, and many of them are still in use. A class of metal-truss bridge using pin-and-eyebar construction was the most common type until the early twentieth century. In these bridges eyebars were used for the main tension members, which were joined together by pins, much like a bicycle chain. The pins and eyebars form the primary structural system and are essential to the support of the bridge. Current federal bridge-inspection standards require a thorough evaluation of pin-and-eyebar truss bridges. The tension elements in truss bridges may be non-redundant, or fracture critical, because the failure of a single member can cause the collapse of an entire span. Furthermore, modern code provisions may impose higher load requirements than were used in the original bridge design. As a result, a complete evaluation of both structural capacity and the condition of critical members is required when returning historic truss bridges to service. Because thorough visual inspection of pin-and-eyebar connections is often difficult or impossible, non-destructive evaluation methods may be required. These methods, such as ultrasound, have become efficient and accurate for steel structures, but examination of wrought iron has met with little success. This paper discusses the application of modern structural analysis combined with state-of-the-art non-destructive test methods for the evaluation of a wrought-iron truss bridge.

Historical Background

The Faust Street Bridge (Figs. 1, 2) is located in the city of New Braunfels, Comal County, Texas. Built in 1887 by the King Iron Bridge and Manufacturing Company of Cleveland, Ohio, the bridge features four spans for a total length of 640 feet. The Faust Street Bridge spans the Guadalupe River, one of Texas’s main waterways, at the historic crossing of an east-west route that was variously known as the Austin-San Antonio Post Road, the Old San Antonio-Nacogdoches Road, and El Camino Real, dating from

Fig. 1. Main spans of the 1887 Faust Street Bridge across the Guadalupe River in New Braunfels, Texas. All illustrations by authors.
the time of Spanish colonialism. The bridge is one of fewer than twenty metal-truss bridges in the state constructed prior to 1890. It is the longest, most complex, and important of these examples and is eligible for listing on the National Register of Historic Places.

Unlike many historic bridges, it has undergone only minor changes; the only significant alteration occurred in 1947, when a pedestrian walkway was added and the timber deck was replaced.

The bridge consists of two 100-foot, Pratt truss approach spans and two double-intersection Pratt (Whipple) truss main spans of 220 feet. Tension members, such as the diagonals or hanger rods, consist of double eyebars with rectangular sections. The bottom chord consists of 20-foot-long eyebars, in sets of two or four. Built-up riveted sections are used for compression members, such as the top-chord and vertical-post members. The truss connections at the intersection of the eyebars and vertical posts are held together by cylindrical pins.

(Fig. 3). There are as many as 12 eyebars nested on a single pin.

Preliminary Investigation

The Faust Street Bridge was open to vehicular traffic until the 1980s. The County of Comal, the bridge's owner, is planning to rehabilitate it for pedestrian use. A detailed assessment of the bridge, starting with a thorough visual inspection, was conducted by Law Engineering and Environmental Services to determine the scope of needed repairs. Damage and deterioration were evaluated, with emphasis on reductions in cross-sectional areas of members due to corrosion. The bridge structure was found to be in remarkably good condition for its age. Heavy corrosion damage was limited to a few connections lacking proper water drainage and to the roller bearings on the central pier. A small fire, started by vandals, had caused limited damage to one of the spans where a pair of vertical hanger rods had broken as a result of overheating. Because the hangar-rod pair was non-critical, the result was only localized deflection of the bridge deck and bending of the bottom chord. The restoration plan for the bridge would include replacement of the roller bearings, repair of the fire-damaged area, and a new protective coating of the trusses.

Because of the age of the bridge, its fracture-critical structural type, and a mandatory design loading for pedestrian use, a thorough structural evaluation was required. This structural evaluation consisted of the following four phases:

- Material testing, to determine engineering properties for analysis
- Structural analysis, to establish bridge capacity and to identify fracture-critical members
- Fracture mechanics, to calculate critical flaw sizes for typical pins and eyebars
- Non-destructive testing, using ultrasound to evaluate fracture-critical pins and eyebars.

