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# Bridge Safety Dangers-Fatigue Cracks, Brittle Failures and Grit Blasting

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**Abstract:** Fatigue failures in bridges have been extensively studied for decades, and experimental data was applied to create fatigue curves to be used for bridge designs, however, new research questions the validity of these curves with respect to safe bridge design. Specifically, grit blasting for coating adherence creates surface damage in the form of sharp indentations and peaks over entire steel surfaces. These imperfections act as stress raisers that accelerate bridge failures by reducing the number of cycles to failure and the stresses required to cause failure. Strong differences of opinion exist with respect to this complex issue. This author believes that there is a significant threat to bridge safety, while other authors believe that there is no safety threat at all. The goal of this article is to effectively refute opinions which claim that bridge safety is adequate. To do so, a thorough review of earlier publications is combined with new developments on grit blasting fatigue. Bridge safety is questionable since bridge design requirements in the form of fatigue curves are questionable. There is limited information, one way or the other, to prove the full extent of grit blasting effects on steel bridge fatigue failures, and this paper fosters an understanding of this dangerous threat. Available results clearly prove that bridge fatigue properties are reduced by grit blasting, which in turn reduces the safety of design practices for bridges. An open and unknown question exists, what is the complete extent of grit blasting effects on large structures? That is, bridge failure mechanisms are not fully understood, there are uncertain risks with respect to bridge fatigue damages, and a paramount risk concerns grit blasting. Grit blasting safety effects cannot be dismissed. Moreover, evolving facts prove that the inherent dangers in bridge design practices must be addressed and resolved. Specifically, bridge design curves account for repeated loads on bridges caused by traffic, and further research is mandatory to determine the safety errors inherent in these curves, which are shown to be inadequate by this innovative research. A resistance to new ideas serves as an unacceptable reason to curtail technology that will improve bridge safety.

**Keywords:** Fatigue Failures of Bridges, Bolted Joint Failures for Bridges, Steel Bridge Safety, Grit Blasting of Bridges, I-40 Bridge Crack, Hoan Bridge Crack, Diefenbaker Bridge Crack, Mianus River Bridge Collapse

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## 1. Introduction

Steel bridges are in service that have welded construction or bolted joint constructions, where the predominant number of fatigue cracks occur at either holes or welds, but some cracks occur on the surfaces of components due to the random nature of fatigue crack initiation at defects. Following the advent of welded bridge construction since the 1970s, the number of fatigue cracks in bridges markedly increased. An industry response improved bridge designs to reduce the number of cracks in bridges, but cracks continued to occur [1, 2-4]. Another industry response increased bridge inspections, which has prevented major bridge collapses for decades, but

major damages continue to occur. The risk that one of these cracks may cause a future bridge collapse is unknown. A recent I-40 bridge crack sheared a primary support beam to endanger lives and a discussed is added in an Addendum.

Recent research has shown that grit blasting significantly affects fatigue properties of metals. When metals are blasted, the number of cycles to failure, the fatigue stresses to cause those failures, and the fatigue limits, or constant amplitude fatigue thresholds (CAFT) are reduced.

Part of the literature review for this evolving research concerns a fundamental disagreement between this author and J. Lloyd, R. Connor, and K. Frank. They contend that grit blasting tests for 5 to 7 inch wide bolted plate test specimens

prove that grit blasting does not affect fatigue performance for any bridge components, and this author disagrees. Specifically, fatigue stresses in bolted joints are significantly affected by stress redistributions and a reduction in stresses in the joints, where compression stresses due to bolt tightening reduce the surface fatigue stresses on the bolted plates. These important compression effects do not influence the stresses on welds, which occur on free surfaces of welds that are subject to bending stresses rather than the axial stresses evaluated in bolted joint tests. These two types of tests are completely different, and the compressive versus tension stresses that occur for these two different types of tests are fundamentally different during steel bridge component failures.

Accordingly, the effects of grit blasting on weld fatigue failures are unknown. To date, the only fatigue test data available to evaluate grit blasting effects comes from Padilla, et al. [5], and their data conclusively proves that fatigue properties are affected by grit blasting. The implied question is how much bridge steels are affected by grit blasting, where bridge steels are softer than the 4140 steels tested by Padilla, and this softness further implies that bridge steels will be affected more than 4140 steels, since softer materials can be more easily deformed to create sharper stress raisers on steel surfaces. V-notched and scratched specimen fatigue testing also further the theory presented here. The goal of this work is to encourage others to consider this potential safety problem for bridge design, and perform appropriate research to better understand safety implications that can affect public safety.

The following discussion starts with a summary of an article written by this author and an article written by Lloyd, et al. The discussion then turns to refute their objections and provide technical discussions to support that repudiation. In other words, the goal of this paper is to advance technology by comparing different theoretical opinions and resolve those differences through a discourse of new ideas.

## 2. Literature Review

The literature review for this work primarily consists of two papers and their associated references [6, 7]. There is a significant disparity of opinion between these two papers, and this paper works to close that gap of understanding. Basically, a difference of opinion serves to advance an understanding of technology with respect to bridge failures.

### 2.1. Summary of an October 2020 Structure Magazine Article

The following quotes and Figure 1 [8, 9] paraphrase Leishear's Structure Magazine article [6]. "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<sup>1</sup>. 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, and 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 (Figure 1), and the fatigue limits from cyclic loading that were used in the design are inadvertently altered.

[Consideration of] fatigue curves is necessary to gain a basic understanding of fatigue failures.... 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. ... The slopes for all fatigue curves shown in Figure 1 are the same for any design detail, but the type of design detail dictates the stresses needed to induce cracks. ... 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 important 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....

[Additionally], 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. ... 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.... [And], 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....

Test results for 4140 steel are conclusive, and fatigue limits and cycles to failure are significantly reduced by grit blasting steel.... Are these 4140 steel test results applicable to bridge design? For the few failures that occur in locations away from welds the answer to this question is simply yes. But the fatigue effects will be more significant for bridge steels that are softer than 4140 steel....

[With respect to 4140 fatigue test results shown in Figure 2]: 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

<sup>1</sup> As a matter of fact, this author failed to recognize this problem for many years while working in the piping and rotating machinery industries. This discovery dawned while attending corrosion courses to augment decades of material failure research. That is, new technology was born to relate grit blasting and fatigue

failures in multiple industries, including bridge design.

cracking. Grit blasting creates many more stress raisers at weld toes to reduce fatigue limits and cycles to failure. That is, more microscopic, sharp pointed valleys that are caused at weld toes increase the probability of cracks. Imbedded grit particles in blasted valleys were observed to be crack initiation sites during 4140 steel fatigue tests. These particles compounded the stresses at the sharp points of the valleys, and additional imbedded particles are expected during blasting of softer bridge steels...

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 were also called into question since blasted surface finishes were not evaluated during previous investigations. Grit blasting fatigue (The Leishear Fatigue Stress Theory [6, 10, 11]) 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, 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.”

**2.2. Summary of the Response to an October 2020 Structure Magazine Article**

The following quotes paraphrase pertinent comments from Lloyd, et al.’s Structure Magazine article [7]. “Blast cleaning has been used in the coating process of steel bridges for

decades. Shot and grit blasting techniques are approved cleaning methods used in fabrication shops, as well as field painting for new and existing bridges. The most common media is a shot/grit mixture. The grit blasting processes are regulated for bridge design or rehabilitation projects....

The opinions in the October 2020 article are based on the misapplication of the work by Padilla, Berrios, and Puchi Cabrera,... [and] we fully disagree with applying those results to steel bridge fatigue life design and safety. [That research] included ... mechanically polished described as “mirror-like”) [and] grit blasted [surfaces] ...made from 4140 steel (which is not a structural steel used in bridges), [and] were... sensitive to surface condition effects.... The mirror-like surface commonly used in rotating beam tests is vastly different than the as-fabricated and as-rolled surface conditions of steel used in highway and railway bridges. The fatigue design requirements in the AASHTO specifications are based upon full-scale girder tests with as-received mill scale surfaces,... as well as bolted connection tests with blasted and blasted-then-coated surfaces [12-14]. The research is conclusive; fatigue resistance is governed by welded or bolted connection details, not by minor surface conditions. This is particularly true at the low effective stress ranges experienced by in-service bridges, which, based on extensive field testing of the authors, is typically only about 4 to 8% of the yield strength. [Also] extensive fatigue studies of bolted connections with blasted and blasted-then-painted surfaces have been performed [13, 14]. These studies showed that the coated specimens had a slightly higher resistance due to the reduction in fretting caused by slippage of the connection. These large-sized bolted connections... confirmed the adequacy of the AASHTO specifications.

