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# Steel Bridge Fatigue Life Estimate Using Probabilistic Method – Part 2

Anna M. Rakoczy, Duane Otter, and Stephen Dick

## Summary

Transportation Technology Center, Inc. (TTCI) is testing five riveted steel girder railway bridge spans for fatigue and safe service life performance at the Facility for Accelerated Service Testing (FAST), located at the Transportation Technology Center (TTC) in Pueblo, CO. These bridges carry approximately 150 MGT per year of heavy axle load (HAL) traffic. TTCI is using these bridges to investigate improved safe service life estimates for common steel railway bridge spans. This *Technology Digest* presents fatigue life estimation using a probabilistic method and statistical parameters for fatigue resistance based on data collected specifically from riveted girders. This method can be used when a higher probability of crack initiation is accepted, with the condition that inspection efforts must be increased accordingly. This method can provide additional information about the life of a bridge that may allow a bridge to be used in revenue service two to three times longer with appropriate inspections.

- By using a probabilistic method, the number of load cycles or accumulated traffic is estimated in terms of probability of fatigue crack initiation. Inspections should be scheduled more often if a bridge member approaches a higher probability of crack development.
- Rather than using standard fatigue categories, the proposed method uses test data specifically from full-size riveted girders, which in some cases allows longer life estimates in the stress ranges experienced by many railroad spans.
- Results from the proposed probabilistic method show that the 24-foot span at FAST has less than 1 percent probability of fatigue crack initiation with 476 MGT of HAL traffic accumulated, and the mean life will likely be reached at about 9,000 MGT, i.e., after more than 50 years of FAST operation.
- The new resistance parameters provide confirmation that for lower stress ranges, riveted steel bridges are closer to the performance of fatigue Category C than that of fatigue Category D. Using Category D for fatigue life estimates can be conservative.

For better use of the probabilistic method on revenue service bridges, it is recommended to develop statistical parameters for load spectra. Related research focused on developing statistical parameters for load distributions of typical unit trains and mixed freight operations.<sup>1</sup> This research is being conducted as part of the Association of American Railroads' (AAR) Strategic Research Initiative (SRI) on bridge life extension.



**INTRODUCTION**

Current bridge fatigue life evaluation procedures do not account for the considerable degree of uncertainty in load and fatigue resistance of bridges. Simplified calculations can lead to significant reductions in estimated life. Many methods for fatigue life evaluation have a low probability of fracture. That means, even if a bridge reaches the estimated fatigue life, the structure is likely to be fit for future service with more frequent inspection.<sup>2</sup> Life estimates can be assessed more accurately using probabilistic methods that provide fatigue life in terms of probability of crack initiation. This method can be used when a higher probability of crack initiation is accepted, with the condition that inspection efforts must be increased accordingly. For minimum life estimate, and stress ranges from 6 ksi to 7.65 ksi with sub-punched and reamed or drilled holes the proposed probabilistic method is more conservative than current AREMA guidelines.

By using a probabilistic method, the number of cycles or accumulated traffic is estimated in terms of probability of fatigue crack initiation. A fatigue life estimate is contingent on the applied load and the fatigue category; which, in turn, depends on member type and its connections. Inspections should be scheduled more often as a bridge member approaches a higher probability of crack initiation. The reliability analysis can also be used for estimating predicted years of service life (or MGT) of a bridge with different levels of safety. This method is demonstrated on a 24-foot riveted deck plate girder (DPG) span located at FAST. The description of the span and fatigue life estimate using traditional deterministic methods are published in a previous digest.<sup>3</sup>

**LITERATURE REVIEW**

The current evaluation procedure does not account for the considerable degree of uncertainty in load and resistance that have a significant influence on the fatigue life evaluation. NCHRP Report 721<sup>4</sup> indicates that a larger amount of uncertainty is involved in fatigue evaluations as compared to bridge strength evaluations or load ratings. The sources of uncertainty in the fatigue evaluation process include the scattered nature of the S-N curves, variable loads including site-to-site variations, and approximations in structural analysis or load effect estimation. Inherent uncertainties, however, can be reduced using more refined analyses or field measurements to better define the stress range at the details in question.<sup>4</sup> In addition, the use of probabilistic methods is recommended to determine the level of safety for various evaluation cases.

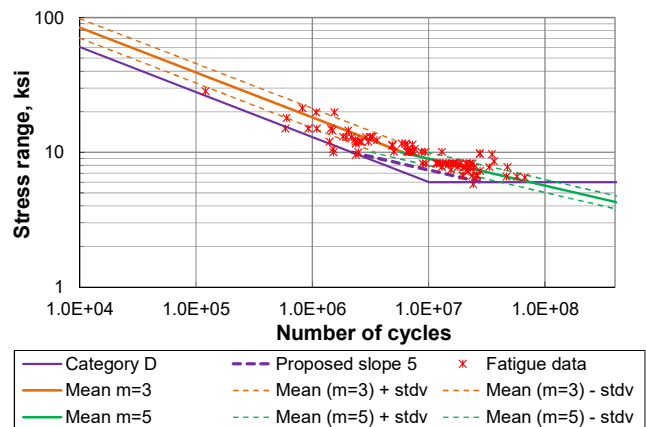
NCHRP Report 721<sup>4</sup> provides guidance on evaluations at four levels of finite fatigue life for estimation:

