Coating Preparations Reduce the Strength of Bridges

By Robert A. Leishear, Ph.D., P.E., PMP

What we had here was a failure to communicate – corrosion engineers found an excellent method to make high-performance coatings stick to steel much better than previous methods. However, nobody talked to the structural engineers to notice that bridge safety was reduced.

Overlooked as a design problem for decades, grit blasting is the standard process to improve coating adherence to steel surfaces. This process significantly degrades the strength of steel bridges, endangering safe design. In particular, engineers design a bridge, construction and welding are performed, and then construction is inspected and accepted. After acceptance of structural construction, painting staff grit blast steel surfaces and the fatigue limits from cyclic loading that were used in the design are inadvertently altered.

These new fatigue limits provide a lower estimate of the minimum failure stresses required to cause cracks experienced by a bridge due to repeated traffic loads from passing trucks. That is, grit blasting impacts high-speed shards of grit into steel to create a jagged steel surface that significantly reduces the fatigue failure limit (*Figure 1*) and consequently endangers previous and future designs.

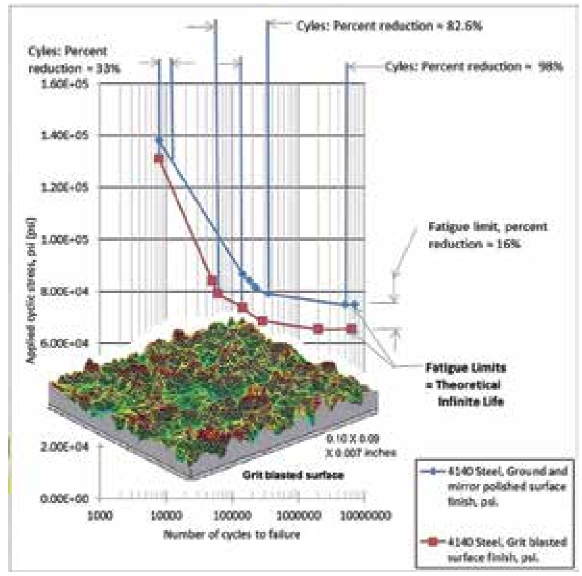


Figure 1. Grit blasting effects on 4140 steel before thermal sprays (Adapted from K. Padilla, et al.).

In fact, significant industry improvements since the 1960s reduced the number of failures, where biennial inspections and improved inspector training find many cracks in time to make repairs before significant bridge damages occur. Even so, cracks still occur that potentially endanger bridge safety. The goal of this article is to enlighten a recently discovered cause of cracks, i.e., grit blasting fatigue.

Fatigue Failures of Bridges

Consider fatigue failures of steel bridges, where fatigue cracking has long been known as a failure problem for bridges. Although corrosion is a contributor to some bridge failures, fatigue is the primary cause. Fatigue cracks occur when a structure is subjected to repeating loads that flex, or stretch, the structure (*Figures 2* and *3*). Undetected cracks have resulted in the collapse of bridges, and numerous other cracks have been identified and repaired before major bridge damage occurs.

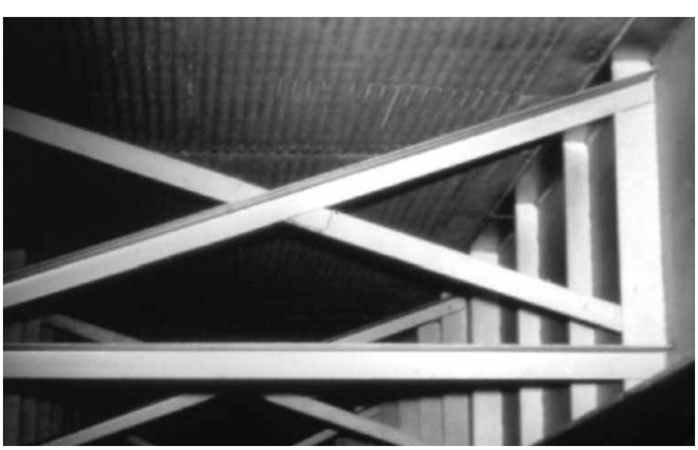


Figure 2. A fatigue crack is shown on an X-braced bridge, but nearly all cracks start at weld toes (U.S. DOT, Bridge Design Handbook, Design for Fatigue).

