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Fatigue Life and Fitness-for-Service Analysis: 32-foot Steel Deck Plate Girder Bridge Span at FAST

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Summary

Transportation Technology Center, Inc. (TTCI) recently installed two short, steel deck plate girder bridge spans at the Facility for Accelerated Service Testing (FAST) in Pueblo, Colorado. Both steel spans are secondhand, of riveted fabrication, and over 100 years old. Additionally, both are being loaded above their normal rated capacity by the FAST train. TTCI is using these spans to investigate life extension and life estimates for common steel spans as part of the Association of American Railroads' Strategic Research Initiative program.

Preliminary measurements and analysis of the 32-foot span indicate the following:

- Spans that are shorter than the inside axle spacing of the cars experience full unloading under each car; and thus full stress range cycles for each car making them more susceptible to fatigue.
- Estimated fatigue life based on strain gage measurements is almost three times longer than life estimated based only on simple theoretical calculations for the 32-foot span.
- Use of AREMA¹ fatigue rating recommendations implemented using guidance from the NSBA *Fatigue Primer*² can provide a much greater life estimate as compared to simple use of fatigue Category D.
- In an effort to provide better estimates of fatigue stress ranges with ease of computation, the use of zero impact and gross section properties provided evaluation stress ranges somewhat closer to measured values for this span.
- To date, this span has performed well with no maintenance required, no defects noted, and over 245 MGT of HAL traffic accumulated.

One of the primary goals of this research is to provide better estimates of steel bridge life to facilitate better planning for bridge capital and maintenance work. This *Technology Digest* is one in a series of fatigue life analyses for each of the four steel spans at FAST. Because of the different span lengths, designs, and track curvature conditions, each span must be analyzed somewhat differently.



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INTRODUCTION

TTCI recently installed two short, steel deck plate girder bridge spans at the Facility for Accelerated Service Testing (FAST). The secondhand, riveted steel spans replaced the two prestressed concrete, double-cell box girder spans in the conventional concrete bridge, now referred to as the West Steel Bridge (Figure 1). Canadian Pacific Railway donated a 33-foot span built in 1904 from near Fernie, British Columbia. This span was shortened by about 7 inches at each end to fit the opening at FAST. TTCI is using these spans to investigate improved life extension and life estimates for common steel bridge spans. The bridge is in a 5-degree curve with 4 inches of superelevation. The open deck spans are also superelevated by the same amount.



Figure 1. West Steel Bridge at FAST: 24-foot and 32-foot Riveted Deck Plate Girder Spans

Span Response and Performance

Both spans are being overloaded by the heavy axle load (HAL) train at FAST. The normal rating of the 32-foot span is Cooper E-54, provided by Canadian Pacific. The FAST train loading on the high rail girder of this span is E-72 at the normal operating speed. To date, this span has performed well with no maintenance required, no defects noted, and over 245 MGT of HAL traffic accumulated.

Figure 2 shows mid-span tension flange stress measured using strain gages under normal FAST train operations at 40 mph. The train on the day of these measurements consisted of 3 locomotives (6-axle) and 108 cars, with a total weight of 17,395 tons. A few of the cars near the end of the train were only loaded to 286,000 pounds, while most were loaded to 315,000 pounds. The measurements shown are for the south girder, or high rail girder, for each span.

Note that the stress goes down to 0 ksi between the lead and trail trucks of each car. This is expected as the span length is less than the inside axle spacing on the cars; so there is a brief period beneath each car when there are no axles on the span. Since fatigue is governed by stress range or magnitude of the stress cycles, these short spans can be more susceptible to fatigue as compared to longer spans that do not experience full unloading as the train traverses.

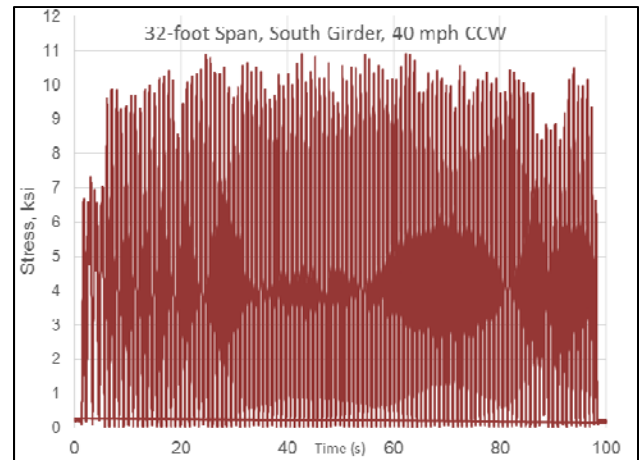


Figure 2. Tension Flange Stress at Mid-span of 32-foot Span under FAST Train Loading

Bridge Fatigue Life Estimates

The fatigue life of this span can be estimated in a number of ways. For short spans, with span length less than the inside axle spacing of the cars, the spans experience a complete loading and unloading cycle for each car that traverses the span. The FAST train consists primarily of 53-foot rotary dump cars with an inside axle spacing of about 34.5 feet. The effective span length (center to center of bearings) of this span is about 31 feet. For typical short steel girder spans, the governing cross section will be near mid span and bending moment will be the governing load.