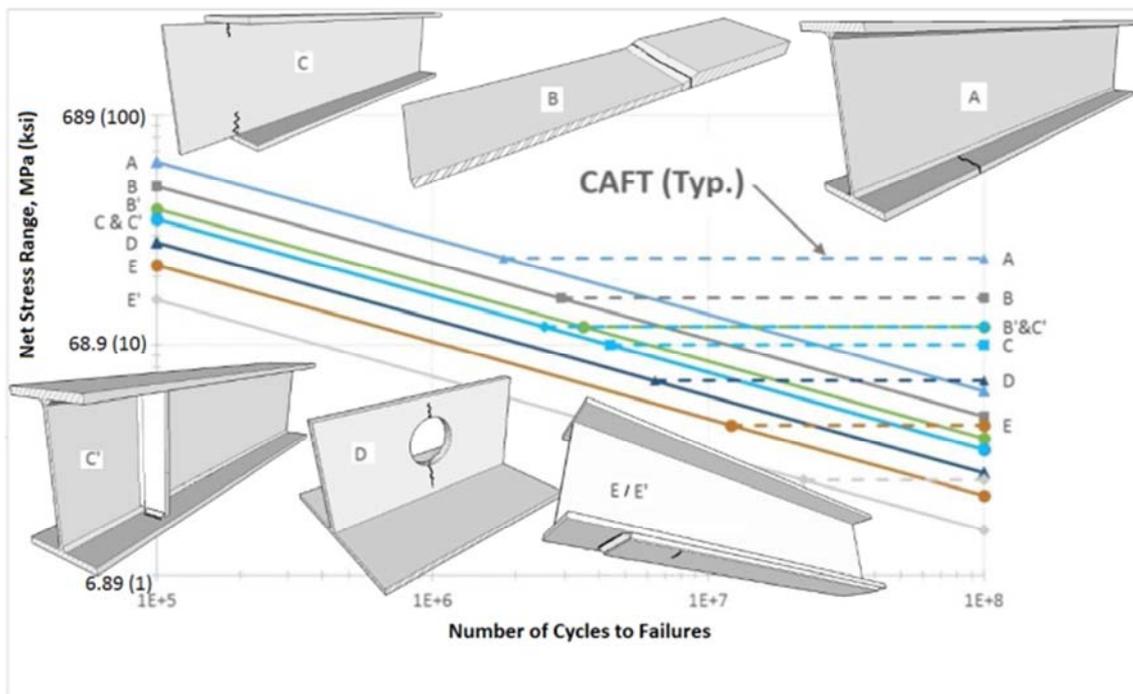


Figure 1. AASHTO Fatigue Curves [8].

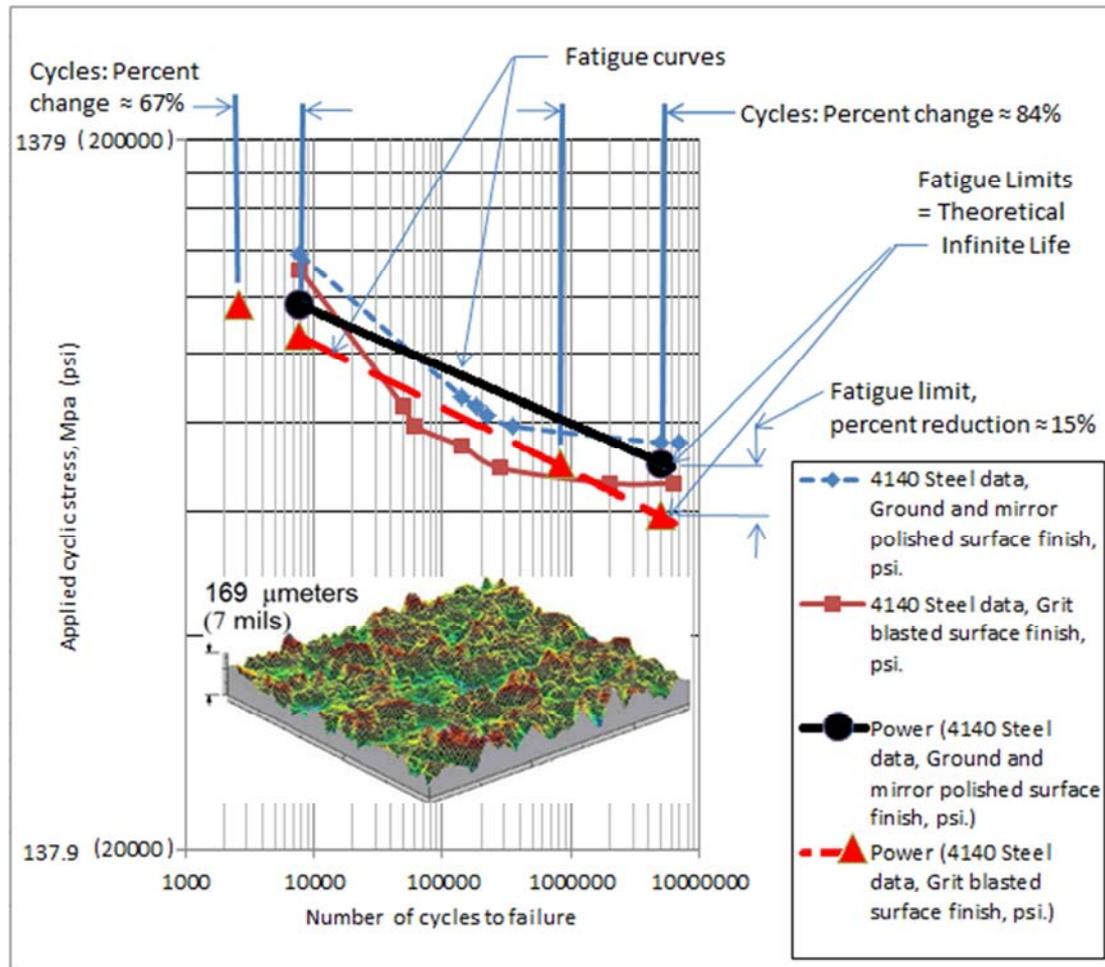


Figure 2. Grit blasting effects on 4140 steel before thermal sprays (Adapted from [5]).

It must be kept in mind that the current AASHTO specifications [represent] 95 percent confidence... for an approximate 97.5% survival, [corresponding] to the shortest lives, [which] means that a substantial majority of details in a given category will have longer lives than predicted by a design curve. [Additionally], the tests by Padilla et al.] greatly exceeded the fatigue life of steel bridge welded connection details....

There is an extensive experimental data base that was used to develop the AASHTO fatigue curves, which are based upon large-scale test specimens having different surface conditions, constraints, and residual stresses, [and] a claim that bridge designs are “in jeopardy” is egregious<sup>2</sup>. The claimed reduction in fatigue strength has not been found in large-scale fatigue tests of bridge components or in the observed excellent performance of steel bridges over the past 45 years.”

Obviously, Lloyd, Connor, and Frank, and I disagree on

<sup>2</sup> In my opinion, these authors should have expressed this opinion differently. As written, they state that my claim is “egregious”, i.e. conspicuously bad. That is, they falsely imply that my research is incompetent. Having spent many decades to establish an outstanding record of competent research at nuclear facilities and through private volunteer research, such a false personal claim is totally rejected and proved to be incorrect by this author through this publication, even though strong disagreements are expected when new concepts are invented.

numerous technical issues. The following discussion serves to address these differences of opinion to effectively refute their comments.

### 3. Updates to October 2020 Structure Magazine Article

In summary, a Response by Lloyd, Connor, and Frank to an October 2020 Structure Magazine article by Leishear (Coating Preparations Reduce the Strength of Bridges) disagreed with opinions and information that were presented by this author to consider potential fatigue failure problems for steel bridges, which are caused by grit blasting for coating adherence. Mirroring their own words, some of the information in their article provides misleading or unsubstantiated claims with respect to bridge safety of existing and future steel bridges. The issues need to be fully investigated to ensure bridge safety<sup>3</sup>.

<sup>3</sup> This discussion refutes statements that I consider false and dangerous to public safety, and this paper works to improve public safety. Granted that Lloyd, et al., are bridge failure experts, but their arguments against my research are effectively refuted in this paper, where, in my opinion, their arguments are shown to be incorrect or inapplicable to the issues at hand. Although we disagree, public safety impacts dwarf our disagreements.



**Figure 3.** 2000, I-794 Hoan Bridge brittle fracture [15].

To open this discussion, there is a fundamental difference of opinion on what constitutes bridge safety. Lloyd, Connor, and Frank seem to imply that bridges are safe as long as they do not collapse, since they conclude that there has been “excellent in-service fatigue performance of steel bridges over the past 45 years”. If cracks in bridges do not represent safety hazards, then I stand corrected with respect to bridge safety. However, I think not, since the safety hazards of ongoing bridge cracks due to fatigue are indeterminate. They also conclude that “the claimed reduction in fatigue strength has not been found in large-scale fatigue tests of bridge components”, but based on their article fatigue tests of large welded bridge components have not been performed at all to evaluate grit blasting effects, even though limited tests have been performed for bolted joints on small plates to evaluate the effects of grit blasting on fatigue failures. Additionally, we disagree on the interpretation of fatigue test results, and those authors mischaracterized conclusions by this author to support their conclusions.

I certainly understand their concerns with respect to my opinions, but being affronted by new opinions is not sufficient cause to dismiss new technological developments. In other words, I found their statement that my claims were “egregious” to be unpleasant and false, where Merriam Webster defines egregious as conspicuously bad: flagrant, egregious errors, egregious padding of the evidence. I understand that my research questions long-held beliefs, and my statements about earlier research may be unpleasant to them as well. Although ethics demand that we, as engineers, view our work and the work of others objectively, personal feelings frequently come into play when engineers care about their work. However, the issues should be considered in accordance with the facts, since competent bridge designs must be paramount. My article questioned bridge safety, and since the quantitative effects of grit blasting on bridge component fatigue strengths are incomplete, that article and this paper recommend further research to understand the scope of this valid safety concern.

#### 4. Bridge Safety

Considering bridge safety first, safety has dramatically improved since 1967 when the Silver Bridge between Ohio and West Virginia collapsed and killed 46 people. Improvements to bridge design followed these accidents, which included redundancy requirements of structural

members. Particularly significant safety advancements in the national bridge inspection program also allowed yearly inspections to be extended to two years with DOT approval. These mandatory inspections have arrested bridge collapses for decades, but during the past 45 years there have been many smaller fatigue cracks in bridges as well as several large brittle fracture cracks and a bridge collapse due to fatigue.



