TTCI TECHNOLOGY DIGEST
TRANSPORTATION TECHNOLOGY CENTER, INC.
MAY 2021
TD21-010

Fitness-for-Service Analysis of 30-foot FAST Steel Span

Duane Otter, Anna M. Rakoczy, and David Linkowski

The research described was performed by Transportation Technology Center, Inc., a wholly owned subsidiary of the Association of American Railroads.

Key Findings:

- More than 567 MGT of HAL traffic has been accumulated on this span at FAST, and over 2,200 MGT in total including prior revenue service.
- A simple fatigue estimate, based on theoretical maximum live load stress near midspan and fatigue Category D, is only 260 MGT.
- Estimated service duration based on proposed adjustments to theoretical live load stress range is about 1,400 MGT.
- Estimated service duration, based on strain gage measurements, is about 3,700 MGT for this 30-foot span using the FAST train loading.
- A reliability analysis shows this span has a 50 percent chance of accumulating over 6,000 MGT before development of a detectable fatigue crack. This may be acceptable with an increased level of inspection.
- Further analysis and testing is needed to determine the effects of analysis methods on spans of other lengths and subject to different train loadings. Further analysis also is needed to estimate cycle accumulation over the service history of various bridges

TTCI is testing short- and intermediate-length, riveted steel deck plate girder (DPG) bridge spans. The spans were removed from revenue service and installed at the Facility for Accelerated Service Testing (FAST) where the spans are loaded at or above their normal rated capacity by the FAST train. TTCI is using these spans to investigate service duration estimates for common steel spans as part of the Association of American Railroads' (AAR) Strategic Research Initiatives (SRI) program on bridge life extension.

INTRODUCTION

In recent years, TTCI has installed short and intermediate length steel deck plate girder bridge spans at FAST. A 30-foot span, built in 1912, was donated by BNSF Railway in 2017. Figure 1 shows the span at FAST. Installation was completed in early 2018 and has been described elsewhere.[1] For the previous four decades, the span was subjected to significant unit coal train traffic, in addition to unit grain train traffic and mixed freight, typically accumulating 70 to 100 million gross tons (MGT) per year.

Figure 1. 30-foot riveted deck plate girder span at FAST

SPAN LOADING AND PERFORMANCE

The span is loaded about 18 percent above its normal rated capacity in bending by the heavy axle load (HAL) train at FAST. The normal rating of the 30-foot span in bending is Cooper E-61 with an open deck. The FAST train loading on this span is E-72 in bending at 40 mph on the 5-degree curve with 4 inches of superelevation. At more than 567 MGT of HAL traffic to date, this span has performed well with no fatigue-related defects noted.

BRIDGE SERVICE DURATION ESTIMATES

The service duration of this span can be estimated in a number of ways, yielding varying results. Normally, bridge service duration estimates are first made using conservative theoretical calculations. If the theoretical estimate is too conservative, improvements in analysis and strain gage measurements of the bridge under traffic are options that can often lead to a more accurate estimated service duration.[2] A reliability analysis can provide estimates for various probabilities of fatigue, which can be accompanied by increased level of inspection.

Service Duration Estimate based on Theoretical Calculated Maximum Stress

The most expedient and conservative estimate, which will typically also yield the shortest estimated service duration, uses the maximum live load stress in the span, with one cycle per car and fatigue Category D.[2] The FAST train consists primarily of 53-foot rotary-dump cars with a truck axle spacing of 6 feet and a truck center spacing of 40.5 feet. The cars are loaded to 315,000 pounds gross rail load. The loading from these cars is used for the service duration estimate. The Cooper E-80 design load is not appropriate for estimating service duration, as it does not simulate the actual loading in terms of fatigue cycles and stress ranges.