Bridge fatigue life estimates are normally first made using theoretical calculations. The quick and simple calculations using basic load rating information are conservative. More detailed calculations taking full advantage of the AREMA rating provisions can provide a better estimate. Where actual strain gage data is available, it provides a more accurate estimate of fatigue life for a particular structure.¹ Several fatigue life estimates will be demonstrated using both theoretical and measured stress ranges. Past traffic history is also necessary to determine the remaining life of a bridge; that subject will be addressed in a future document.

Life Estimate Based on Theoretical Calculated Stress Range

To begin a fatigue life estimate for a short steel span, it is necessary to use a loading that is as close as possible to the actual loading. The Cooper design load is not appropriate for a fatigue rating. It does not provide the same fatigue stress range as revenue traffic. For the FAST spans, the loading used is a train of 53-foot rotary dump cars (72-inch axle spacing, 40.5-foot truck centers) with a gross rail load of 315,000 pounds. (Note: for a typical 53-foot, 286,000-pound rotary dump car, the axle spacing is 70 inches with the same truck centers.)

The maximum bending moment from this loading is increased to account for impact. The design impact is computed and reduced for the normal train operating speed of 40 mph at FAST. The bending moment is also adjusted for the effects of superelevation since this bridge is on a 5-degree curve with 4 inches of superelevation. Maximum stress is computed using the net section modulus of the girder. These calculations are all made in the same manner as is done for a load capacity rating.

For a fatigue life estimate, the amount of impact can be further reduced per Table 15-1-8 in the AREMA *Manual for Railway Engineering*.¹ Girder spans are calculated using 35 percent of the impact used for load capacity rating. This results in a reduced bending moment to use for calculating the stress range.

The stress range is the key number for further fatigue calculations. Dead load stresses are not considered in a fatigue life estimate. This makes the fatigue life estimation process relatively simple for these short spans at FAST. For short spans (spans that experience full unloading under each car), the stress range is simply equal to the maximum live load stress. And the number of load cycles per train will be approximately the same as the number of cars in the train, with a few miscellaneous cycles due to locomotives and end of train. The theoretical stress range under the HAL train is 13.85 ksi (net section stress, adjusted for fatigue impact and superelevation at 40 mph). For stress ranges above 9 ksi, AREMA¹ and the American Association of State Highway and Transportation Officials (AASHTO), per the National Steel Bridge Alliance (NSBA),² both recommend the same life estimation procedure for riveted spans, i.e., the standard Category D fatigue life (S-N) curve. Using fatigue Category D for riveted details, the fatigue life is estimated at 0.82 million cycles for the 32-foot span. This number corresponds to 130 MGT of HAL traffic for the 315,000-pound cars at FAST. This life estimate is likely acceptable only on lines carrying minimal amounts of traffic. National Cooperative Highway Research Program (NCHRP) Report 72 provides some guidance on evaluations at various probability levels.³ While the bridge will show an increase in estimated fatigue life, use of increased probabilities of fatigue carry increased risk and should be accompanied by an increased level of inspection.

Life Estimates Based on Measured Stress Range

One method AREMA suggests for improving a fatigue life estimate is to obtain more accurate stress range information by means of strain gage measurements under actual traffic. Comparison of the theoretical stress range above to the measured data in Figure 2 indicates that the measured stresses are considerably lower. Thus, use of the measured stress range should produce more acceptable life estimates for these spans.

As can be seen in Figure 2, the peak stresses vary from car to car. In order to use the data from a typical train pass, the cycles should be counted using a rain flow cycle counting method.² Figure 3 shows the distribution of the stress ranges. This distribution represents two passes of the FAST train, one in each direction, to provide a full representation of the traffic. However, constructing a representative distribution for a revenue service bridge carrying a variety of trains might require collecting data from more than just two trains.

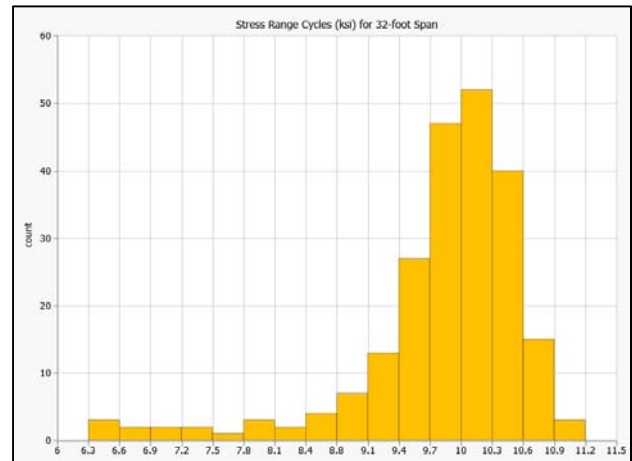


Figure 3. Stress Range Cycles for the FAST 32-foot Steel Span

Following AREMA guidelines, an equivalent stress range can be calculated using the root-mean-cube method.