**Figure 4.** Hoan Bridge fracture propagated into two girders to cause brittle fractures [15].

That is, there have been serious damages to bridges in the past 45 years, which were not mentioned in the article by Lloyd, et al. Several bridges experienced major cracks that were attributed to design defects and brittle failure, initiated by cyclic loads. Cited in well documented reports, notable brittle failures occurred at the 2000 Hoan Bridge (Figures 3-6, [15]), the 2003 U.S. 422 bridge (Figure 7) where poor weld quality was present at the crack site [16], and the 2011 Diefenbaker Bridge [17] (Figure 8). Connor coauthored references [15, 16]. Grit blasting surface defects may have initiated or accelerated crack growth on the bottom of the cracked beam. Further improvements for bridge design and inspection continue, but the mechanics of these complex bridge failures are not fully understood, fatigue is a probable factor in these cracks, and the effects of grit blasting on fatigue deterioration were not considered in any of these bridge failure investigations. Even so, cracks observed all the way through bridge girders are detrimental to bridge safety, even though Lloyd et al. stated that bridges are safe. Again, we disagree. I do not believe that bridge safety is guaranteed solely because bridges did not collapse when cracks occurred.

There have been no evaluations of whether or not surface conditions like grit blasting affect observed brittle failure cracks, but stresses were shown to be sufficient to cause failure regardless of surface finish (Figure 5). Since fatigue has not been thoroughly studied in such complex geometries, an initial fatigue crack initiated these brittle type fractures. At the Hoan Bridge, surfaces were significantly corroded at the crack initiation site (Figure 6), indicating that the initial crack started long before the major destructive crack. Of importance to this brittle fracture evaluation, DOT reports state that material properties were not a contributing factor to the Hoan Bridge crack, where temperature effects are frequently cited as causes for brittle failures since steel properties deteriorate with lowered temperatures. As noted, the effects of grit blasting on fatigue deterioration were not considered in this bridge failure investigation, and grit blasting surface effects may have initiated or accelerated crack growth on the bottom of the cracked beam.

For the Diefenbaker Bridge, fatigue cracks were found on other bridge spans, indicating that an initial fatigue crack triggered the larger brittle failure crack. Also, brittle fractures have been attributed to initial fatigue initiation [18], and the effects of grit blasting on fatigue deterioration were not considered in this bridge failure investigation by Connor, et al.

Presented as a new insight into brittle fractures, small cracks are initiated by fatigue, which then induce the sudden snap of heavily loaded beams, or structures, to cause brittle fractures. These sudden cracks are similar to Charpy V-notch, brittle fracture tests that are performed by pre-notching beam specimens, and then striking a specimen to cause a sudden fracture at the notch (Figure 9). That is, in-service fatigue cracks serve the same purpose as pre-notches in laboratory tests. This different approach to the understanding of brittle fractures is more plausible than the concept that bridge beams suddenly snap after years of use without an initiating flaw. In fact, grit blasting surface defects may have initiated or accelerated crack growth on the bottom of the cracked beam.

Additionally, this new insight into fatigue failures has applicability to brittle fractures for piping, machinery, and structures throughout industry. Ensuring that steels do not operate below the ductile to brittle transition temperature is common practice. That is, inherent assumptions that operating below this temperature will prevent structures from brittle cracks are fundamentally flawed. Fatigue cracks initiate requisite flaws to crack structures when brittle failures damage structures.

At a minimum, fatigue cycling weakens and hardens materials at weld locations to initiate brittle fractures, where this author has used a hand-held Vicker's hardness tester to measure hardness near a fatigue crack on a pressure vessel, and the hardness increased to a constant value a few inches from the crack. Once a crack occurs in a highly stressed weld on a bridge, that crack can be transmitted into the beam web or flange, and the original fatigue design then becomes a problem of a fracture mechanics failure, where beams are not designed with inherent cracks at welds. The DOT fatigue testing concluded that the maximum stress was the important parameter during fatigue failures, but that conclusion was based on uniaxial fatigue tests. Past brittle bridge fractures start at locations with conditions that are different than those that were evaluated in DOT bridge fatigue tests, where bridge fatigue failures are incredibly complex.

For example, DOT fatigue limits are applicable to numerous design details for "load-induced fatigue that is due to the in-plane stresses in the steel plates that comprise bridge member cross sections". Present DOT fatigue curves consider multiple bridge details, but do not consider distortion-induced fatigue, which occurs "due to secondary stresses in the steel plates that comprise bridge member cross sections". Further research is needed for two and three dimensional fatigue evaluations to fully understand the interrelationships between fatigue and brittle fractures.

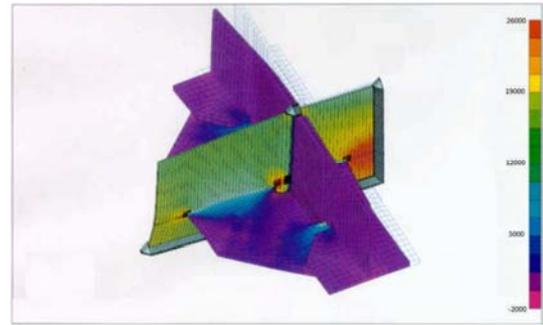


Figure 5. Hoan Bridge finite element analysis showed that the fracture initiated in the web of the girders [15].



Figure 6. Hoan Bridge fracture initiation [15].

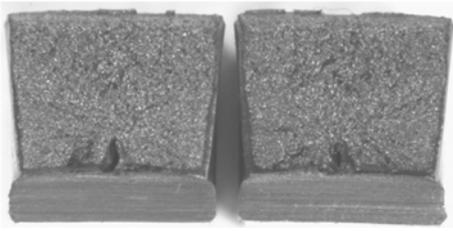


Figure 7. 2003 US 422 Bridge crack [16].



Figure 8. 2011 Diefenbaker Bridge cracks [17].

This opinion for a combined fatigue and brittle failure mechanism contradicts previous opinions that the dead load does not affect fatigue failures, but these types of failures have not been imitated in testing. In other words, the dead load may not affect the initiating fatigue crack, but the dead load significantly affects the brittle fracture through a beam when that beam is finally subjected to a load on a well-formed fatigue crack. Also, the fact that these failure mechanisms are not clearly understood also affects the reliability of computer models to investigate this concern. Accordingly, additional experimental research is warranted to investigate the relationship between fatigue cracks and brittle fractures.



**Figure 9.** A Charpy V-notch impact test for bridge steels at 55°F [8].

Furthermore, the complex dynamics of failures in bridges are not completely understood, where the sudden failure of one member not only moves that load to a redundant member, but that load may be effectively doubled due to processes represented by dynamic load factors [19]. In other words, dynamics, fatigue, and brittle fractures are mechanistically interrelated. Also note that a mathematical relationship between fatigue and fracture mechanics theories has not been established, which demonstrates that a comprehensive understanding of fatigue mechanisms is yet to be discovered.

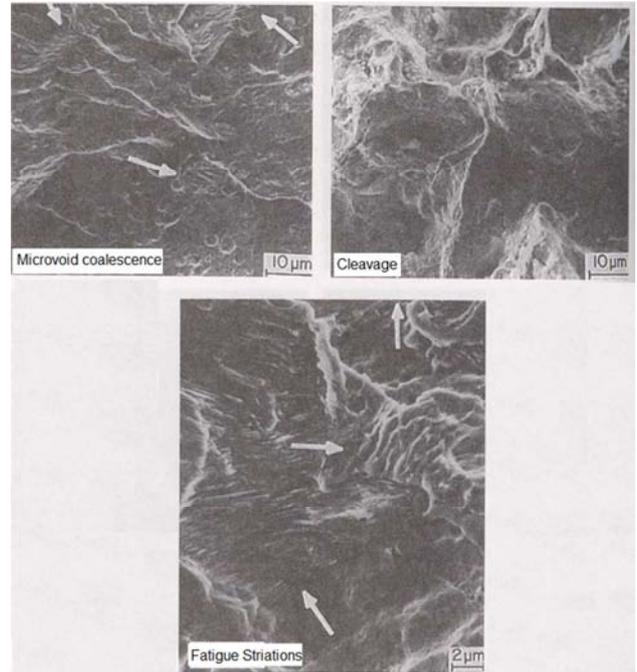
Also of importance to the evaluation of bridge cracks and brittle fractures, fatigue evaluations at Savannah River Site determined that fatigue striations that are indicative of fatigue are frequently found to be eradicated during industrial fatigue failures (Figure 10). Striations form as cracks incrementally grow through a metal, and striations are more obvious in laboratory fatigue tests when friction between crack surfaces is controlled to occur in only one direction [19]. That is, in-service fatigue fracture surfaces frequently look like brittle fracture surfaces, and both brittle and fatigue fractures initiate at structural imperfections. When fatigue cracks grow in length for three dimensional structures, fatigue striations are rubbed away. The fact is that the exact causes of bridge failures are not always completely understood.

Within the past 45 years, the Mianus bridge collapse was attributed to corrosion and fatigue, where corrosion first damaged a 7 inch diameter pin which was critical to the bridge design (Figure 11). According to reports, when this pin failed due to corrosion, a complex deformation caused the load to double on a second 7 inch diameter pin and caused a fatigue crack failure, and a resultant bridge collapse killed 3 people and injured 3 other people [20].