Testing

Fatigue curves are necessary to gain a basic understanding of fatigue failures. Extensive research and numerous fatigue tests were performed (J. W. Fisher, et al.) and were published in 1974. Their research – extended by research from others through 1986 – is the basis for the fatigue curves in use today.

Various design details were tested that are used in bridge design to explain fatigue failures. There are eight design categories, or design details, that include butt welds, stiffener attachments, plate girders, and cover plates (*Figure 4*).

Design Rules

There were numerous important findings during bridge fatigue failure research.

- All fatigue cracks are initiated at defects or flaws in the steel.
- The size of the defect does not affect whether or not a crack will occur. Only the presence of a flaw is essential to crack formation.
- The amplitude, or magnitude, of the changing stress dictates whether a crack occurs or not. The dead load, or constant load due to the weight of the bridge, is not critical to fatigue failures.
- Nearly all fatigue failures occur at the toes of butt welds and fillet welds, where the sudden change in geometry induces high stresses and occasional microscopic, sharp-pointed valleys

caused by welding serve as defects to initiate cracks. This observation is valid for in-service cracks on bridges as well as cracks during fatigue testing.
- Residual stresses due to heat contractions following welding initiate fatigue cracks.
- Grinding butt welds to a flat surface profile on steel plates increases the fatigue limit of those welds since the weld toe is eliminated.
- Slag inclusions or porosity in welds also cause cracking.
- The slopes for all fatigue curves shown in *Figure 4* are the same for any design detail, but the type of design detail dictates the stresses needed to induce cracks.
- The fatigue limit, or lower limit to failure, is dependent only on the type of design detail.
- Each curve is parallel for different types of steel, and only the design detail dictates the curve to be used in the design.
- The fatigue limit is also referred to as the constant amplitude fatigue threshold (CAFT). In theory, fatigue failure cannot occur if stresses in bridge structures are below the fatigue limit.
- Although outside the scope of this article, ASME experimental tests of welded piping indicate that fatigue limits do not exist for welded structures. That is, fatigue limits due to applied loads continue to decrease over time, rather than remain constant, as shown in *Figure 4*.
- Codes for bridge materials ensure that fracture toughness is adequate to prevent brittle fractures during cold weather.
- Codes for bridge materials also ensure that surface finishes are controlled at the time of purchase to inhibit fatigue cracks after installation, but grit blasting changes those surfaces after installation.

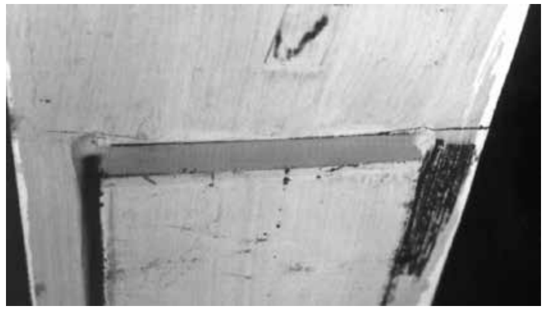


Figure 3. Fatigue crack at the end of a cover plate fillet weld toe (U.S. DOT, Bridge Design Handbook, Design for Fatigue).

Coatings and Grit Blasting

Consider the processes for high-performance coatings. Many decades ago, paint was commonly used for coatings, but coatings have been remarkably improved in their performance with a wide selection of different coatings. The National Association of Corrosion Engineers and the Society for Protective Coatings (NACE/SSPC) issue several specifications for surface preparations, which include solvent cleaning, hand tool cleaning, water jetting, power tool cleaning, and several grades of sandblasting (*Figure 5*).

When high-performance coatings were first used, shot blasting with rounded particles was a common form of sandblasting. However, shot blasting forms rounded surfaces, which provide poor adherence for coatings. Consequently, grit blasting with jagged particles is commonly used to prepare surfaces to a commercial finish before coating to ensure excellent coating adherence. A near white metal finish is used in saltwater environments. The finished, grit-blasted surface consists of microscopic, sharp-pointed peaks, and depressions. These sharp depressions or valleys act as stress raisers where cracks can initiate.

