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# Fatigue Life Analysis for 55.5-foot Steel Girder Bridge Span at FAST

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## Summary

Transportation Technology Center, Inc. (TTCI) has installed two intermediate length steel deck plate girder bridge spans in a steel bridge at the Facility for Accelerated Service Testing (FAST). Both steel spans were removed from revenue service and of riveted fabrication, and one of them is over 100 years old. Both spans are being loaded at or 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' (AAR) Strategic Research Initiatives (SRI) Program on bridge life extension.

Preliminary measurements and analysis of the 55.5-foot span indicates:

- Spans that are longer than the inside axle spacing of the cars, such as the intermediate length spans at FAST, do not experience full unloading under each car; thus, the stress range cycles for each car are less than the maximum stress. If this is properly accounted for, it can be of tremendous benefit in a fatigue life analysis.
- A simple fatigue life estimate based on theoretical maximum stress near midspan and one full loading and unloading cycle per car is only 268 million gross tons (MGT).
- Accounting for partial unloading cycles at the governing cover plate termination, the theoretical fatigue life estimated using American Railway Engineering and Maintenance of Way Association (AREMA) rating provisions[1] can be as high as 1,330 MGT.
- Estimated fatigue life based on strain gage measurements is essentially infinite for this 55.5-foot span.
- For spans of intermediate length or longer, fatigue life analysis should be performed not only at midspan, but also at cover plate termination locations to determine the governing stress range.
- The AREMA fatigue rating recommendations[1] can provide a much longer life estimate compared to simple use of the basic fatigue design Category D.
- Over 1,100 MGT of HAL traffic has been accumulated on this span in addition to 98 years of revenue service traffic.

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## INTRODUCTION

TTCI has installed two intermediate length steel deck plate girder bridge spans at FAST. The 55.5-foot span, built in 1912, was donated by Norfolk Southern. Figure 1 shows the span in the East Steel Bridge at FAST. It was installed in 2009 and has been described further in previous documents.[2]

**Figure 1. 55.5-foot Riveted Deck Plate Girder Span in the East Steel Bridge at FAST**

### Span Loading and Performance

The span is loaded at the full amount of its normal rated capacity by the HAL train at FAST. The normal rating of the 55.5-foot span is about Cooper E-61 when the rating is adjusted for corrosion. The FAST train loading on this span is also E-61. At ~1,100 MGT of HAL traffic thus far, the main girders of this span have performed well.

### Bridge Fatigue Life Estimates

The fatigue life of this span can be estimated in a number of ways, yielding varying results. Normally, bridge fatigue life estimates are first made using theoretical calculations. If the theoretical estimate comes up shorter than is desired, improvements in analysis and strain gage measurements of the bridge under traffic are options that can often lead to a longer estimated fatigue life.[1]

### Life Estimate Based on Theoretical Calculated Maximum Stress

The most expedient and conservative estimate, which will typically also yield the shortest estimated fatigue life, uses the maximum stress in the span, with one cycle per car and fatigue Category D. The FAST train consists primarily of 53-foot rotary dump cars with a truck axle spacing of 6 feet and a truck spacing of 40.5 feet. The loading from these cars is used for the fatigue life estimate. The Cooper E-80 design load is not appropriate.

The effective span length (center-to-center of bearings) of this girder span is about 54 feet. The maximum bending moment from the HAL train loading is increased to account for impact at the normal 40 mph train operating speed at FAST. Maximum stress is computed using the net section modulus of the girder. These calculations are all made in the same fashion as is done for a load capacity rating. For a fatigue life estimate for girder spans, take 35 percent of the impact used for load capacity rating.

The magnitude of the live load stress range is the most influential parameter for further fatigue calculations. For the most simple, conservative fatigue life estimate based on the design criteria, the stress range can be assumed to be equal to the maximum live load stress. Further, it is conservative to assume the number of load cycles produced per train to be the same as the number of cars plus locomotives in the train. The theoretical maximum stress near midspan under the HAL train is 10.87 ksi.

For stress ranges above 9 ksi, AREMA recommends the standard Category D fatigue life (S-N) curve.[1] The fatigue life is estimated at 1.7 million cycles for this 55.5-foot span. For the 315,000-pound cars at FAST, this number corresponds to only 268 MGT of HAL traffic.

Note that this span has already accumulated over 1,100 MGT at FAST, in addition to 98 years of prior revenue service traffic. This suggests that use of this simple fatigue life estimate might be overly conservative.