Dynamic load factors that were largely unknown at that time contributed to even higher loads than initially estimated. For example, when the first pin sheared, the load was assumed to double on the second pin, where each pin supported half of the load. However, a suddenly applied load exerts a dynamic load factor of two. Then, the second pin had a momentary maximum load of nearly four times the original load on that pin, and the second pin then sheared, i.e., two times the load due to the removed support from the first pin and two times the load for dynamic effects.

There was so much corrosion damage that this failure was not well understood, where large cracks in the road surface occurred before collapse. Although grit blasting was unrelated to this failure, fatigue was certainly an issue. Evolving technology is changing fatigue evaluations for multiple industries. The Mianus Bridge collapse 38 years ago

contradicts Loyd's concise statement that bridges operated safely for the past 45 years.



**Figure 10.** Photomicrographs of fracture surfaces (Adapted from Brooks and Choudhury [21], Leishear [19]).

Many fatigue fractures are readily available for review in DOT reports (Figure 12), but the number of fatigue cracks that did not lead to catastrophic failures of U.S. bridges is unknown, and the potential of fatigue cracks to cause catastrophic failure is unknown. That is, the full scope of the fatigue problem at present is unknown, but an older paper highlights the extent of the problem, where the paper is titled "Hundreds of Bridges, Thousands of Cracks" [22], and corrective actions followed that paper. Also, ongoing fatigue cracks in steel bridges have occurred in every state in the U.S [23]. Interestingly, Dr. Connor of Lloyd et al. was co-author to this paper. There have not been any previous failure investigations that considered the effects of grit blasting for even a single bridge crack. All in all, I adamantly disagree with the claim of "excellent in-service fatigue performance of steel bridges over the past 45 years".



**Figure 11.** 1982 Mianus River Bridge collapse due to corrosion and fatigue [8].

## 5. Large-Scale Fatigue Testing Results

To better understand fatigue cracks in bridges, consider the facts about fatigue test statistics with respect to safety. The yield strengths of tested steels for Figure 1 varied from 248 MPa to 689 MPa (36 ksi to 100 ksi) for A36, A441, and A514 low carbon content steels (less than 0.25% carbon), and the fatigue limits were found to be nearly the same for all of these steels, and fatigue limits varied between 17.93 MPa to 165.5 MPa (2.6 ksi to 24 ksi) for different designs.

As Lloyd, et al. noted, full-scale tests of bridge components were performed to understand fatigue failures, and they are correct that the DOT fatigue curves were established with 95% confidence which means that the curves are statistically correct 97.5% of the time, and this confidence level does in fact ensure that most of the time these curves are adequate. However, Lloyd, et al. do not emphasize the fact that the curves are incorrect one time out of forty which may be important to crack formation in bridges. That is, these curves do not correspond to the “shortest lives experimentally observed”, but the DOT has accepted 95% confidence for these curves. Is 95% confidence acceptable? The Interstate 40 bridge crack (discussed in an Addendum) fits within this 95% acceptance criterion, but the potential collapse of an interstate highway bridge is completely unacceptable.

A 95% confidence level is common for instrumentation calibrations and many applications, but in some cases 99% confidence (one out of 200 permitted failures) is used, e.g., some nuclear power processes. For example, The ASME B31.3 fatigue curves for high cycle fatigue [24, 25], are recommended for a  $3\sigma > 99\%$  uncertainty, but a  $2\sigma > 95\%$  uncertainty may be used and is shown in Figure 13. Perhaps a 99% confidence level or higher is appropriate for bridges as well.

Also of importance is the fact that the confidence level does not mean that 1 out of 40 bridges will fail, it means that 1 out of 40 designs that are designed at the fatigue limit will fail. For example, many designs may be well below the fatigue limit, where Lloyd et al. claimed that bridge designs are typically 4% to 8% of the yield strength. Although low observed bridge stresses were true for the experiences of Lloyd, et al., this observation is not universally factual. The number of bridge designs that approach the fatigue limit is unknown, and ongoing fatigue cracks indicate that fatigue stresses are reached and exceeded, since observed bridge cracks only occur when the fatigue limit is exceeded.

In 1967 the number of bridges in the U.S. was not even known, where there are hundreds of thousands of bridges in the U.S., and stresses are not always known. For example, contrary to Lloyd’s low fatigue stress claims for bridges, a 2007 collapse of an I-35 bridge in Minneapolis, Minnesota killed 35 people and injured 145 people, where 24 gusset plates for the bridge were  $\frac{1}{2}$  of the required thickness, and one of those gussets exceeded the yield stress and reportedly buckled to initiate the bridge collapse [16, 26]. That is, all bridges do not operate at the “low effective stress ranges” asserted to be typical by Lloyd, et al. Also, design and

inspection procedures were changed after this accident to prevent gusset plate buckling, where the understanding of bridge collapse continues to advance.

Additionally, other recent developments in fatigue research showed that fatigue limits are questionable in welded structures for very high load cycles, where most fatigue tests have historically been performed below  $10^7$  cycles. Common piping test specimens for B31.3 are 4 inch diameter, Schedule 40, A106 steel, butt welded pipes, and fatigue cracks typically initiate at the toes of welds. Considering high cycle fatigue, ASME B31.3 provides a decreasing fatigue stress curve for high cycle fatigue as shown in Figure 13.

Basically, a fatigue limit has been assumed to exist for steels for many decades, and the concept of fatigue limits, or CAFT, are now in question for bridges as well. According to B31.3 design curves, fatigue limits do not exist at all for very high numbers of cycles. Perhaps additional research is required for bridges, where many bridges perform below the high cycle fatigue range.

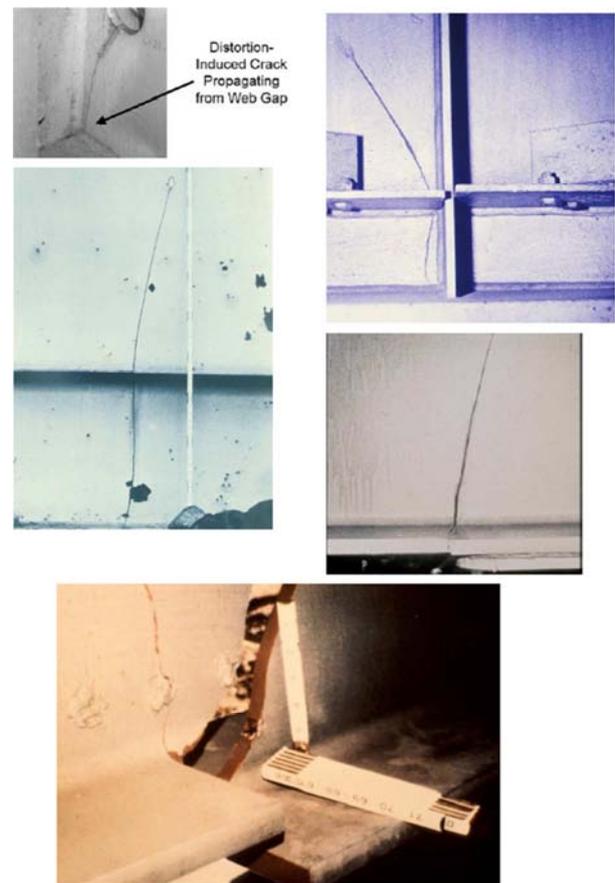


Figure 12. Reported fatigue cracks [8].

## 6. Grit Blasting

Next, consider the facts about grit blasting. Lloyd, et al. mentioned different grit blasting profiles that are specified for bridges. Those profiles are not questioned here, but surface profiles are helpful to understand fatigue issues. Profiles were not used to evaluate fatigue properties in any large-scale tests

since only small-scale tests have been performed, and are not directly applicable to large-scale bridge structures with respect to grit blasting of welds and surfaces. For example, 25.4 to 76.2  $\mu$ -meter (1 to 3 mils) profiles were noted for inorganic Zinc coatings which require a smaller surface profile to prevent flash rusting between coats when the metallic tips of the surface protrude through the thinly applied Zinc coatings, where thick coatings crack during drying of the high solids content Zinc coatings. The larger 63.5 to 127  $\mu$ -meter (2.5 to 5 mils) surface profiles are blasted for thicker thermal spray coatings to provide greater coating adherence. Also note the fact that coal slag, called Black Beauty, is used for coating preparation in the field, in addition to the use of shot/grit mixtures mentioned by Lloyd, et al.

The exact extent of use for different combinations of grit or shot is uncertain, where combinations of grit and shot are common for shop blasting of bridge components. In other words, some bridge components may be blasted with combined grit and shot prior to assembly, but field coatings at installation or later maintenance coatings may use grit blasting alone for surface preparations.

While considering surface profiles, mention should be made of the fact that some blasting was performed during steel beam fatigue testing. In one set of tests, blasting was reportedly used on surfaces to clean the flame cut, unwelded edges of steel beams [12], and in another set of tests blasting was reportedly performed on the areas where welding was to be performed [29]. However, this blasting was performed to remove slag caused by cutting steel beams with an acetylene torch, and surfaces were not fully blasted for coating adherence since coatings were not used in these tests. Although sand blasting / grit blasting may have been used for beam fatigue tests, the type of blast material was not specified.

Blast material is important since grit, shot, or a combination of grit and shot may be used, where shot improves fatigue properties, and grit decreases fatigue limits and the number of cycles to failure for any given stress. In fact, a combination of grit and shot is a method to control fatigue limits while enhancing coating adherences, but this method needs further investigation to quantify the effects of different grit mixtures.