Grit Blasting Fatigue Tests

Test results for 4140 steel are conclusive, and fatigue limits and cycles to failure are significantly reduced by grit blasting steel. In *Figure 1*, the number of cycles to failure is reduced by an order of magnitude, and the fatigue limit is reduced by 16%. The AASHTO fatigue curves shown in *Figure 4* could change significantly if grit blasting was considered. Consequently, predicted fatigue failure stress calculations for repetitive truck loads on bridges could be in error, and bridge safety that is determined during design is affected. That is, bridges are not as safe as intended.

Even so, few tests have been performed to understand how fatigue properties are affected by grit blasting. There are a few studies on titanium dental implants and a single study on 4140 steel; these tests are all that have been performed.

Grit Blasting Effects

Are these 4140 steel test results applicable to bridge design? For the few failures that occur in locations away from welded toes, the answer to this question is simply yes. But the fatigue effects on bridge steels will be more pronounced since bridge steels are softer than 4140 steel.

For fatigue cracks at weld toes, the answer to this question requires more discussion.

- As noted, the size of the flaw has a negligible effect on the initiation of fatigue cracks.
- Microscopic defects at weld toes are typical weld defects that cause cracks.
- Historically, differences in surface finish reduce fatigue properties, e.g., polished bars are more resistant to fatigue than as milled bars of steel.
- Accordingly, the number of defects on surfaces is the primary contributor to fatigue cracking.
- Grit blasting creates many more stress impacts at weld toes to reduce fatigue limits and reduce the cycles to failure. That is, more microscopic, sharp-pointed valleys that are created at weld toes increase the probability of cracks.
- Embedded grit particles in the valleys were observed to be the crack initiation sites during 4140 steel fatigue tests. These particles compounded

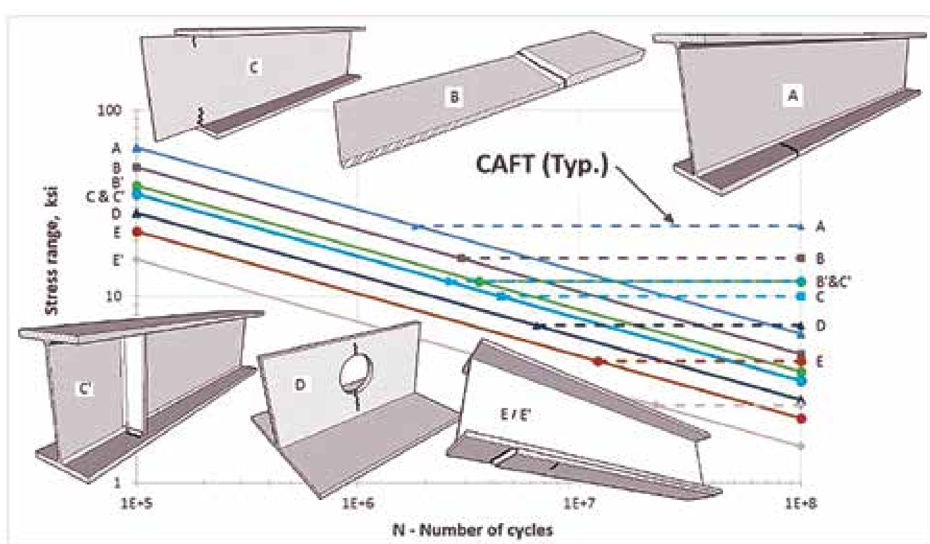
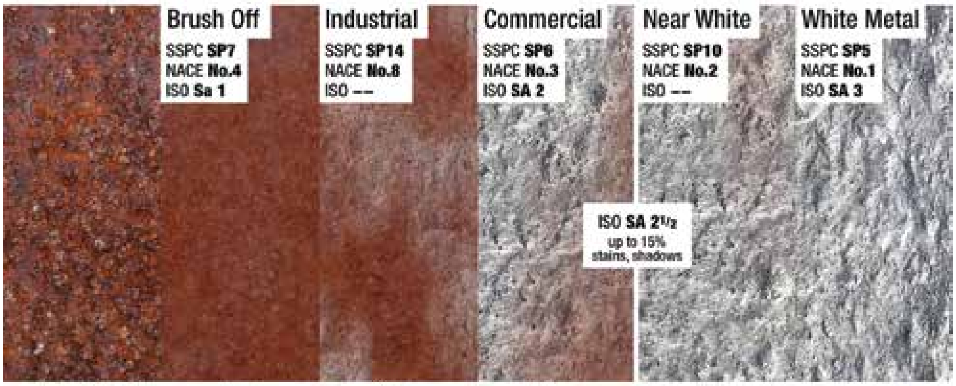


Figure 4. AASHTO Fatigue Curves (U.S. DOT, Design and Evaluation of Steel Bridges for Fatigue and Fracture).