### Life Estimates Based on Theoretical Calculated Stress Range

For spans that do not experience full unloading under each car, the stress range for most of the load cycles is normally less than the maximum live load stress. Unlike maximum bending moment, which is always near midspan (for simply supported intermediate length bridge spans subjected to typical North American railroad loadings), the location of the maximum moment range can vary considerably depending on car length and span length.[3] A further complication is the consideration of the partial length cover plates commonly found in riveted railroad girders. The resulting variation in girder cross section properties must also be taken into account when computing stress range for a fatigue life analysis.

Figure 2 shows the theoretical stress range along the tension flange of the 55.5-foot girder. This figure was generated by computing maximum and minimum bending moments at many locations along the girder due to several 53-foot HAL cars traversing the span, neglecting end of train effects. The moment range is calculated as the difference between maximum and minimum moments. The stress range at each location is computed using the section modulus at that location. The locations of the cover plate terminations (8 feet and 15 feet) can be seen in the figure. The maximum stress range for the HAL cars on this span is 6.92 ksi at the short cover plate termination (15 feet). Adjusting the stress range to account for fatigue impact gives 7.98 ksi.

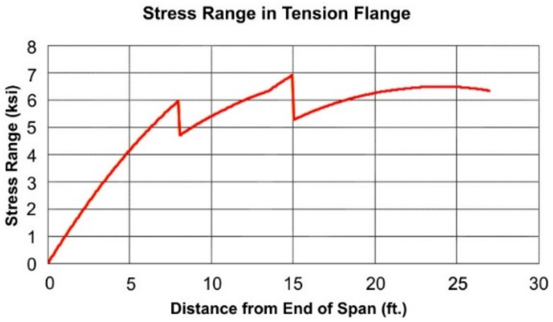

**Figure 2. Stress Range along Tension Flange of 55.5-foot Girder Span under 53-foot HAL Cars**

For a typical train traversing an intermediate length span, there is one cycle at the maximum stress range, and about one cycle per car at a reduced stress range. The total number of load cycles per train is approximately the same as the number of cars plus locomotives in the train.

For a typical pass of the FAST train, with three locomotives and 110 HAL cars, there will be 1 cycle at the maximum stress of 10.87 ksi, and about 112 cycles of 7.98 ksi at midspan. This is much less severe compared to assuming the maximum stress for all cycles. The equivalent stress range (root-mean-cube) for a Category D fatigue life analysis is 8.01 ksi. Category D fatigue life for this stress range is 4.2 million load cycles (670 MGT) of HAL traffic. While computation of the maximum stress range is more extensive, the resulting fatigue life estimate using this method is 2.5 times the estimate using theoretical midspan maximum stress.

Most of the stress range cycles for this 55.5-foot span are below 9 ksi, so a further option is available using the AREMA rating guidelines. For riveted spans and stress range cycles below 9 ksi, Category C may be used to determine the fatigue life for those cycles. Category D is still used for the one large cycle per train. 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.*[4] The equivalent stress range equation (root-mean-cube) given in AREMA cannot be used. The resulting fatigue life estimate using this provision is 8.4 million cycles (1,330 MGT), or about five times the estimate using theoretical maximum midspan stress.

AREMA Chapter 15 has a provision (7.3.2.2.d(2)) to allow continued operation of a span with equivalent stress range less than 9 ksi provided certain requirements are met for lateral bracing and frequency of inspection. In the case of this particular span, some lateral bracing components are significantly corroded, and some have cracked or broken. Some were intentionally left unrepaired for test purposes for a time. So this provision is not appropriate.

## Life Estimates Based on Measured Stress Range

One method for improving a fatigue life estimate is to use strain gage measurements under actual traffic. Comparison of the theoretical stresses and stress ranges noted above to the measured data in Figure 3 indicates that the measured stresses are considerably lower. Therefore, use of the measured stress ranges should produce increased life estimates for these spans.

Figure 3 shows midspan tension flange stresses in one of the girders as measured using strain gages in the 55.5-foot span under normal FAST train operations at 40 mph. The train on the day of these measurements had three locomotives (6-axle) and 108 cars, with a total weight of 17,395 tons. As predicted in the theoretical computations, the stress does not return completely to zero between the lead and trail trucks of each car. Since cycles below 6 ksi need not be included when using the AREMA rating method, Figure 3 shows that there is only one cycle (the entire train) that must be considered.