Material Testing

Because of the historic character of the bridge, it was desirable to limit the
amount of historic fabric that would be removed for material testing. The fire-damaged area provided an opportunity to remove samples from the broken hanger rod.

Chemical tests of samples showed that the material had a composition of nearly pure iron, without significant carbon or alloying metals. Metallographic characterization showed a grain structure, including laminations and silicon-slag inclusions, typical of wrought iron. Tensile tests gave a yield value of 47,000 psi, with 26% elongation, 41.8% reduction in area.

Fracture toughness of the material was estimated using the standard Charpy V-Notch test.\(^2\) Charpy V-Notch test values at room temperature ranged from 25 ft.-lb. to 105 ft.-lb., meeting the minimum fracture-toughness criterion for bridge steels for the local climate.\(^3\) Wrought iron is known to have low, and highly variable, toughness values compared to modern steels. This is balanced somewhat by wrought iron’s fibrous, “wood-like” character, which gives it a certain ability to arrest the development of perpendicular cracks.\(^4\) Overall, the tested material properties were generally consistent with data from modern and historical sources for wrought iron.\(^5,6,7,8\)

Only limited tests could be performed on material from the pins, because obtaining samples large enough for mechanical testing would have required the difficult, risky, and expensive removal of a pin. However, results of chemical analysis, hardness tests, and microscopic examinations showed that the pin material was also wrought iron with similar character to the sampled hangar-rod material. Due to the lack of extensive sampling of structural material, reduction factors were applied to the material properties in the structural and fracture-mechanics analyses to account for probable variations of material properties throughout the trusses.

Structural Analysis

The goal of the structural analysis was two-fold: first, to determine whether the bridge would have the capacity required by modern codes and second, to identify specifically which truss eyebars and pins were truly fracture-critical and would therefore require detailed field evaluation. A code-prescribed pedestrian bridge live load of 85 psf\(^9\) was used in the analysis. From limited information about the load history of the bridge, it was concluded that the pedestrian live load could represent a more severe loading condition than the truss structure had previously experienced.

The governing load case combined dead loads, live loads, and wind loads. Pedestrian live load was applied to a deck width of 16 feet, and the wind load was based on a 55-mph wind applied to the projected area of the structure. A finite-element computer model was developed using realistic material and cross-sectional member properties. The analysis showed that the bridge has the capacity for the proposed pedestrian use.

All pins of the top and bottom chords were considered fracture-critical. The eyebars forming the truss diagonals and bottom chords were also potential fracture-critical members.\(^10\) Structural calculations simulating failure scenarios were conducted to determine which eyebars were fracture-critical. The redundancy, and therefore the criticality, of the eyebars was assessed by simulating the loss of one eyebar from tension members composed of two or four eyebars. Based on this analysis, only some of the bottom-chord eyebars were found to be fracture-critical. All of the hanger rods and diagonal eyebars had sufficient redundancy under service loads. This significantly reduced the total number of connections that had to be examined.

Fracture-Mechanics Evaluation

The purpose of the fracture-mechanics analysis was to estimate the critical-flaw size for the fracture-critical eyebars and pins and thereby establish detection limits for the inspection. The critical-flaw size is that which will cause a crack to propagate under applied stresses. It is a function of material properties, state of stress, and geometry of the member. The source of such flaws could be fatigue, overloading, corrosion, or manufacturing defects. The critical-flaw size was calculated on the basis of the material tests and the computed stresses, using established fracture-mechanics models for hypothetical cracks.\(^11\) The stress-intensity factors were based largely on the stress-concentration effects in edge-notched beams and tension bars.\(^12\) Fracture toughness was derived from the measured Charpy V-notch values, using
an empirical correlation developed for older wrought-iron material.13

From these fracture-mechanics models and the conservative approximation for fracture toughness, a critical flaw size of about 0.5 inches for both the pins and the eyebars was calculated. Ultrasonic techniques can usually detect significantly smaller flaws, so these techniques were selected as the most suitable.

