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Fatigue Life and Fitness-for-Service Analysis: 24-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), 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 24-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 more than 20 times longer than life estimated based only on simple theoretical calculations for the 24-foot span.
- Use of AREMA[1] 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 basic beam calculations with zero impact and gross section properties provided 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 million gross tons (MGT) of heavy axle load (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.

INTRODUCTION

TTCI recently installed two short, steel deck plate girder (DPG) 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). A 24-foot span built in 1913 was donated by Norfolk Southern Railway (NS), from the former Norfolk and Western Railway Company near Salem, Virginia. 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- and 32-foot Riveted Deck Plate Girder Spans

Span Response and Performance

Both spans are being overloaded by the HAL train at FAST. The normal rating of the 24-foot span is Cooper E-69, as provided by NS. The FAST train loading on the high rail girder of this span is E-74 at the normal operating speed of 40 mph. To date, these spans have performed well with no maintenance required, no defects noted, and over 245 MGT of HAL traffic accumulated.

Figure 2 shows midspan tension flange stresses as measured using strain gages in the 24-foot span 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.

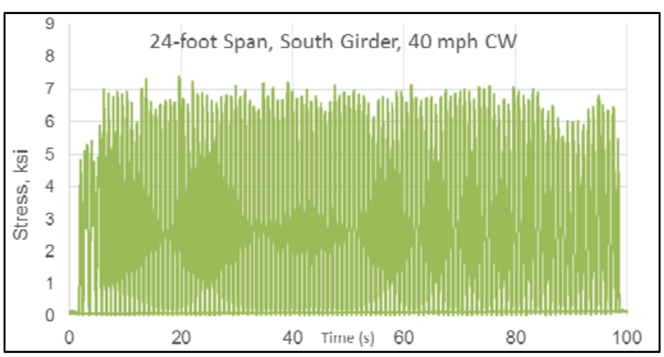

Figure 2. Tension Flange Stress at Midspan

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.

Bridge Fatigue Life Estimates

The fatigue life of this span can be estimated in a number of ways. As will be demonstrated, the life estimates can sometimes vary widely. 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 short girder span is about 21 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 for this span 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 Estimates 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, as it does not provide the same fatigue stress range as revenue traffic. For the FAST spans, the loading 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 10.96 ksi (net section stress, adjusted for fatigue impact and superelevation at 40 mph).

For stress ranges above 9 ksi, AREMA[1] 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, which is the standard Category D fatigue life (S-N) curve. Using fatigue Category D for riveted details, the fatigue life is estimated at 1.66 million cycles for the 24-foot span. This number corresponds to 261 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. For a main line carrying 50 MGT per year, this is just over five years. National Cooperative Highway Research Program (NCHRP) Report 721 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 ranges above to the measured data in Figure 2 indicates that the measured stresses are considerably lower. Thus, use of the measured stress ranges should produce more acceptable life estimates for this span.

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 distributions of the stress ranges for the 24-foot span. 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 would require collecting data from more than just two trains.

Following AREMA guidelines, an equivalent stress range can be calculated using the root-mean-cube method. AREMA recommends ignoring cycles below the fatigue limit (6 ksi for AREMA rating).[2]

Figure 3. Stress Range Cycles

For the 24-foot span, the majority of the cycles are above the fatigue limit (for AREMA rating) of 6 ksi. The equivalent stress ranges using the root-mean-cube method is 6.64 ksi (neglecting cycles less than 6 ksi). The corresponding fatigue life based on the Category D S-N curve is 7.5 million cycles (1,160 MGT). The Category D fatigue life estimate using the measured stress ranges is more than four times the theoretical life. 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 can hide small cracks.

For this 24-foot span, the measured stress range cycles are all below 9 ksi, so further options are available using the AREMA rating guidelines. For riveted spans with no stress range cycles above 9 ksi, Category C may be used. This essentially doubles the life to 15 million cycles (2,300 MGT), or about nine times greater than the estimate using theoretical stresses. If this AREMA provision is used, NCHRP 721 provisions mentioned above are not applicable.

The AREMA rating guidelines offer a further life increase if the rivet holes were drilled or reamed and the rivets are in tight condition. In this case, stress cycles less than 7.65 ksi can be compared against a fatigue life curve that extends out to 100 million cycles at 6 ksi. In order to properly implement this AREMA provision, the cycles must 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. While the computations are more extensive, the resulting fatigue life estimate using this provision is 36 million cycles (5,700 MGT), or more than 20 times the first simple estimate using theoretical stresses. For a 50 MGT per year mainline, this span would be expected to provide more than 100 years of service, carrying exclusively HAL traffic (all loads, no empties) based on this life estimate. Again, if this AREMA provision is used, the NCHRP 721 provisions mentioned above are not applicable because they apply only to a Category D evaluation.

Possible Alternate Theoretical Stress Range for Fatigue Evaluation

The significant improvements in fatigue life estimates using strain gage measurements suggest 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 it is currently defined as 1.0.

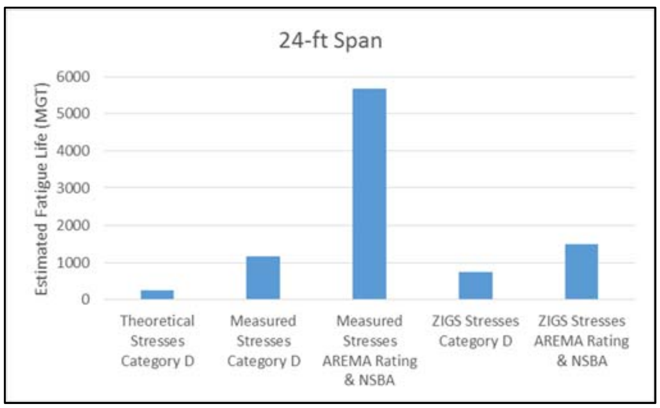

Figure 4. Comparison of Fatigue Life Estimates Using Various Stress Cycle Ranges and Rating Provisions

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 7.76 ksi. Corresponding Category D fatigue life is 4.7 million cycles (736 MGT). Using AREMA Rating with NSBA implementation, the fatigue life estimate is 9.5 million cycles (1500 MGT). Figure 4 shows a comparison of the fatigue life estimates.

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 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. This makes them more susceptible to fatigue.
- Estimated fatigue life based on strain gage measurements and AREMA fatigue rating recommendations implemented per NSBA is more than 20 times longer than life estimated based only on simple theoretical calculations for the 24-foot span.
- When calculating fatigue stress ranges, the use of basic beam computations with zero impact and gross section properties provides evaluation stress ranges 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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References:

1. American Railway Engineering and Maintenance of Way Association, *Manual for Railway Engine*ering, Chapter 15 – Steel Structures, Lanham, Maryland, 2015.
2. John W. Fisher, Geoffrey L. Kulak, and Ian F.C. Smith. *A Fatigue Primer for Structural Engineers*, National Steel Bridge Alliance, USA, 1998.
3. Mark D. Bowman, Gongkang Fu, Y. Edward Zhou, Robert J. Connor, and Amol A. Godbole. "Fatigue Evaluation of Steel Bridges," National Cooperative Highway Research Program, Report 721, Transportation Research Board, Washington, D.C., 2012.