Loose Material	None	None	None	None	None
Tight Material	100%	up to 10%	None	None	None
Stains, Shadows	100%	100%	up to 33%	up to 5%	None

Figure 5. NACE/SSPC surface finishes, grades of blast cleaning (Adapted from ISO 850-1).

the stresses at the sharp points of the valleys, and additional embedded particles are expected during the blasting of softer bridge steels.

In short, grit blasting fatigue reduces the stresses needed to form fatigue cracks, whether on a flange or at a weld. In *Figure 4*, all of the sloped lines will move downward, and all of the fatigue limits, or CAFTs, will move downward as well. The extent to which these fatigue curves are revised requires further experimental fatigue testing.

Solutions

Bridge designs – past, present, and future – are in jeopardy unless fatigue strength reductions due to grit blasting are evaluated for bridge safety. Yes, more research is needed and recommended, but the verdict is evident. Grit blasting reduces fatigue strengths of bridges, and this problem must be addressed to ensure bridge safety. The full effects on bridge safety are not yet known, and earlier accident investigations are also called into question since blasted surface finishes were not evaluated during previous investigations. Grit blasting fatigue (The Leishear Fatigue Stress Theory) is a new tool to troubleshoot bridge failures.

The problem of grit blasting and fatigue affects multiple industries. The fatigue designs of grit-blasted structures are potentially unsafe for pressure vessels, industrial and municipal piping, cross country oil and gas pipelines, and nuclear power plant piping systems, and any other structure or equipment that is designed for fatigue and grit blasted for coating adherence. Much work remains to be done.▪

The online version of this article contains references. Please visit **www.STRUCTUREmag.org**.

Robert A. Leishear, a Consulting Engineer for Leishear Engineering, LLC, is an ASME Fellow, a NACE Senior Internal Corrosion Technologist, and a Journeyman Sheet Metal Mechanic. Dr. Leishear has written many peer-reviewed publications, including the topics of fatigue failures and failure analysis. (leishear@aol.com)

References – online only

ASME B31.3-2018, *Process Piping, Appendix W, High-Cycle Fatigue Assessment of Piping Systems, ASME Code for Pressure Piping*, B31, 2018, American Society of Mechanical Engineers, New York, New York.

J. Collins, "*Failure of Materials in Mechanical Design*," 1993, John Wiley and Sons, New York, New York.

C. Hinnant, T. Paulin, *Experimental Evaluation of the Markl Fatigue Methods and ASME Piping Stress Intensification Factors*, 2008, PVP2008-61871, American Society of Mechanical Engineers, New York, New York.

R. Leishear, *Water Hammer and Fatigue Strength Reduction from Grit Blasting for Coatings*, 2020, National Association of Corrosion Engineers, Houston, Texas.

R. Leishear, "Grit Blasting for Coatings Accelerates Piping and Structural Failure," 2019, *Empowering Pumps and Equipment eMagazine,* Tuscaloosa, Alabama.

Load and Resistance Factor Design (LRFD) for Highway Bridge Superstructures, Publication No. FHWA-NHI-15-047, 2007, Revised 2015, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Steel Bridge Design Handbook, Design for Fatigue, Publication No. FHWA-HIF-16-002–Vol. 12, 2015, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Design and Evaluation of Steel Bridges for Fatigue and Fracture, Publication No. FHWA-NHI-16-016, 2016, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Fatigue Strength of Steel Beams With Welded Stiffeners and Attachments, National Cooperative Highway Research Program Report, 147, 1974, National Cooperative Highway Research Program in association with the U.S. Department of Transportation, Federal Highway Administration, Washington, D.C.

Bridge Fatigue Guide, Design and Details, 1977, American Institute of Steel Construction, Chicago, Illinois.

K. Padilla, A. Velásquez, J.A. Berríos, E.S. Puchi Cabrera, *Fatigue Behavior of a 4140 Steel Coated with a NiMoAl Deposit Applied by HVOF Thermal Spray*, Vol. 150, 2002, Elsevier Press, Amsterdam, Netherlands.