

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

Steel Bridge Fatigue Life Estimate Using Probabilistic Method

Anna M. Rakoczy, Ph.D. and Duane Otter, Ph.D., P.E.

Summary

Transportation Technology Center, Inc. (TTCI) is testing four riveted steel girder railway bridge spans located at the Facility for Accelerated Service Testing (FAST) for fatigue and safe service life performance. 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 riveted steel railway bridge spans. This *Technology Digest* presents fatigue life estimation using a probabilistic method. This method can be used when a higher probability of crack initiation is accepted, understanding that inspection efforts must be increased accordingly.

- By using a probabilistic method, the number of cycles or accumulated traffic is estimated in terms of probability of fatigue crack initiation. Inspection should be scheduled more often if a bridge member approaches a higher probability of crack development.
- A fatigue life estimate depends on the applied load and the fatigue category, which depends on member type and its connections.
- Probability of fatigue crack initiation depends on the selection of values of statistical parameters representing a relevant fatigue category.
- Results using a probabilistic method show the 32-foot span at FAST has greater than 97 percent probability of fatigue crack initiation with 1,950 MGT of accumulated traffic when considered as fatigue Category D, but only about 10–20 percent probability if considered as fatigue Category C.
- A large increase in predicted fatigue life is noticed when the span was considered to be in Category C as compared to be in Category D. This scenario doubled or sometimes tripled the estimated span life for the same probability of crack initiation when compared to fatigue Category D.

For better use of the probabilistic method, it is recommended to develop statistical parameters for a particular detail of a bridge, such as riveted girders only. Future research will be focused on developing statistical parameters for fatigue resistance of riveted details. This research is being conducted as part of the AAR's Strategic Research Initiative on bridge life extension.



INTRODUCTION

Estimation of fatigue life is sometimes used when making decisions regarding bridge upgrades or span replacement. While load capacity and results of periodic inspections are typically primary concerns for bridge capital and maintenance planning, fatigue life is sometimes a factor as well. However, it can be challenging to obtain a reasonable fatigue life estimate. Simplified calculations can lead to significant reductions in estimated life. Many methods for fatigue life evaluation have 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.¹ The best estimates are obtained when measured stresses are used. In addition, life estimates can be assessed 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, understanding that inspection efforts must be increased accordingly.

A probabilistic method is presented using statistical parameters available from the literature. This method is demonstrated on a 32-foot riveted deck plate girder span located at the Facility for Accelerated Service Testing (FAST) at the Transportation Technology Center (TTC) near Pueblo, Colorado. The description of the span and fatigue life estimate using traditional deterministic methods are published in a previous digest.²

LITERATURE REVIEW

The current evaluation procedure does not account for the considerable degree of uncertainty in load and resistance. The fatigue limit and the uncertainty in the model have a significant influence on the fatigue life evaluation. NCHRP 721³ 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 significant 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.³ Therefore, it is recommended to use probabilistic methods to determine the level of safety for various design cases.

NCHRP Report 721 provides guidance on evaluations at various probability levels.³ Four levels of finite fatigue life for estimation are:

- Minimum expected fatigue life (which equals the conservative design fatigue life)
- Evaluation Life 1 (which equals a conservative fatigue life for evaluation)
- Evaluation Life 2 (safety level that corresponds to a probability of crack initiation of 32.9 percent)
- Mean fatigue life (which equals the most likely fatigue life)

The probability of crack initiation associated with each level of fatigue life is 5, 15.9, 32.9, and 50 percent for the Minimum, Evaluation Life 1, Evaluation Life 2, and Mean fatigue lives, respectively. The desired fatigue life estimate is obtained by multiplying the resistance factor R_R by a detail category constant. While a bridge will show an increase in estimated fatigue life, use of higher probabilities of fatigue initiation carry greater risk and should be accompanied by more frequent inspections.

UNCERTAINTY IN FATIGUE RESISTANCE

S-N curves present the number of cycles to failure as a function of constant stress ranges for different categories of details. Design guidelines provide several S-N curves for categories of welded and riveted connections. S-N curves are developed based on a lower bound to a large number of full-scale fatigue test data with a 97.5 percent survival limit. Therefore, an optimally designed detail according to S-N curves and actually exposed to the design stress ranges has a 2.5 percent probability of cracking during the specified lifetime.

S-N fatigue data results obtained in a laboratory do not always represent actual conditions and often contain a considerable degree of variation, even for carefully machined standard specimens out of the same lot of material. Figure 1 shows results of the fatigue Category D laboratory specimens tested with a constant-amplitude stress range. The plots were developed based on the available fatigue data.^{4,5}

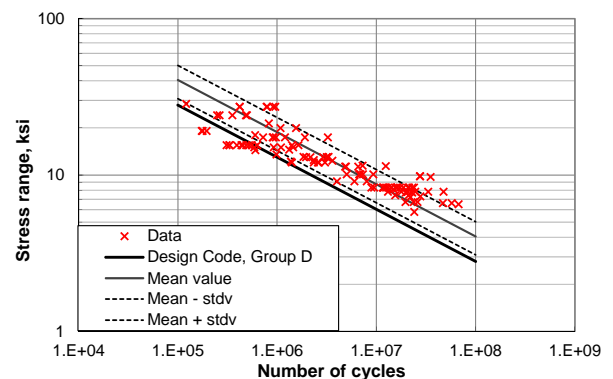


Figure 1. S-N data for Fatigue Category D

The scattered nature of S-N curves is one of the factors that influences uncertainty of fatigue life estimates. In this situation, fatigue resistance should be considered as a random variable (i.e., the variation about the mean value is normally distributed).