More importantly, blasting was not used for any reported fatigue tests on final welds for beams, and the effects of grit blasting on fatigue are therefore not fully understood for the series of AASHTO steel beam tests that were very carefully performed to understand fatigue failures of bridges. Again, the effects of grit blasting on fatigue of beams were not evaluated at the time of those tests, and grit blasting will reduce published fatigue limits.

## 7. Fatigue Testing for Plates with Holes

Furthermore, Lloyd et al. stated that “Extensive fatigue studies of bolted connections with blasted and blasted-then-painted surfaces have been performed”. This statement, while based on extensive research, is misleading since test data is inadequate with respect to the issues of welds loaded in tension and cracks at welds or on non-welded surfaces.

Tests were performed on test plates much smaller than those used on bridges, where Lloyd et al. criticized rotating beam tests for being smaller than bridge components. How can one type of small scale test have value for considerations, but another type of test automatically has no value by virtue of size and the number of fatigue cycles? Also note that the number of fatigue cycles used for Padilla’s fatigue tests are in the range of cycles for AASHTO fatigue tests, contrary to the claim by Lloyd et al. that fatigue cycles during testing “greatly exceeded the fatigue life of steel bridge welded connection details” (See Figures 1 and 2).

One set of the quoted tests were performed for single shear tests without grit blasting [13]. For 26 of 32 tests, two plates were bolted together and fatigue cycled to stretch the bolt holes and cause cracks at the holes, where the highest stresses occur. The other 6 tests were performed with open holes and no bolts. These mill scale surface tests noted that dull drill bits used for drilling holes in steel components reduced fatigue properties, which further proved that surface roughness is important to fatigue properties.

The other set of quoted tests considered both grit blasted and grit-blasted-then-painted surfaces from Frank and Yura [14], where grit blasted data was also used for comparisons in Brown’s report [13]. Results from multiple studies were incorporated into Frank and Yura’s report, and one section of their detailed report considered fatigue failures. A different view of the results from Brown, Frank, and Yura is provided here.

Data from grit blasted tests were within the range of fatigue values found for mill scale surfaced beam tests, however, grit blasting test results are rather complicated. These grit blasting tests were performed for double shear, bolted connections to investigate the effects of coatings on faying surfaces that permit relative motions between plates. In these double shear tests of 4-3/4 to 7 inch wide specimens with different patterns of holes, the fatigue damaged plate is sandwiched between two other plates, and both surfaces of the test specimens are steel to steel (Figure 14).

When slip does not occur between plates with pre-stressed bolts, compression causes a complex process that forces the peaks of the profiles into one another. This distributed compression process reduces the tensile stresses near the bolt holes to cause fatigue cracks away from the holes at locations through the gross metal area. When slip occurs, cracks occur through the net cross section at the bolt holes since the compressive interference is momentarily removed during motion.

The question at hand is whether or not fatigue tests on bolted plates are applicable to beams in bending. Failures depend on the net stress ranges, which are determined from the maximum stresses, where net failures occur through the net area between the bolts and gross failure occurred through the gross area or the entire cross sectional area of the plates (Figure 14). That is, the net stress equals the maximum stress during a cycle times the joint efficiency, and the joint efficiency is the ratio of the stress through the net area to the stress through the gross area.

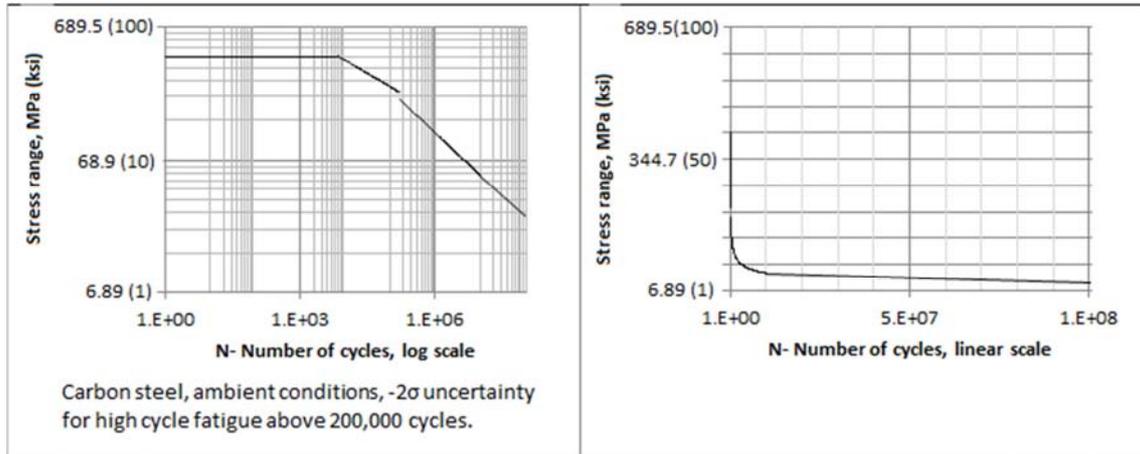


Figure 13. Decrease in piping fatigue stresses beyond the theoretical fatigue limit.

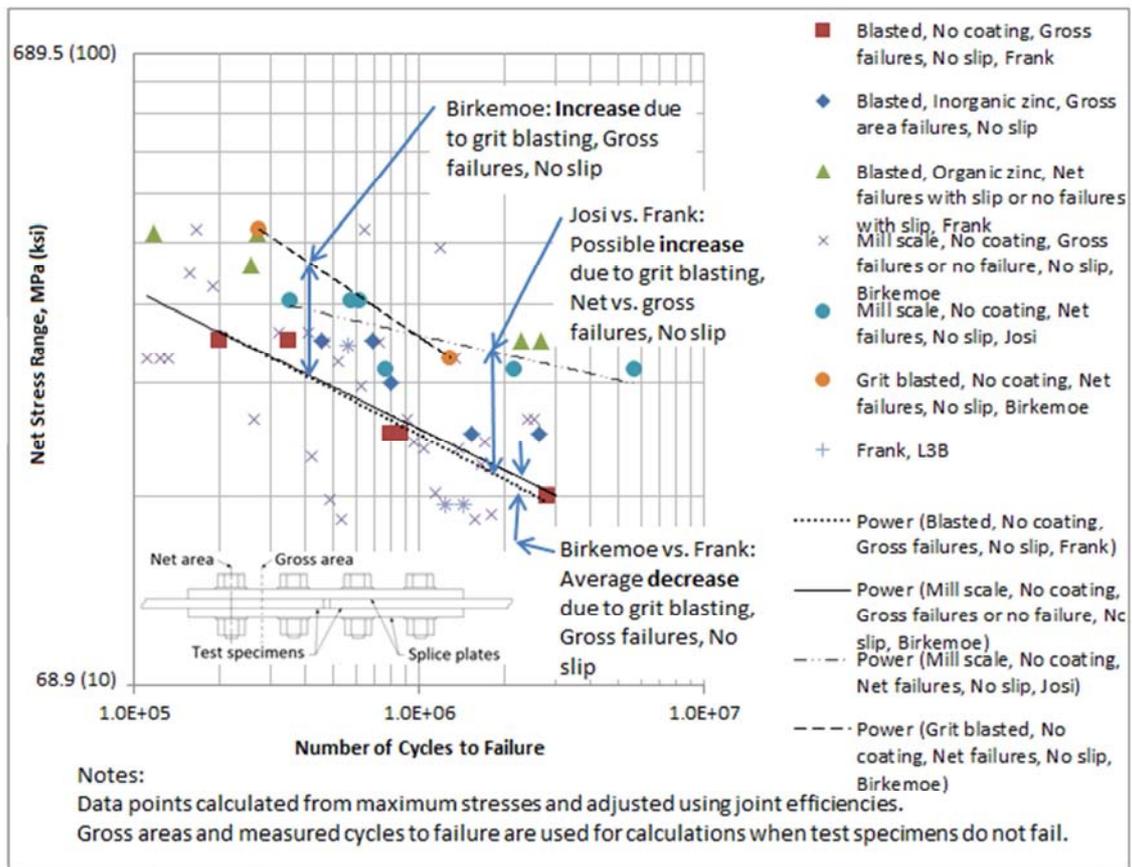


Figure 14. Bolted joint, double shear; fatigue tests – bolt patterns and the number of rows of bolts varied (Adapted from [14, 27-30]).

There are several sets of data to compare grit blasted surfaces to mill scale surfaces and coated-blasted surfaces, using limited data for each set. Note that mill-scale surfaces are not installed in bridge service. The scatter of test data leads to high uncertainties and questions the reliability of the following results, as shown in Figure 14.

A review of Frank and Yura's data [14] for 5 tests tends to indicate that grit blasted surfaces yield fatigue properties slightly less than mill surfaces when the average stresses are considered without slip. However, average stress values are

not conclusive since fatigue failures in bolted plates are dependent on joint efficiency. Birkemoe, et al. [27, 28] performed two tests to evaluate the effects of grit blasting for identical bolted joint configurations (identical joint efficiencies), and they showed that the fatigue strengths increased during slip, and concluded that the surface profile interference fit increased the fatigue stress. These two tests provide the most applicable data to date for grit blasted bolted joints to compare grit blasted to mill scale surfaces.

Data from Josi, et al. [30] is compared to data from Frank, et

al. for tests with similar joint efficiencies (0.732 vs. 0.721, respectively), and fatigue strengths due to grit blasting may increase. However, net stresses are compared to gross stresses due to differences in bolt loading and resultant joint compression, where the effects of grit blasting are significantly magnified, and this result may not be valid for consideration of grit blasting. Also, Josi's tests showed that fatigue limits increase as torque is reduced to reduce joint compression.