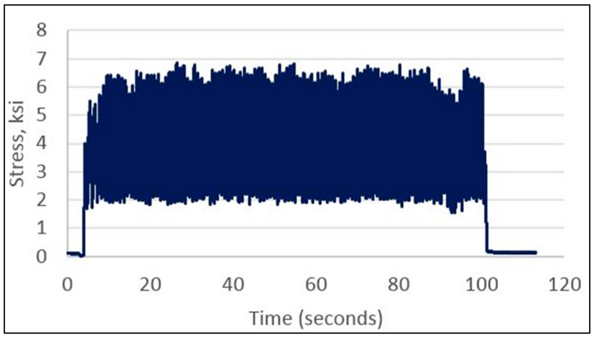

**Figure 3. Tension Flange Stress at Midspan of 55.5-foot Span under FAST Train Loading**

The magnitude of that cycle is the maximum recorded stress of 6.8 ksi. Based on the AREMA rating provisions, using Category C for a stress range less than 9 ksi, the number of cycles to failure is 14 million. With only one cycle per train, it would take over 250,000 MGT of the HAL train to accumulate this many cycles, which is essentially an infinite life. Furthermore, since this span was fabricated with reamed rivet holes, AREMA (Figure 15-9-11) allows an alternative life calculation, which gives about 30 million cycles to failure.

## Comparison of Fatigue Life Estimates

Vast 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 agrees more closely with the measured values. 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. Work is underway to develop improved methods to evaluate these effects for better bridge life estimates.

Comparison of the various stresses and stress ranges used in the above life estimates is shown in Figure 4. Note that both the use of stress range rather than midspan maximum and measured stresses rather than theoretical stresses lead to reductions which provide more favorable fatigue life estimates. Figure 5 shows a comparison.

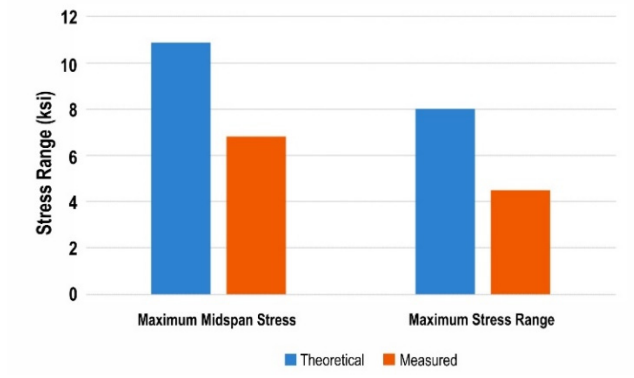

Figure 4. Stresses and Stress Ranges Used for Fatigue Life Estimates of 55.5-foot Girder Span

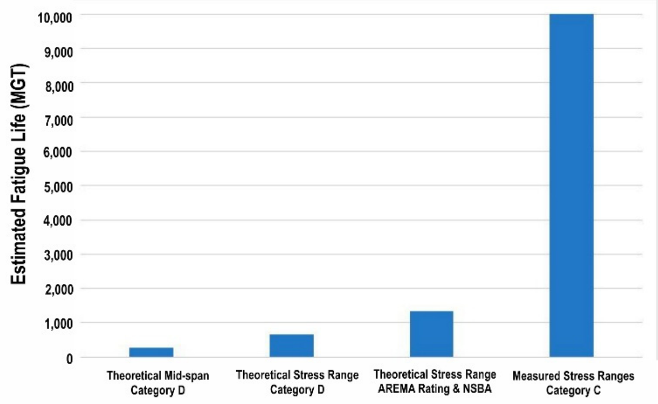

Figure 5. Comparison of Fatigue Life Estimates for FAST 55.5-foot Span using Various Stress Cycle Ranges and Rating Provisions (Bar to 10,000 MGT is truncated)

Included are the different stress ranges used (full cycles at midspan stress or use of maximum stress range with partial unloading for intermediate cycles), as well as stress estimation methods (theoretical per AREMA, or measured). Also included are the different rating provisions discussed (Category C, D, or AREMA Rating with NSBA implementation).

## CONCLUSIONS

TTCI has performed fatigue life estimates for the 55.5-foot span at FAST. Measurements and analysis indicate:

- For spans that do not experience full unloading under each car, stress range cycles for each car are less than the maximum stress. If this is properly accounted for, it can be of tremendous benefit in a fatigue life analysis.
- A simple fatigue life estimate based on theoretical maximum stress using design criteria near midspan is likely very conservative. The tonnage carried by this span at FAST (not including prior revenue service traffic) is already more than four times the estimated fatigue life.
- The theoretical fatigue life estimate using AREMA rating provisions is about five times higher than the simple midspan analysis for this span.
- Estimated fatigue life based on strain gage measurements is essentially infinite 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 estimate fatigue accumulation over the service history of various bridges.

## ACKNOWLEDGEMENTS

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