1. Minimum expected fatigue life (conservative design fatigue life, 5 percent probability of crack initiation)
2. Evaluation Life 1 (conservative fatigue life for evaluation, 15.9 percent probability of crack initiation)
3. Evaluation Life 2 (safety level that corresponds to a probability of crack initiation of 32.9 percent)
4. Mean fatigue life (the most likely fatigue life, 50 percent probability of crack initiation)

While a bridge will show an increase in estimated fatigue life, use of higher probabilities of fatigue initiation carries greater risk and should be accompanied by more frequent inspections.

**UNCERTAINTY IN FATIGUE RESISTANCE**

NCHRP Report 721 refers to the standard fatigue categories C and D, which cover a variety of steel connection details. For better fatigue life estimates, data from full-scale riveted bridge girders was gathered to evaluate fatigue resistance of riveted details. A plot of the selected fatigue test data (Figure 1) reveals that the data follows two trends. The data points below a stress range of about 9 to 10 ksi have a different distribution than data points above. Details about the data and the process of developing the statistical parameters is described in an AAR research report.<sup>5</sup>



**Figure 1. Two-slope S-N Curve**

TTCI developed a two-sloped S-N curve based on research done by Zhou (1994)<sup>6</sup> and a recommendation used in Eurocode.<sup>7</sup> The first part of the curve, for stress range above 10 ksi, is taken with a slope of 3, as is common; the second part of the curve, from 10 ksi to 6 ksi, is assumed to have a slope of 5, similar to Eurocode. The fatigue limit is taken to be 6 ksi, as in most current recommended practices. Equation 1 is used to estimate the expected number of cycles:

$$N = \frac{A}{S_{eff}^m} \tag{1}$$

where  $N$  = number of cycles to failure,  $A$  = fatigue constant,  $S_{eff}$  equivalent stresses, and  $m$  = the slope of the log-log curve again determined by fitting.

Based on the data presented in Figure 1 and Equation 1, TTCI developed improved statistical parameters for fatigue resistance for riveted members and connections. The parameters are listed in Table 1 and graphically presented in Figure 1.

**Table 1. Statistical parameters for riveted members**

Slope	Mean N	Mean A	Variation
$m=3, \sigma > 10\text{ksi}$	$N = 1815^3 \cdot S^{-3}$	$60 \times 10^8$	15.2%
$m=5, \sigma \leq 10\text{ksi}$	$N = 225^5 \cdot S^{-5}$	$58 \times 10^8$	15.3%

The parameters derived in this section were used to calculate the probability of crack initiation for the 24-foot DPG span at FAST.

**UNCERTAINTY IN LOAD SPECTRA**

The 24-foot span was originally located near Salem, Virginia, on the Norfolk & Western Railway (N&W). It is assumed that the bridge was located on the eastbound track that carried the coal loads to Roanoke and Norfolk.

Prior to about 1960, stresses due to steam locomotives were the only ones that clearly exceeded the 6 ksi threshold. N&W used the Y class of steam locomotives over this territory. Static weight per driver was 65,360 pounds on a 2-8-8-2 wheel arrangement with six-axle tender.

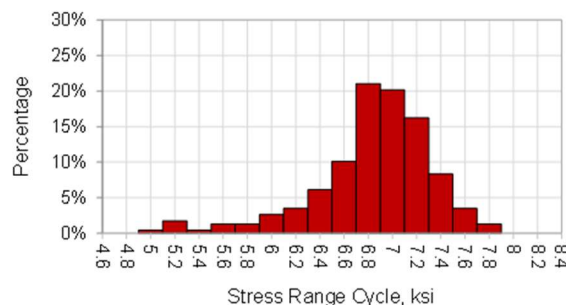
The total tonnage accumulated during revenue service operations was about 1,000 MGT, but it corresponds to a very small amount of fatigue accumulation. After the 1960 merger with the Virginian, most of the loaded coal traffic was diverted from this bridge. After that time, very few significant fatigue cycles were accumulated on this span in revenue service.

The FAST train loading on the high rail girder of 24-foot span is E-74 at the normal operating speed of 40 mph. To date, the span has performed well; no maintenance has been required and no defects have been noted during the 476 MGT of HAL traffic accumulated.