Table 1 shows statistical parameters for fatigue category D based on NCHRP 721,³ SHRP 19B,⁶ and a report by Rakoczy and Nowak.⁷ Values of these statistical parameters vary among different sources, which is related to the samples used for the analysis. Most likely the data in Table 1 was developed for welded and riveted details taken all together. For better use of the probabilistic method, it is recommended to develop statistical parameters for a particular detail instead of using all available data.

Table 1. Statistical Parameters for Fatigue Category D Based on NCHRP 721

Detail Category	NCHRP Report 721		SHRP 19B (Table 6.35)		Rakoczy (2012)	
	Mean Fatigue A x 10 ⁸	V, %	Mean Fatigue A x 10 ⁸	V, %	Mean Fatigue A x 10 ⁸	V, %
A	725.0	22	724	24	744	20
B	240.0	14	291	22	265	14
B'	115.9	13	127	11	119	11
C	92.4	15	108	21	143	20
C'	92.4	15	108	21	86	18
D	44.0	14	56	10	59	14
E	17.6	10	18	12	17	12
E'	7.4	13	15	20	15	21

FATIGUE EVALUATION USING PROBABILISTIC METHOD

Probabilistic methods are the only approach for evaluation of bridge fatigue life with consideration of the uncertainties involved in load and resistance. The limit state function for fatigue of steel railway bridges can be expressed in terms of the accumulated fatigue ratio, as seen in Equation 1, where S_{Ri} and N_{Ri} are the equivalent stress and number of cycles representing the design criteria; S_{Qi} and N_{Qi} are the equivalent stress and number of cycles due to live load.⁸

$$D = \frac{\sqrt[3]{\sum_i S_{Qi}^3 \cdot N_{Qi}}}{\sqrt[3]{\sum_i S_{Ri}^3 \cdot N_{Ri}}} \leq 1 \tag{1}$$

Once the statistical parameters of load and resistance are quantified, the reliability index can be calculated using Equation 2, which later can be converted to the probability of crack initiation:

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}} \tag{2}$$

where μ_R and μ_Q are mean values of resistance and load respectively, and σ_R and σ_Q are standard deviations. The accumulated fatigue ratio is a function of two parameters: effective stress, S , and number of cycles, N . However, when analyzing a particular detail in a bridge, the equivalent stresses are on the same level for a given load type. The variability in stresses is only related to the axle load. But the major time variation is involved in N , number of cycles to failure. Therefore, in the developed reliability analysis procedure, only N is treated as a variable in time and S is treated as a constant value.

The relevant fatigue detail category depends on complexity of geometry and stress concentration. Riveted details are usually fatigue Category D, which may include punched holes and not all rivets completely tight. For riveted spans with drilled or reamed holes and tight rivets, behavior close to fatigue Category C has been noted, as per AREMA Chapter 15.⁹

The 32-foot span at FAST has reamed holes, according to the original drawing, and the stress level in revenue service was below 9 ksi based on the records provided by the previous owner. Therefore, two scenarios were considered for this span. The first scenario assumes fatigue Category D for the entire bridge life. The second scenario assumes fatigue Category C. The lower stress levels in revenue service are related to the lower axle loads of the traffic and the bridge location in tangent track with no unbalanced curving loads (see Table 2).

Table 2. Load History

Load History	Accumulated MGT	Car Type	Equivalent Stress, ksi
Revenue Service	900 MGT	263 kip	7.10
Revenue Service	800 MGT	286 kip	7.72
FAST Operations	250 MGT	315 kip	9.85

The probability of fatigue crack initiation depends on statistical parameters for resistance. Figure 2 shows plots on a probability scale of three sets of statistics that were used to demonstrate how different parameters influence the results.

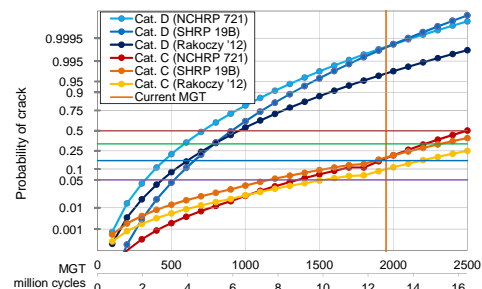


Figure 2. Fatigue Life Estimates for FAST 32-foot Span Using Probabilistic Method

Figure 3 shows the comparison of the probabilistic fatigue evaluation using different values for statistical parameters. The results show that the bridge span has greater than 97 percent probability of fatigue crack initiation with the current traffic of at least 1,950 MGT when considered as Category D, but only between 10–20 percent probability if considered as Category C. The Minimum Fatigue Life with 5 percent probability of failure was reached sometime between 1,284–1,500 MGT.