In general, coated surfaces result in reduced fatigue strengths of bolted joints. The greater the thickness, the greater the fatigue strength. Again data is limited, but as the interfering tips of the surface finish move further from each other, the fatigue limits tend to increase.

From limited data, grit blasting may or may not increase fatigue strengths for bolted joints, depending on surface profiles, coatings, bolt torque, and joint efficiency, where coatings also affect grit blasting response and tend to improve fatigue performance for bolted joints.

Even so, the interference and compression effects within bolted joints represent a completely different set of operating conditions than the conditions experienced on free surfaces and surfaces encountered for welds on beams, where flexural beam fatigue stresses are affected by stress raisers in the valleys of grit blasted surface profiles. That is, bending in tension is not the same process as compression with shear. Also, Collins [31] noted that fatigue properties changed little for rotating bars that were zinc coated, i.e., bending fatigue failures were unaffected by coatings. The mechanics of compression and slip are complex and argumentative without more data. In other words, available tests are inconclusive, inadequate, and misrepresentative to judge whether or not grit blasting influences crack formation on the non-welded surfaces of weld surfaces on bridge structures.

There is no experimental data directly applicable to bridge beams in bending, and the only available data to indicate the performance of beams is Padilla's data. In short, Lloyd et al. referenced numerous grit blasted test specimens for bolt geometries, but only 7 of those tests are applicable to direct comparisons between mill scale surfaces and grit blasted surfaces. Since the grit blasting tests that were performed are not representative of bending fatigue for beams, the sweeping conclusion that "These large-sized bolted connections... confirmed the adequacy of the AASHTO specifications" for beams is not supported by facts, and such a claim is therefore incorrect.

## 8. Fatigue Test Interpretations

### 8.1. Previous Research

Stating that I misapplied research by Padilla, et al., Lloyd et al. misrepresented my discussion of fatigue test data. The research that I presented never claimed that Padilla's research data was identical to steel bridge performance where scale-up effects and the type of material are obviously important to fatigue responses. However, my article provided details to point out that similar, and probably worse, fatigue

performance is expected for bridge steels when grit blasted. Padilla noted that some of the fatigue failures occurred at locations where grit was imbedded in the 4140 steel surface, where 4140 steels are not used in bridge construction. One implication is that commonly used brittle coal slag may have a more deleterious effect on steels than garnet or steel grits, which are not so brittle. Also, as discussed in the earlier Structure Magazine article for this work, bridge steels are softer than 4140 steel, and are expected to be damaged more than the harder 4140 steel since grit can cut sharper surface profiles into softer steel surfaces, which in turn provide higher stress raisers to induce fatigue failures.

Again, grit blasting effects were not tested for fatigue effects for any large-scale bridge components used for AASHTO fatigue curves. Note that grit blasting is important since most failures occur at the toes of the welds where fatigue stresses are typically, but not always, the highest near welds and holes.

### 8.2. Research Applicability

Another significant disagreement between this author and Lloyd, et al. is whether or not small-scale fatigue tests using polished bar tests and grit blasted specimens have any validity with respect to bridges. Granted that scale-up changes fatigue performance, but polished bar tests provide indications of relative performance between surface finishes. Throughout the engineering literature the facts are widely accepted that surface finishes affect fatigue limits, and I was surprised when I read that "minor surface conditions" were stated to not affect fatigue failures of steel structures. For example, Collins' text [31] on *Failure of Materials in Mechanical Design* provides several examples of significant decreases in fatigue properties for aluminum alloy extrusion tests, polished bar tests, and chromium-molybdenum tube tests. Collins also states that "A very high proportion of all fatigue failures nucleate at the surface of the affected part; hence surface conditions become an extremely important factor influencing fatigue strength". That is, surface conditions affect fatigue properties at all stresses as shown by Padilla and Collins. Contrary to these facts, Lloyd et al. stated that surface conditions have no influence on bridges. Such an assumption requires proof.

Even so, Fisher, who performed and directed much of the research to establish DOT fatigue curves, mentioned that surface finishes had little effect on fatigue properties, but grit blasting that causes stress raisers in steel surfaces was never considered for beams in Fisher's outstanding research for beams. However, as noted, fatigue tests for beams to date have been performed for steels with mill scale surfaces, which are not representative of the final, grit blasted surfaces after bridges are constructed. Grit blasting affects small-scale polished bar tests as well as large-scale bridge components, and there is no experimental evidence to prove otherwise. In fact, fatigue strengths are known to decrease as part sizes increase.

Apparently, I was not completely correct when I stated that "What we had here was a failure to communicate-nobody talked to the structural engineers to notice that bridge safety

was reduced". Some engineers were, in fact, aware of grit blasting effects on surface finishes, but they were not aware of the dangerous fatigue effects due to grit blasting. As discussed here, Lloyd et al. recently published that grit blasting has no effect at all on fatigue failures of bridges. I adamantly disagree with those claims, and believe that such claims represent a hazard to the public, since the effects of grit blasting on fatigue of bridge components are not fully understood. Again, we disagree, and this publication presents an opportunity to advance technology and improve public safety. Professional disagreements compelled harder work to better this research and take the next right step for this research. The facts are clear – grit blasting causes fatigue cracks.

## 9. Other Applicable Research

### 9.1. Fatigue Tests for V-notched Steel

Although grit blasting data is limited, fatigue tests for V-notched rotating bar tests are available, and such tests provide insight into grit blasting effects on beam fatigue failures.<sup>4</sup>

Specifically, research was performed for low carbon, medium carbon, and high carbon steels to compare finite element model results to experimental results to determine the applicability of models to designs [32]. In general, models under-predict experimental results as shown in Figures 15 and 16.

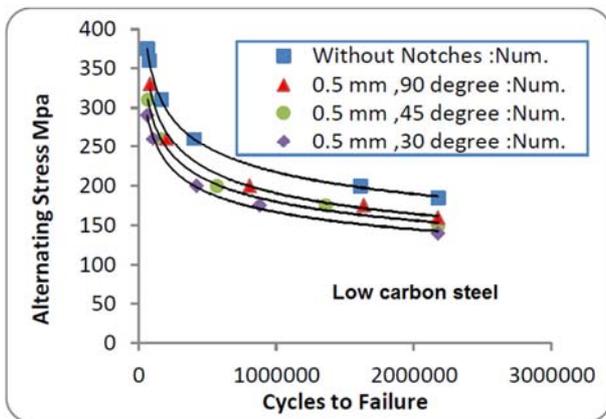


Figure 15. Finite Element Predictions for Steel Failures [32].

With respect to this research, experimental results are important. Tests were performed for polished bars without notches and for polished bars with a 0.5 mm depth and a 0.075 millimeter root radii, and varied groove angles of 30, 45, and 90 degrees. As shown in Figure 16, fatigue limits were reduced by nearly one quarter, and the number of cycles to failure was reduced by more than an order of magnitude at the fatigue limit.

While this data is pertinent to low carbon bridge steel failures, the importance to grit blasting is a concern. The fact

is that grit blasting will create far sharper grooves than V-notches, and grit blasting is therefore expected to have a greater effect than notches with respect to bridge failures. This expectation is also based on the fact that grit blasting introduces thousands of stress raisers on the surface, and this multitude of fracture initiation sites increases the probability of a fatigue failure.

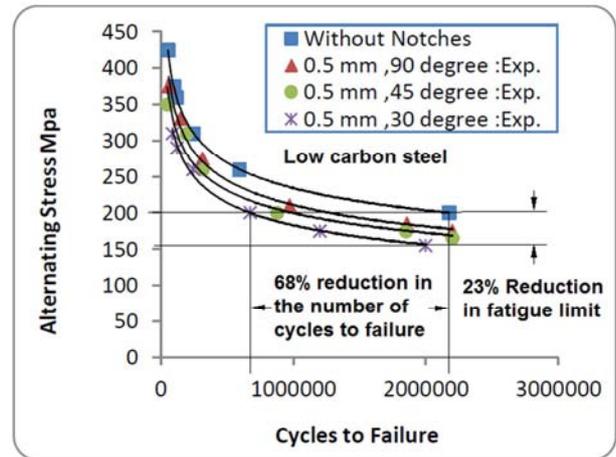


Figure 16. Experimental Fatigue Test Results for Steel Failures (Adapted from [32]).

### 9.2. Fatigue Tests for Scratched and Shot Blasted Steel

Tests have been performed to evaluate shot blasting and the effects of small scratches on fatigue. Rotating bar tests with polished surfaces were modified to determine the effects of shot blasting and scratches on the surfaces of SAE 4340 steel, which is a medium carbon steel (carbon content = 0.38% – 0.43%) used for some bridge components. Scratches on test specimens were machined into 4340 surfaces at an approximate 45 degree groove angle and a depth of 0.0508 mm (0.002 inches). The small dimensions of these machined cracks mandate that the root radius for these tests is significantly less than the .075 millimeter root radius for the V-notch tests discussed above, which were approximately 10 times as deep as these scratch tests.

Figures 17 and 18 show some results, and other test results follow.

“In general shot peening had a noticeable effect on crack growth life by increasing the time to failure from a factor of 2 to 4 for the lower applied stress level tests, 10 ksi (68.9 MPa), or from 1.2 to 2.7 for the higher stress level, 13.3 ksi (91.7 MPa).

Shot peening of high strength 4340 steel produced a higher endurance limit by about 10 percent.

A machine-like scratch in high strength 4340 steel reduced the endurance limit by about 40 percent.