Non-Destructive Testing

The primary method of evaluating pin-and-eyebar bridges has generally been visual inspection.14 While non-destructive methods, such as ultrasound, have become well-developed for quality control of steel fabrications and have gained extensive application in monitoring the condition of industrial equipment, their application to field evaluation of metal-truss bridges has been limited.

Ultrasonic testing of wrought iron is complicated by the presence of laminations and slag inclusions inherent in the material. Application of ultrasonic testing to wrought iron is limited by the difficulty of sending and receiving a clear signal through this noisy material.15 Typical applications use low-frequency transducers, which are able to resolve only large defects.16 Such tests on wrought iron may be inconclusive because of the high noise-to-signal ratio.

Pilot study. To establish the ultrasonic-testing technique, a pilot study was performed prior to the actual testing program. The ultrasonic pulse-echo method was chosen as the most suitable technique for evaluating the pins and eyebars. In this method a transducer sends out an ultrasonic pulse, which is echoed back when it hits a flaw or the back wall of the object. The distance to the flaw is determined from the speed of sound in the material and the time to reflection. The reflected signal is processed, and the signal is displayed on an oscilloscope-type screen. Ultrasonic testing requires highly skilled technicians to calibrate the instruments, perform the tests, and interpret the results.

As expected, the ultrasonic signature in wrought iron was highly attenuated and noisy when using standard transducers. Back-wall signals could not be reliably obtained on the bridge pins using even low-frequency 1.0-MHz transducers. A new type of ultrasound transducer, called a composite transducer, is now being used in industrial applications when a high noise-to-signal response is anticipated, as in coarse-grained metals. Using a 2.25 MHz composite transducer allowed scanning of the full length of the wrought-iron pins with a strong back-wall signal. Based on the pilot study, it was determined that the most appropriate ultrasonic transducer for the pins would be a 2.25-MHz, longitudinal-wave, composite transducer.

Because the faces of the eyebar heads are generally not accessible for visual inspection, it was necessary to develop a technique for scanning the inner diameter of the eyebar head, where cracks or flaws would be most detrimental.17 In the case of the Faust Street Bridge, this was possible only by scanning around the curved outer edge of the eyebar head, with the ultrasound beam directed along the tangent to the inner diameter. A special transducer was manufactured for this project.18 The sole of the transducer was machined to a 5-inch radius to enhance coupling to the curved edge of the eyebar and constructed to transmit a longitudinal wave along a sound path oriented 20° to the radius of the eyebar head. Fig. 4 shows the application of this transducer. It was determined that this configuration would best suit the geometry of most of the eyebars. A small transducer was preferred to promote good coupling and to fit the typical 1.25-inch thickness of the eyebar. A transducer with a focused beam was chosen to enhance resolution in the area of greatest interest, the inner diameter of
the eyebar head. The final design was a dual-element 0.5-inch by 0.5-inch, longitudinal-wave composite transducer, with the sound beam focused at 3.5 inches.

Coupling the transducer to the material requires a reasonably smooth surface to allow transmission of the ultrasound waves without excessive interference. The pin ends and eyebar edges were found to be sufficiently smooth that satisfactory ultrasound transmission could be obtained using a gel-type couplant between the transducer and the wrought iron.

The pilot study showed the feasibility of using ultrasound on wrought-iron pins and eyebars, and a complete testing program was developed for the evaluation of all fracture-critical members.

**Calibration.** Because of the expense of removing a pin for laboratory calibration, an in-place calibration method was developed by saw-cutting a 3/16-inch-deep notch in the end portion of one of the bridge pins. The notch was placed in an unstressed area to avoid damaging the pin. Setting the ultrasound equipment to make this notch clearly identifiable provided a calibration for testing the other pins.