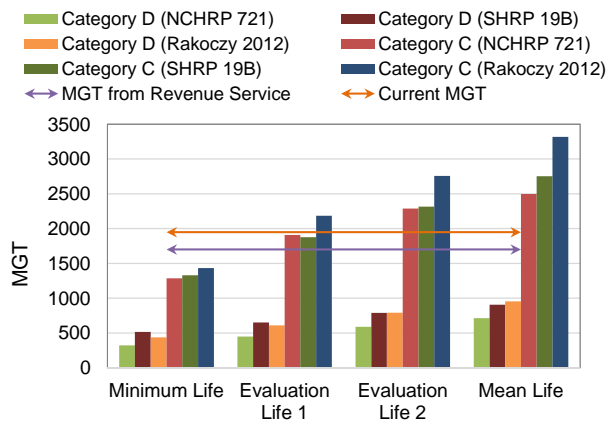


Figure 3. Comparison of Fatigue Life Estimates for FAST 32-foot Span Using Probabilistic Method and NCHRP 721 Provisions

Despite small differences, all three sets of statistical parameters of fatigue give similar results. A large increase in predicted fatigue life is noticed when the span is considered to be in Category C as compared to Category D. This scenario doubled or sometimes tripled the estimated span life for the same probability of crack initiation when compared to the scenario of Category D for the entire bridge life.

CONCLUSION

Probability of failure can provide the most versatile estimate of the remaining safe service life of a span. The service life estimate depends on fatigue category and applied load for various levels of risk (probabilities of fatigue crack initiation). During the service life of a bridge, the accumulated fatigue is increasing 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 can 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 32-foot span at FAST has performed well with no maintenance required, no defects noted, and total accumulated MGT of 1,969 with over 269 MGT of HAL traffic. This level of traffic corresponds to 10–20 percent probability of crack initiation for fatigue Category C and more than 97 percent probability for fatigue Category D. For better use of the probabilistic method, it is recommended to develop statistical parameters for a particular detail, such as full-size riveted girders only, instead of using all available data for a given fatigue category. Future research will be focused on developing statistical parameters for fatigue resistance of riveted details.

REFERENCES

- Sweeney, Robert A. P. “Resistance and Loading for Steel Bridge Fatigue Life Evaluation.” *Proceedings of AREMA Conference*. 2015.
- Otter, Duane, Anna M. Rakoczy, and Stephen Dick. “Fatigue Life and Fitness-for-Service Analysis: 32-foot Steel Deck Plate Girder Bridge Span at FAST.” *Technology Digest TD-16-025*, AAR/TTCI, Pueblo CO, 2016.
- Bowman, Mark D., G. Fu, E.Y. Zhou, R.J. Connor, and A.A. Godbole. “Fatigue Evaluation of Steel Bridges.” NCHRP Report 721, 2012.
- Fisher, John W., Pedro Albrecht, Bent T. Yen, David J. Klingerman, and Bernard M. McNamee. “Fatigue Strength of Steel Beams with Welded Stiffeners and Attachments.” NCHRP Report 147, 1974.
- Zhou, Yi. “Fatigue strength evaluation of riveted bridge members.” PhD diss., Lehigh University, 1994.
- Azizinamini, Atorod, Edward H. Power, Glenn F. Myers, and H. Celik Ozyildirim. *Bridges for Service Life beyond 100 Years: Innovative Systems, Subsystems, and Components*. No. SHRP 2 Report S2-R19A-RW-1. 2014.
- Rakoczy, Anna M. and Andrzej S. Nowak. “Development of System Reliability Models for Railway Bridges.” Report # MATC-UNL: 426, University of Nebraska-Lincoln, 2012.
- Rakoczy, Anna M., Andrzej S. Nowak, and Stephen Dick. “Fatigue reliability model for steel railway bridges.” *Structure and Infrastructure Engineering* (2016): 1-12.
- American Railway Engineering and Maintenance of Way Association, *Manual for Railway Engineering AREMA*. Chapter 15 – Steel Structures, Lanham, MD, 2015.

Visit our website at <http://www.ttciaar.com>

Disclaimer: Preliminary results in this document are disseminated by the AAR/TTCI for information purposes only and are given to, and are accepted by, the recipient at the recipient's sole risk. The AAR/TTCI makes no representations or warranties, either expressed or implied, with respect to this document or its contents. The AAR/TTCI assumes no liability to anyone for special, collateral, exemplary, indirect, incidental, consequential or any other kind of damage resulting from the use or application of this document or its content. Any attempt to apply the information contained in this document is done at the recipient's own risk.