The effective span length (center-to-center of bearings) of this girder span is 29 feet. The live load stress is computed using the net section modulus of the girder and increased to account for impact at the normal 40-mph train operating speed at FAST. For fatigue design and service duration estimates for girder spans, American Railway Engineering and Maintenance-of-Way Association (AREMA) Chapter 15 bridge fatigue procedures recommend using 35 percent of the full design impact.[2]

The magnitude of the live load stress range (difference between maximum and minimum stresses under the axle load configuration of the train) is the most influential parameter for service duration calculations. For short spans that experience full unloading under each car, the stress range is simply equal to the maximum live load stress. For this 30-foot span, and cars with 34.5 feet between inside axles, the span experiences full unloading under each car that traverses the span.

For unit trains, the number of load cycles per train will be approximately the same as the number of cars in the train, with a few additional cycles due to locomotives and end of train. For this span, the theoretical maximum live load (including fatigue design impact) bending stress near midspan under the HAL train is 11.0 ksi on the high rail girder at the normal 40 mph train operating speed.

For stress ranges above 9 ksi, AREMA recommends the standard Category D fatigue (S-N) curve.[2] Service duration is estimated at 1.6 million cycles for this 30-foot span. For the 315,000-pound cars at FAST, this number corresponds to only 260 MGT of HAL traffic. With more than 567 MGT accumulated at FAST, in addition to decades of heavy haul traffic in revenue service, this estimate is less than the currently accumulated MGT.

Service Duration Estimate based on Recent Revisions to Theoretical Calculated Maximum Stress

Realizing that simple theoretical calculated live load stress values are typically higher than actual live load stresses from testing,[3,4] revised factors have been approved for use in 2021 in AREMA Chapter 15 for use in fatigue estimates for typical North American steel railway spans. Instead of using the fatigue design impact (35 percent of full design impact), a fatigue rating impact is suggested at 15 percent of full design impact. In addition, a factor of 0.85 is suggested to be applied to the live load stress range for typical riveted girders. Applying these factors, the maximum live load stress becomes 7.96 ksi. For stress ranges below 9 ksi, AREMA Chapter 15[2] allows the use of a Category C evaluation, resulting in a predicted duration of 8.8 million cycles, or about 1,400 MGT at FAST.

AREMA Chapter 15 has a provision (7.3.3.2.d(2)) to waive some fatigue requirements of a span with equivalent stress range less than 9 ksi provided certain conditions are met for lateral bracing and frequency of inspection. As this span has no bottom lateral bracing, this provision cannot be applied, and other methods should be considered to improve the service duration estimate.

Service Duration Estimates based on Strain Gage Measurements

One method for improving a service duration estimate is to use strain gage measurements under actual traffic. Comparison of the theoretical live load stresses noted above to the live load stresses calculated from measured strain data in Figure 2 indicates that the stresses from measured strains are somewhat lower. Therefore, use of the stress ranges from measured strains should produce an increased duration estimate for this span.

Figure 2 shows midspan tension flange stresses in the high rail girder calculated from strain gage measurements in the 30-foot span under normal FAST train operations at 40 mph. The FAST train normally has three locomotives (six-axle) and about 110 cars, with a total weight of over 17,000 tons.

The equivalent stress range calculated from the measured strains is 7.0 ksi. Based on the AREMA rating provisions, using the provision for stress ranges less than 7.65 ksi, the number of cycles to crack initiation is over 23 million. With one cycle per car of the FAST train, which translates to about 3,700 MGT of HAL traffic.