Shot peening a material that contains a machine-like scratch restored the endurance limit of the material to within about 10 percent of its original value” [33].

The reduction in the number of cycles at the fatigue limit is about one order of magnitude (Figure 18).

Comparisons of scratch tests to V-notch tests provide some

4 This discussion of V-notches and scratches was added after initial publication, since this insight into this complex problem evolved as research continued.

interesting results with respect to grit blasting. A decrease in the root radius decreased the fatigue limit from a 23% reduction to 40% reduction for V-notches versus scratches, respectively. That is, sharper root radii apparently increase fatigue failures, but note that 4340 steel has a higher fatigue limit than A36 steel [34], which was one of the tested bridge steels for the AASHTO Fatigue curves. The softer bridge steels for beams will have even greater fatigue limit reductions than those observed for 4340 scratch tests, but again more research is needed.

The root radius for scratch tests was unavailable to compare scratch test radii to grit blasting radii, where a direct comparison between grit blasted and scratched surfaces is complicated. Also note that a 2 mil scratch (0.0508 mm) is on the order of the sharp pointed indentation depths for a grit blasted surface shown in Figure 2, which implies that there are similarities of results between scratch tests and grit blasting. Even so, the massive number of defects during grit blasting will reduce fatigue properties even further than scratch or V-notch tests.

**9.3. Fatigue Tests for Sharp Cracks**

Earlier tests for a very sharp crack demonstrated a 57% reduction in the fatigue limit [35]. As shown in Figures 19 and 20 for those tests, the fatigue limit dropped from 70 MPa to 30 MPa when rotating polished bars of 4340 steel were notched at 60 degrees with a depth of 0.635 mm (0.25 inches) and a root radius of 0.254 mm (0.010 inches). As cracks get progressively sharper fatigue limits progressively decrease. The sharpest cracks expected in service are those experienced in bridge steels that are softer than these 4340 steel fatigue specimens.

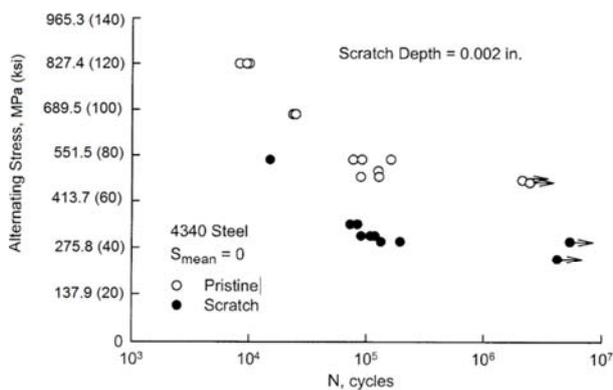


Figure 17. Experimental Fatigue Test Results for Scratched Steel Failures [33].

By extension of test data to bridge components, grit blasting may reduce fatigue limits by more than 23% and perhaps more than 57% or more. Even so, the influence of scale-up for large structural bridge components needs evaluation to determine such effects on these coarse approximations obtained from small-scale polished bar fatigue tests. All in all, grit blasting reduces fatigue properties and shot blasting improves fatigue properties.

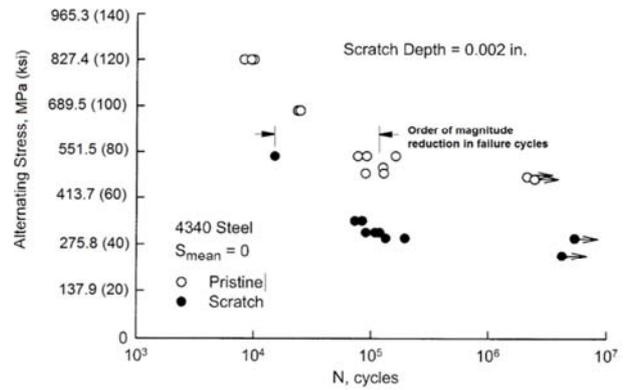


Figure 18. Experimental Fatigue Test Results for Scratched and Shot Peened Steel Failures (Adapted from [33]).

**9.4. Polished Bar Fatigue Tests and Bridge Fatigue**

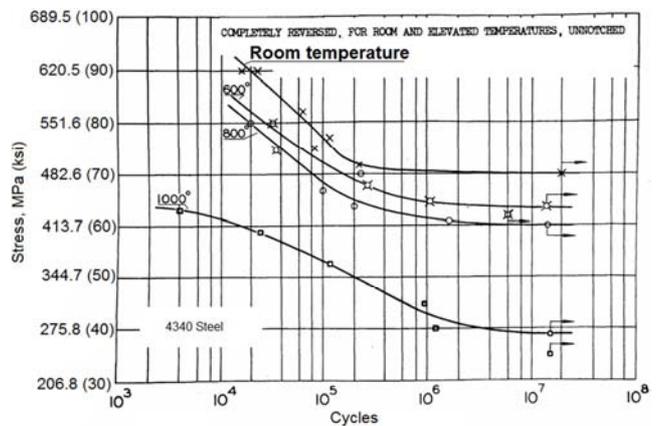


Figure 19. Experimental Fatigue Test Results for Unnotched Steel Failures (Adapted from [35]).

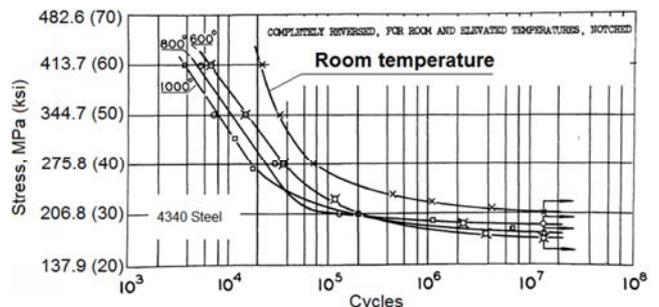


Figure 20. Experimental Fatigue Test Results for Notched Steel Failures (Adapted from [35]).

**10. Conclusions**

Surface defects affect fatigue failures, and to better explain the effects of surface defects, some tests are available in the literature. For grit blasted 4140 steel, which is not used in bridges, a 15% reduction in the fatigue limit was observed. V-notch tests were performed for steels similar to those used in bridge beams, and a 23% reduction in the fatigue limit was observed. Other fatigue tests were performed on scratched steel specimens that had scratch depths similar to grit blasted surfaces, and fatigue limits were reduced by as much as 40%,

and these tests were performed on 4340 steels that are harder than the steels used for AASHTO fatigue curves. In still another set of 4340 steel fatigue tests, a very sharp crack reduced the fatigue limit by 57%. Grit blasting effects are expected to reduce fatigue properties even further for softer bridge steels, since cracks are expected to be sharper for grit blasted surfaces, and thousands of stress raisers occur all over grit blasted surfaces. Even though these fatigue limit reductions will be affected by scale-up issues, this data demonstrates that current AASHTO fatigue curves used for bridge design are dangerously incorrect. Again the exact impact to fatigue design curves needs to be established through further experimental tests.

Lloyd et al. and I disagree, and I recommended, and still recommend, that further research should be performed. Based on this research, the opinions of Lloyd et al. should not be accepted without sufficient proof and facts before disregarding grit blasting effects, even though they have worked extensively on impressive fatigue research. Note that all of their objections have been competently addressed and refuted in this article, and previous research should be augmented by an investigation of grit blasting effects on bridge fatigue cracks. Their primary objection was that previous research for bolted joints was generally applicable to all bridge components, but bending of welded joints is markedly different than bolted compression joints. The results from grit blasted joints was simply assumed to apply anywhere on a structure, but such an assumption is not justifiable without proof.

In other words, Lloyd, Connor and Frank provided no credible evidence at all to contradict this author's claim that grit blasting affects bridge safety, and their opinions need technical supporting facts. They may not like the opinions presented here, but their personal preferences fall short of the technical proof required to ensure public safety. Proof is mandatory to ensure public safety<sup>5</sup>.

There is no question that nearly all fatigue failures occur at holes and welds, and bridge safety continues to improve, but grit blasting accelerates fatigue failures on both blasted surfaces and blasted welds, where the comprehensive effects of grit blasting on welded joints is presently indeterminate.

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5 Dr. Lloyd and the Editor of Structure Magazine refused to respond to repeated requests for comments on this paper. In fact, the Editor for Structure refused to answer email requests to explain why my original article [6] from the October issue was deleted from the Structure website, but Structure retained the November article from Lloyd, et al. To ensure availability, my article is now provided on the internet. An email to the Structure Editor and Lloyd stated that "To summarize our discussions: I greatly appreciate the opportunity to have published in Structure; Without explanation, an offer was withdrawn to publish an article in Structure to refute arguments against my research; A suggestion was made to contact Lloyd, but he does not respond to emails ... This experience has been interesting, and challenges to my research served to improve my research accomplishments. Advances in technology are often hindered by a natural resistance to changes in the world around us. I choose to act against such resistance. Our discussions are at an end, but I thank you very much for your time to address complex issues". A follow up letter to Structure Editor stated that "I noticed that Structure does not include my article in the electronic version of the October edition, but Lloyd's article is included in the December edition. Your choice of course, but was this action intentional?" New ideas are hard to hold on to.

Many fatigue cracks are documented in the literature and grit blasting affected many of them.

The concept that grit blasting affects fatigue in bending is new and may be difficult to accept at first, but grit blasting effects on fatigue cannot be fully understood without testing. Although the results from grit blasted joints were simply assumed to apply anywhere on a structure, such an assumption is not justifiable. This opinion was the basis for my previous statements that "Bridge designs – past, present, and future – are in jeopardy unless fatigue strength reductions due to grit blasting are evaluated for bridge safety".