For the 32-foot span, all the cycles are above 6 ksi, so all cycles should be included. The equivalent stress range for the 32-foot span is 9.85 ksi. This is significantly lower than the theoretical value of 13.85 ksi. At 9.85 ksi, the fatigue life estimate using Category D is 2.3 million cycles, or 355 MGT for the HAL train. This life estimate is about three times greater than the estimate based on simple theoretical calculations. However, it is likely still only acceptable for lower tonnage lines. Since this estimate is based on a simple Category D life curve, once again the provisions of NCHRP 721 regarding higher risk life estimates are applicable with the caveat that inspections are also increased accordingly. The provisions in NCHRP 721 regarding revised life estimates based on inspections with no cracks found are not recommended for riveted spans, as rivet heads hide small cracks.

The AREMA rating guidelines offer a further life increase for stress range cycles below 9 ksi. In that case, stress cycles can be compared against what is essentially a Category C fatigue life curve. In order to properly implement this AREMA provision, the cycles need be evaluated against different portions of the S-N curve using the Palmgren-Miner rule as described in the NSBA *Fatigue Primer*.² The equivalent stress range equation given in AREMA cannot be

used. Because there are so few stress range cycles below 9 ksi for this span, the resulting fatigue life estimate is improved only slightly, to 2.4 million cycles (368 MGT). However, if this AREMA provision is used, the NCHRP 721 provisions mentioned above are not applicable.

Possible Alternate Theoretical Stress Range for Fatigue Evaluation

The significant improvement in fatigue life estimate for this span using strain gage measurements suggests that there is tremendous potential benefit in developing an improved theoretical stress range calculation that would agree more closely with the measured values. AREMA has an alpha factor that attempted to serve this purpose at one time. It is noted that full impact does not occur on every cycle, and other factors also serve to reduce the stress range cycles. The factor was empirical, but at present is set to 1.0.

There are several possible factors contributing to measured stress range being less than that calculated using basic beam theory: 1) distribution of wheel loads by the rail and deck; 2) partial fixity of the bearings in translation and rotation; 3) partial section contribution from the rail and deck; 4) actual impact (due to smooth continuous welded rail) being less than that assumed; and 5) all components of the girders acting in unison. The first three factors require a detailed finite element model to estimate. A simplified approach is to use basic beam calculations but assume zero impact and gross section (rather than net section). The resulting stress range using zero impact and gross section (ZIGS) is 9.97 ksi, which compares well with the 9.85 ksi measured stress range above, and much less than the 13.85 ksi theoretical. Corresponding fatigue life is 2.2 million cycles (347 MGT). Figure 4 shows a comparison of the fatigue life estimates for the 32-foot span.

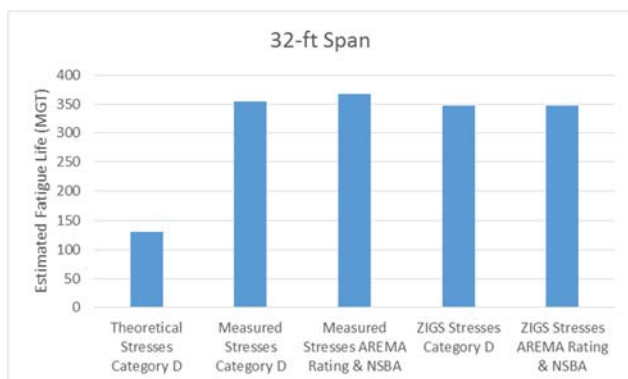


Figure 4. Comparison of Fatigue Life Estimates for FAST 32-foot Span Using Various Stress Cycle Ranges and Rating Provisions

The rating provisions discussed (simple Category D and AREMA Rating with NSBA implementation) are included.

CONCLUSIONS

TTCI has performed fatigue life estimates for two recently installed short, steel riveted deck plate girder bridge spans at FAST. Measurements and analysis of these spans indicate:

- Spans that are shorter than the inside axle spacing of the cars experience full unloading under each car; thus, full stress range cycles for each car making them more susceptible to fatigue.
- Estimated fatigue life based on strain gage measurements and AREMA fatigue rating recommendations implemented per NSBA is almost three times longer than life estimated based only on simple theoretical calculations for the 32-foot span.
- When calculating fatigue stress ranges, use of basic beam computations with zero impact and gross section properties provides evaluation stress ranges much closer to measured values for this span.

Further analysis and testing is needed to determine the effects of rating methods on spans of other lengths and spans subjected to different train loadings. Further analysis is also needed to estimated fatigue accumulation over the service history of various bridges.

Acknowledgements

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