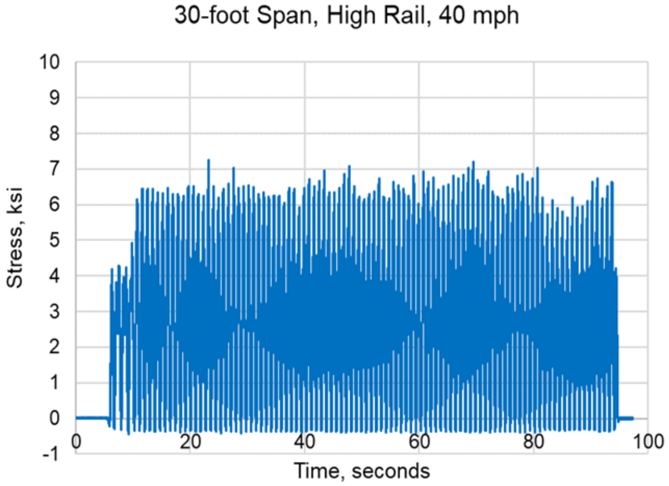

Figure 2. Tension flange live load stress at midspan of 30-foot span under FAST train loading

To provide an estimate of remaining service duration, BNSF provided tonnage records for nearly 20 years of traffic traversing the span. Tonnage for the prior years was estimated based on the provided data, the time period for transitioning from 263,000-pound cars to 286,000-pound cars, and the approximate date for the introduction of unit coal traffic on the line. It is estimated that the span accumulated more than 1,700 MGT of loaded unit train traffic in revenue service before being relocated to FAST.

Comparison of the duration estimates using both previous and new AREMA calculations suggests that the new AREMA calculations are more reflective of actual bridge performance. They account for differences between the infrequent but high load cases that must be considered for design, and the common span behavior for the millions of cycles that contribute to fatigue. Some of the possible factors contributing to lower stress ranges for the vast number of cycles might include: 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 for design; 5) all components of the built-up girders acting in unison; and 6) effective span length.

Service Duration Estimates Using Reliability Analysis

Although the new AREMA calculations are an improvement, a reliability analysis provides a more complete picture of the possible service duration for a bridge span because it provides estimates for various probabilities of detectable crack formation.[5] In order to maintain the same level of risk, use of higher probabilities should be accompanied by increased frequency of inspection.

Based on the available information for previous revenue service traffic, TTCI engineers estimated the span accumulated roughly 812 MGT of 263,000-pound car traffic and 920 MGT of 286,000-pound car traffic. Scaling the stress levels from measurements at FAST to tangent track conditions for the revenue service loadings, the live load stress levels in revenue service were estimated to be 5.54 ksi and 6.05 ksi for the 263,000-pound and 286,000-pound traffic, respectively. The FAST train loading on the high rail girder produces effective stresses of 7.0 ksi. The total tonnage accumulated at FAST is about 567 MGT. Table 1 summarizes the estimated history of loaded unit train traffic for this span.

Table 1. Estimated unit train load history for FAST 30-foot riveted Steel DPG span

Load history	MGT	Car weight	Effective Stress Range, ksi
~ 26 years	812	263 kips	5.54
~ 19 years	920	286 kips	6.05
FAST	567	315 kips	6.98

Figure 3 shows the results of the reliability analysis for this span based on the estimated load history and statistical parameters of fatigue resistance.[5]

At the current unit train tonnage of about 2,200 MGT, the analysis shows about a 5 percent chance of developing a detectable fatigue crack. At the 16 percent and 32 percent evaluation levels,[6] the tonnages are about 3,300 and 4,900 MGT, respectively. At 6,000 MGT, there is less than a 50 percent chance of a detectable fatigue crack. Although a detectable crack does not mean a failure of the structure, increased inspection frequency is recommended in conjunction with the higher probability levels.

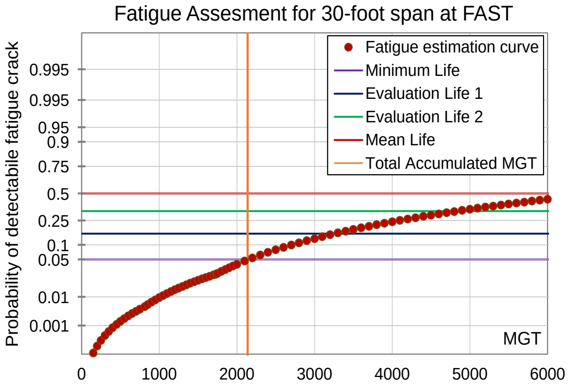

Figure 3. Comparison of fatigue duration estimates for FAST 30-foot span

COMPARISON OF SERVICE DURATION ESTIMATES

Figure 4 shows a comparison of the various duration estimates. Note that the use of the new AREMA refinements, strain gage measurements, and reliability analysis all offer longer duration estimates as compared to the current simple theoretical computation.