The 24-foot span unloads completely (stress goes down to zero) between the lead and trail trucks of each car, and the peak stresses vary from car to car. The example of mid-span tension flange stresses as measured using strain gages in the south girder or high rail girder of the span under normal FAST train operations can be found in a previous publication.<sup>3</sup>

In order to use the data from a typical train pass, the cycles should be counted using a rain flow cycle counting method.<sup>8</sup> The distribution of the stress ranges is shown in Figure 2. This distribution represents two passes of the

FAST train, one in each direction (clockwise and counterclockwise), to provide a full representation of the traffic. The average equivalent stress range for the 24-foot span is 6.5 ksi for the south girder under the high rail. The variations in the equivalent stresses ( $S_{Qi}$ ) for the considered bridge are from 4 percent to 7 percent, and the cumulative distribution functions (CDFs) are close to the straight lines, which indicates a normal distribution.<sup>5</sup>



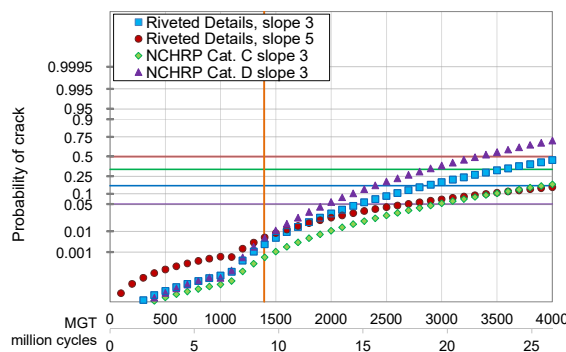
**Figure 2. Stress range cycles**

The variation in number of cycles ( $N_{Qi}$ ) is close to zero, since the unit train that operates at FAST is almost identical for each day of operation.

**FATIGUE EVALUATION USING PROBABILISTIC METHOD**

Probabilistic methods are the only approach for evaluation of bridge fatigue life that consider the uncertainties involved in load and resistance. The limit state function for fatigue of steel railway bridges was presented in the previous publications.<sup>9</sup>

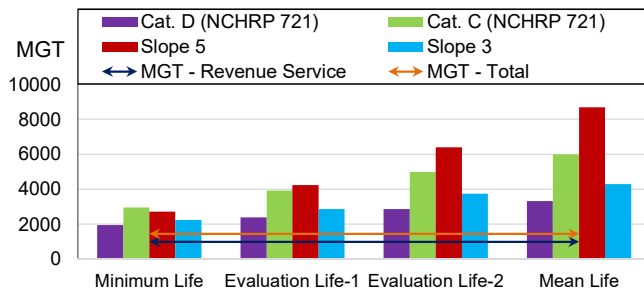
The probability of fatigue crack initiation depends on the statistical parameters of load and resistance. Figure 3 shows plots on a probability scale with four sets of statistics that were used to demonstrate how different parameters influence the results.



**Figure 3. Fatigue life estimates for FAST 24-foot span using probabilistic method**

The first two scenarios assume fatigue Category D and Category C based on the statistical parameters from NCHRP Report 721. The third scenario uses the proposed new statistics developed for the bilinear S-N curve for riveted girders.

The results show that the bridge span has less than 1 percent probability of fatigue crack initiation with the current traffic of at least 1,449 MGT for all four sets of statistical parameters. The minimum fatigue life with 5 percent probability of failure will be reached sometime between 2,000 and 3,000 MGT. Figure 4 shows the comparison of the probabilistic fatigue evaluations using different values for statistical parameters.



**Figure 4. Comparison of fatigue life estimates for FAST 24-foot span using probabilistic method and NCHRP Report 721 provisions**

Despite differences, all three sets of statistical parameters of fatigue give results of comparable magnitude in a range of 2,000–3,000 MGT for minimum life. A large increase in predicted fatigue life is noticed when the span is considered using the proposed new statistical parameters for riveted details with higher MGT. The slope of the red dotted line in Figure 3 decreases after 2,500 MGT. This can be an indication that the span has close to infinite fatigue life. This can be true since the equivalent stress range for the span under current operating conditions is only 6.5 ksi. This scenario doubles or triples the estimated span life for the same probability of crack initiation when compared to the scenario of fatigue Category D for the entire bridge life.

**CONCLUSION**

Use of fatigue life data specifically from full-scale girders, in conjunction with probability of failure, can provide the most versatile estimate of the remaining safe service life of a span. The service life estimate depends on the fatigue category and applied load for various levels of risk (probabilities of fatigue crack initiation). During the service life of a bridge, accumulated fatigue increases in time at different rates, depending on tonnage per year and train type. All these factors must be specified in order to obtain accurate results from the reliability analysis.

Using a probabilistic method, the number of cycles or accumulated traffic is estimated in terms of probability of

fatigue crack initiation. Inspections should be scheduled more often as a bridge member approaches a higher probability of crack initiation. The reliability analysis can also be used for estimating predicted years of service life (or MGT) of a bridge with different levels of safety.

To date, the 24-foot span at FAST has performed well with no maintenance required, no defects noted, and total accumulated MGT of 1,449, with over 476 MGT of HAL traffic. This level of traffic corresponds to less than 1 percent probability of crack initiation. New statistical parameters for riveted details and full-size riveted girders provided better estimation of fatigue life. For the considered span, the mean life will likely be reached at about 9,000 MGT or after more than 50 years of FAST operation.

It is recommended that a probabilistic method be used for a steel riveted span when a higher probability of crack initiation is accepted, with the condition that inspection efforts must be increased accordingly. In particular, it is advised that the probabilistic method be used for steel spans that have exceeded their calculated fatigue life, but show no signs of deterioration and fatigue cracks are not present.

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