The calibration for the eyebar-testing procedure involved scanning the circumference of a 1-inch-thick steel annulus, having an 8-inch outside diameter and 3-inch inside diameter, designed to resemble an eyebar head. A 0.060-inch diameter side-drilled hole, located on the inner diameter of the annulus, provided a known flaw on which to calibrate the ultrasound equipment. The equipment was calibrated to clearly indicate the presence of this small side-drilled hole.

**Findings.** The testing program was conducted over a four-day period by a team of skilled ultrasound technicians. In all, 112 pins and both ends of 56 eyebars were tested.

The pins were tested from both ends because of near-field noise. This was not possible for the pins at the abutments, where only one end was accessible, and in a few of the upper chord pins, where the inboard ends were too corroded to permit coupling. Where scanning was done from one end only, the scanning level was reduced when examining the first 4 inches of the pin to avoid near-field interference. Fig. 3 shows an ultrasonic testing technician evaluating one of the top-chord bridge pins. No flaws of significant size were found in any of the pins.

Each of the fracture-critical eyebar heads was scanned using the procedure developed in the pilot study. No significant flaws were found in approximately 75% of the eyebars scanned. In the remaining 25%, a typical pattern of indications was found in the neck region of the eyebar along its longitudinal axis. Further examination of the neck area of an eyebar using a 45° shear-wave ultrasonic transducer showed the approximate location and extent of this indication. This examination showed an indication in a zone extending along the longitudinal axis of the bar from about 1 inch to 4 inches from the inner diameter of the eyebar (Fig. 6). No indication was found at the inner diameter. Scanning from both faces of the eyebar established that this indication was confined to a narrow zone along the centroid of the cross section. Examination of the eyebar neck using a liquid-dye-penetrant test method showed a uniformly shaped surface-lap condition with no indication of surface cracks. These indications are believed to have resulted from the manufacturing process. Because of their location and orientation parallel to the principal tensile stresses, the indications do not threaten the structural integrity of the eyebars.

**Conclusion**

The non-destructive evaluation of the historic Faust Street Bridge has demonstrated that ultrasonic testing can be used successfully in wrought-iron structures, given proper choice of transducers and adequate procedures. The methods applied in this project could be useful to the evaluation of other wrought-iron structures and artifacts.

Material properties for the evaluation were derived from limited tests to avoid removal of historic fabric. Correlations of hardness, grain structure, and chemical composition, as well as data from similar structures, were used to estimate engineering properties for elements not tested. The bridge was found to meet modern code requirements for a pedestrian bridge. Structural analysis was used to identify truly fracture-critical members of the bridge trusses, minimizing the testing effort. Fracture-mechanics analysis of the wrought-iron pins and eyebars provided an estimate of critical-flaw size and guided the development of
the non-destructive procedure. Consistent zones of inclusions, resulting from the wrought-iron manufacturing process, were found in the neck area of the eyebars. These defects were not found to be structurally significant.

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Notes


2. The Charpy impact test is a dynamic test in which a specimen with a machined notch is struck and broken in a special testing machine that measures the energy absorbed in breaking the specimen. ASTM A 370 Standard Methods and Definitions for Mechanical Testing of Steel Products gives the standard test procedure for Charpy impact testing.


8. Test data from the Second Street Bridge in Allegan, Michigan, was provided in a private communication from Gordon Jones, P.E., of Kalamazoo. This single-span, double-intersection bridge was also constructed by the King Iron Bridge and Manufacturing Co. just one year earlier than the Faust Street Bridge. The pins and eyebars of the Second Street Bridge were also found to be wrought iron. The Second Street Bridge was designated a National Historic Civil Engineering Landmark in 1982.


16. Lower-frequency waves travel farther, with less attenuation, than higher-frequency waves. Higher-frequency waves do not travel as far but pick up more detail.

17. Another area of concern is the neck region of eyebars. In some bridges the eyebar head is forged and then welded to a bar. This weld area can contain flaws or develop cracks. In the case of the Faust Street Bridge, the eyebar head was formed integrally with the bar.

18. The ultrasonic test equipment used in this project, including the specialized transducers, was manufactured by Krautkramer-Branson of Lewistown, Pa.