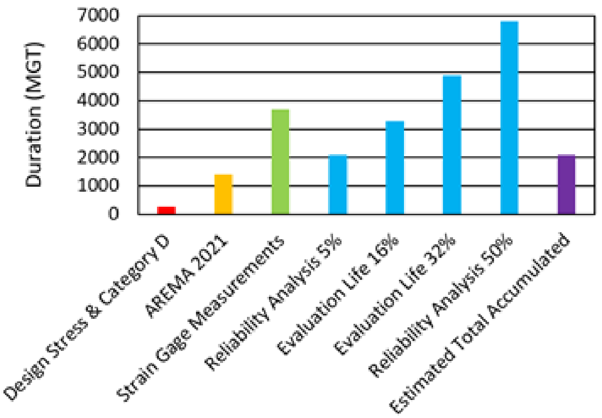

Figure 4. Comparison of fatigue duration estimates for FAST 30-foot span using various methods

For comparison, also note the estimated total unit train tonnage over the span, which includes significant traffic from 263,000- and 286,000-pound cars. Given the tonnage accumulated to date, the new methods all seem to offer the possibility of more realistic fatigue duration estimates.

CONCLUSIONS

TTCI has performed service duration estimates for a 30-foot span at FAST. Measurements and analyses indicate:

- A simple fatigue duration estimate based on theoretical maximum live load stress using design criteria near midspan is extremely conservative. The tonnage carried by this span at FAST already is more than 2.1 times the estimated duration using this conservative method.
- Estimated fatigue duration based on proposed guidelines is about 1,400 MGT at FAST for this span, still below the estimated 2,200 MGT this span has carried.
- Estimated service duration based on strain gage measurements is about 3,700 MGT at FAST for this span.
- Reliability analysis shows that the span currently has about a 5 percent probability of a detectable fatigue crack with 2,200 MGT of total unit train traffic. At 6,000 MGT, the span will have less than a 50 percent chance of having a detectable fatigue crack.

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

ACKNOWLEDGMENT

The authors wish to thank BNSF Railway for their donation of the span and the traffic records.

References

1. Otter, D., September 2019, “Steel Railway Bridge Test Update from FAST.” *Railway Track & Structures*, Vol. 115, No. 9, pp. 6-11, Chicago, IL.
2. American Railway Engineering and Maintenance of Way Association. 2021. *Manual for Railway Engineering*, Chapter 15, “Steel Structures.” Lanham, MD.
3. Sweeney, R., July 2018, “Factors Derived from Tests for Fatigue Evaluation of Typical North American Steel Railway Bridge,” ASCE *Journal of Bridge Engineering*, Vol. 23, Issue 7, Reston, VA.
4. Rakoczy, A., D. Otter, S. Dick and D. Linkowski. May 2019, “Calculated versus Measured Stresses for Typical Steel Girder Railway Bridges.” *Technology Digest* TD19-001, TTCI/AAR, Pueblo, CO.
5. Rakoczy, A. M., Otter, D. E., and Dick, S., “Railroad Bridge Fatigue Life Estimation Using the Probabilistic Method and New Fatigue Resistance for Riveted Details,” AAR Report R-1027, TTCI/AAR, Pueblo, CO.
6. Bowman, Mark D., et al., 2012, “Fatigue Evaluation of Steel Bridges,” National Cooperative Highway Research Program, Report 721, Transportation Research Board, Washington, DC.

For questions about this publication,
contact Duane_Otter@aar.com