Bridges continue to crack in service. Therefore, some bridge fatigue designs operate at the fatigue limits of steel bridge components. Perhaps some designs are faulty, but this new grit blasting theory provides insights into why bridges designed to current AASHTO design requirements can crack during cyclic fatigue loads, where trucks exert the highest design loads. Additionally, current AASHTO fatigue curves use a 95% failure criterion that permits potential bridge fracture for one out of forty designs at fatigue limits.

As clearly demonstrated by the facts presented here, there is no reason to change the opinion that grit blasting contributes to bridge fatigue failures. Unless pertinent tests are performed, the risks to bridge safety are unknown, risks to bridge safety are of paramount importance, and risks to bridge safety should be understood through testing. Unsafe bridge designs risk lives, and this research certainly proves that design standards require improvements for safe fatigue designs related to traffic loads on bridges.

The attached Addendum discusses a bridge crack that occurred after the initial publication of this paper, and further proves that bridge designs are in jeopardy. In fact, the potential collapse of an Interstate 40 highway bridge provides additional insights into the importance of the grit blasting theory presented here. New technology must be addressed now, rather than waiting until people are killed.

## 11. Addendum

### 11.1. A Failure to Communicate

What we had here was a refusal to communicate<sup>6</sup>. The supposed gate keepers for bridge safety closed the gate to new knowledge for the bridge industry. Claims were made that bridge safety is adequate, and the publication of new information to improve bridge safety was thwarted<sup>7</sup>.

Specifically, the Editor of Structure Magazine refused to publish a shortened version of this paper, and refused to respond to repeated requests for comments on this paper. Editors are certainly entitled to print what they want, but are editors expected to prevent the publication of information that can improve public safety? Are editors expected to publish

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6 Adapted from the movie "Cool Hand Luke – "What we've got here is failure to communicate".

7 Lloyd et al. incorrectly stated that these research results were egregious. In my opinion, such a statement appeals to emotions rather than facts, and facts should determine public safety to prevent loss of life.

incorrect information and then refuse to publish sound facts to rebut those opinions? I think not, and a recent bridge failure compels further research into bridge safety.

### 11.2. A New Highway Bridge Fracture

This series of two papers has proven that cracks are created by grit blasting, and although the investigation of the Tennessee – Arkansas, Mississippi River I-40 Bridge is far from complete [36], the potential for surface finish to have contributed to this dangerous failure is certainly probable. As shown in Figures 21-24, the bridge experienced a significant failure, where the crack initiated on the bottom surface of the beam at a location located a distance from bolted connections.



Figure 21. 2021, I-40 Fatigue Crack [36].

The Arkansas Department of Transportation stated that on May 11, 2021, “A routine inspection of the Interstate 40 Mississippi River Bridge (also called the Hernando de Soto Bridge) discovered a mechanical fracture in a steel support beam that is crucial for the structure of the bridge” and further stated that the bridge is “inspected annually because it’s classified as ‘fracture critical’ due to how it’s built”. For a fracture critical bridge, a failure of an affected primary structural beam can cause a bridge collapse since redundant structural beams are not present. Many lives were at risk on the 274 meter long span (900 feet long), since a potential bridge collapse was in process. Note that a steel beam approximately 1 meter high by ½ a meter in width ripped into two pieces. According to the Arkansas Department of Transportation, the fracture started before mid-2019, and according to Fox News “an employee has been fired after a crack on the Interstate 40 bridge over the Mississippi River [that was] visible in a 2019 drone video was missed”. That is the “[Arkansas Department of Transportation Fired an] Employee Over Missed I-40 Mississippi Bridge Crack” [37]. The crack was recorded with a camera on a drone during an earlier inspection, which showed cracks and buckling of non-redundant beams.

The progressive damage of the beam can be discerned in photos from 2019 and 2021 (Figures 22 and 23), and the final extent of damage can be observed in Figure 24. Interim bridge repairs are shown in Figure 25, which clearly envisions the size of the beam that sheared in two. Of major importance, buckling of an attached beam, a possible crack in that attached

beam, and bending of another support accompanied the complete shear of the beam, which sheared over time.

### 11.3. Bridge Failures and New Technology

The notion is glaringly false that cracks in bridges are only important if bridges collapse and kill people. In fact, the Director of the Arkansas Department of Transportation, Lorie Tudor, P. E. stated “Our primary goal is the safety of the road users”. Even so, the Arkansas and U.S. Departments of Transportation were contacted with respect to this important bridge safety issue, and the Office of the U.S. Secretary of Transportation and the Arkansas Department of Transportation failed to respond to opportunities to comment on this research.

A conclusion is reasonable that a chain reaction of bridge failure events was in process. Since a dangerous crack was overlooked during at least two previous yearly inspections, and multiple components were progressively failing, the moment of bridge collapse could have happened at any time. Fortunately, a bridge inspection stopped the havoc of a bridge collapse while hundreds of vehicles crossed the bridge.

The Interstate 40 fatigue crack started on the bottom surface of a beam and not at a weld. As seen in Figure 23 there are no welded or bolted locations at the fracture initiation site on the bottom of the beam. Therefore, the potential for grit blasting to have contributed to this bridge failure is significant and demands investigation, since grit blasting affects the fatigue strength of steels at weld locations and, in this case, on the surfaces of beams to cause fatigue cracks. More importantly, fatigue is a random statistical process, and this crack is the first in a series of fractures that are expected – only the time between cracks is uncertain.

In short, the probable cause of the I-40 bridge failure was grit blasting since the bottom beam surface was not welded or bolted where the crack initiated, and given the excessive loads transmitted to the undamaged parallel span, future fatigue cracks are expected. The only question is when that span will crack. This near-collapse of a bridge provides additional proof of theory, and grit blasting demands investigation for this accident.

The incredible resistance to new technology may impede acquiescence to this demand. In fact the Arkansas Department of Transportation refused a request to supply any information to support this research. I sent a letter to them stating that “I find it difficult to understand when public officials stand in the way of advancing technology, which will promote the health and welfare of U.S. citizens. I have spent years performing volunteer research to this end. Although I cannot expect others to share the same compassion, I am disappointed that public safety is thwarted by others. With respect to the I-40 bridge near-collapse, my interest is to prevent future accidents on this bridge and other bridges throughout the U.S. The I-40 bridge crack could have killed many people. Yes, the law covers the denial of my request, but law and ethics are not always the same”. New ideas are difficult to accept.



Figure 22. May 2019, I-40 Fatigue Crack – Earlier Bridge Inspection Video (Adapted from [37]).



Figure 23. May 2021, I-40 Shear of Bridge Beam-Recent Bridge Inspection [36].

#### 11.4. The Problem and Solution

The hazards to life are quite clear. The current approach to thousands of bridge cracks is to let the bridge fractures continue, perform inspections, and assume that fractures will be stopped in time, i.e., let the bridges break and fix them before they fall. Some people seem to think that this method works, and although this method has prevented serious accidents, the I-40 near-disaster crashes such an opinion into the trash.



Figure 24. 2021, I-40 Fatigue Crack Dimensions [36].

Now consider the actual problem – bridges crack due to grit blasting in preparation for coating application. An I-40 Bridge Inspector has been accused in press reports with respect to this near-disaster since a hazardous fracture was not detected. However, the root cause of the I-40 failure is probably related

to grit blasting, which invalidates designs when bridges are subjected to fatigue cycling. As hammered on over and over in this paper, grit blasting, fatigue, and brittle fracture require further research to clearly understand and safely solve the problem of thousands of bridge cracks, where the I-40 near-collapse is but one more in a torrential series of bridge fractures.

#### 11.5. An Attempt to Close the Gate to New Technology

The Editor of Structure Magazine refused to publish any form of this paper as a rebuttal to the claims made by Lloyd et al., and one of those authors<sup>8</sup> refused to respond as well. The Editor responded that “we cannot publish your article,” and that “it would be better ... to discuss these issues directly with the engineers at AISC”. Essentially, engineers from the American Society of Steel Construction complained about new research, and the original article by this author was later obscured on the Structure Magazine website. The article by Lloyd et al. is readily available by searching the Structure website, but the original article by this author is not. Effectively trying to censor this work is their prerogative, but the original article has been reprinted on the internet to counter their actions. Comments for this paper were requested but not received.

More importantly, deliberate actions attempted to stymie the free flow of sound new ideas to improve public safety. To improve public safety, a moral obligation demands that a stand be taken against the refusal to consider new ideas. If bridge safety problems are dismissed without consideration, the causes cannot be understood, bridge failures will continue to propagate, and lives will be at stake.



Figure 25. I-40 Short-term Bridge Repairs [36].

For the solution, research and subsequent actions can prevent bridge accidents and loss of life. For example, a mix of shot and grit may be a solution to some future bridge failures, such that coating adherence is improved and fatigue properties may be minimally affected for such a mixture. Even so, bridge inspections are a first defense, albeit problematic and dangerous as shown by the I-40 bridge failure. Inspections are one method to deal with engineering design defects, but the primary recommendation is to change the method of grit blasting and faulty design codes to minimize potential

<sup>8</sup> The Editor of Structure provided the email address for one of the three coauthors as the sole contact for these authors.

fatalities such defects in the future. At a minimum, the facts should be recognized that existing bridges may be unsafely designed, that previous safety analyses may be incorrect, and that future safety reports need to consider new theory.

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