SCHOOL OF CIVIL AND
ENVIRONMENTAL ENGINEERING
OKLAHOMA STATE UNIVERSITY

FINAL REPORT:
EXECUTIVE SUMMARY

FATIGUE ASSESSMENT OF BRIDGE MEMBERS BASED ON IN-SERVICE STRESSES

By
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Report No. FHWA/OK 97(06)

July, 1997

1. REPORT NO.
FHWA\OK-97(06)

2. GOVERNMENT ACCESSION NO.

3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE
Fatigue Assessment of Bridge Members Based
on In-Service Stresses—Final Report: Executive Summary

5. REPORT DATE
July 1997

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Farrel J. Zwememan

8. PERFORMING ORGANIZATION REPORT
97-06

9. PERFORMING ORGANIZATION AND ADDRESS
School of Civil and Environmental Engineering
Oklahoma State University
Stillwater, OK 74078

10. WORK UNIT NO.

11. CONTRACT OR GRANT NO.
2196

12. SPONSORING AGENCY NAME AND ADDRESS
Oklahoma Department of Transportation
Research and Development
200 NE 21st Street
Oklahoma City, OK 73105

13. TYPE OF REPORT AND PERIOD COVERED
Final Report: Dec 1993-July 1997

14. SPONSORING AGENCY CODE
Item 2196

15. SUPPLEMENTARY NOTES
Conducted in cooperation with U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

This report summarizes research activities which are described in detail in interim reports entitled "Field Tests, Analyses, and Laboratory Tests" [Zwerneman et al., 1996], and "Data Acquisition System for Strain Measurements" [Zwerneman et al., 1997]. These two interim reports cover two distinct phases of the research project entitled "Fatigue Assessment of Bridge Members Based on In-Service Stresses." This research was undertaken to (1) evaluate the fatigue life of a specific highway bridge on which poor welds had been applied, and (2) construct a system for measurement of strains on an in-service highway bridge. The second part of the project includes demonstrating a procedure for using the measured strains to estimate remaining fatigue life and establish inspection intervals.

Results of the first part of the project have been implemented to reduce the cost of repairs on the evaluated bridge, and results of the second part will be implemented to improve the accuracy of future bridge assessments. The data acquisition system constructed in the second part has been turned over to the Oklahoma Department of Transportation (ODOT) for operation by ODOT personnel. ODOT personnel worked with the researchers to install and operate the system for three load tests on in-service bridges. ODOT personnel also worked with the researchers to evaluate the remaining fatigue life for one of the tested bridges. Using the data acquisition system and the data evaluation procedures developed in this project, ODOT personnel will be better able to manage bridge repair and replacement needs for the future.

The data acquisition system and evaluation procedures developed in this research project have the potential to provide benefits far above the cost of development and implementation. Cost savings result from improved fatigue life estimates, more accurate load ratings, and the ability to set intervals for fracture critical inspections on the basis of measured rather than computed stresses.

17. KEY WORDS
Bridge, Plate Girder, Fatigue, Weld, Repair, Testing

18. DISTRIBUTION STATEMENT
No Restrictions

19. SECURITY CLASSIF. (OF THIS REPORT)
None

20. SECURITY CLASSIF. (OF THIS PAGE)
None

21. NO. OF PAGES
8

22. PRICE

SI (METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units					Approximate Conversions from SI Units				
Symbol	When You Know	Multiply by	To Find	Symbol	Symbol	When You Know	Multiply by	To Find	Symbol
		Length					Length		
in.	inches	25.40	millimeters	mm	mm	millimeters	0.0394	inches	in.
ft	feet	0.3048	meters	m	m	meters	3.281	feet	ft
yd	yards	0.9144	meters	m	m	meters	1.094	yards	yd
mi	miles	1.609	kilometers	km	km	kilometers	0.6214	miles	mi
		Area					Area		
in.^{2}	square inches	645.2	square millimeters	mm^2	mm^2	square millimeters	0.00155	square inches	in.^{2}
ft^2	square feet	0.0929	square meters	m^2	m^2	square meters	10.764	square feet	ft^2
yd^2	square yards	0.8361	square meters	m^2	m^2	square meters	1.196	square yards	yd^2
ac	acres	0.4047	hectares	ha	ha	hectares	2.471	acres	ac
mi^2	square miles	2.590	square kilometers	km^2	km^2	square kilometers	0.3861	square miles	mi^2
		Volume					Volume		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.0338	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.2642	gallons	gal
ft^3	cubic feet	0.0283	cubic meters	m^3	m^3	cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.7645	cubic meters	m^3	m^3	cubic meters	1.308	cubic yards	yd^3
		Mass					Mass		
oz	ounces	28.35	grams	g	g	grams	0.0353	ounces	oz
lb	pounds	0.4536	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.1023	short tons (2000 lb)	T
		Temperature (exact)					Temperature (exact)		
°F	degrees Fahrenheit	(°F-32)/1.8	degrees Celsius	°C	°C	degrees Celsius	9/5+32	degrees Fahrenheit	°F
		Force and Pressure or Stress					Force and Pressure or Stress		
lbf	poundforce	4.448	Newtons	N	N	Newtons	0.2248	poundforce	lbf
lbf/in.^{2}	poundforce per square inch	6.895	kilopascals	kPa	kPa	kilopascals	0.1450	poundforce per square inch	lbf/in.^{2}

FATIGUE ASSESSMENT OF BRIDGE MEMBERS BASED ON IN-SERVICE STRESSES

State Study No. 2196

By

Farrel J. Zwerneman

Prepared as part of an investigation
conducted by the
School of Civil and Environmental Engineering
Oklahoma State University
sponsored by
the Office of Research
Materials and Research Division
Oklahoma Department of Transportation
State of Oklahoma
and the Federal Highway Administration
July, 1997

ACKNOWLEDGMENTS

The investigation reported here was conducted as a project of Engineering Research at Oklahoma State University in the School of Civil and Environmental Engineering under sponsorship of the Oklahoma Department of Transportation and the Federal Highway Administration. The authors wish to thank all who contributed to the success of the investigation, especially Mr. Mark Baker of the Oklahoma Department of Transportation, Mr. Greg Freeby of the Texas Department of Transportation, and Mr. Timothy Rogers of the Federal Highway Administration for their assistance in the first phase of the investigation. Special thanks are also extended to Mr. Brian Windsor and Mr. Ezat Soltani of the Oklahoma Department of Transportation for their patience and assistance in testing and debugging the data acquisition system constructed as a part of this project.

The data acquisition system is modeled after a system built by researchers at The University of Texas at Austin for the Texas Department of Transportation, as described in the report number FHWA/TX+464-1F, "Estimating Residual Fatigue Life of Bridges." The authors of the TxDOT report are G. F. Post, K. H. Frank, and B. Tahmassebi.

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INTRODUCTION

This report summarizes research activities which are described in detail in interim reports entitled "Field Tests, Analyses, and Laboratory Tests" [Zwerneman et al., 1996], and "Data Acquisition System for Strain Measurements" [Zwerneman et al., 1997]. These two interim reports cover two distinct phases of the research project entitled "Fatigue Assessment of Bridge Members Based on In-Service Stresses." This research was undertaken to (1) evaluate the fatigue life of a specific highway bridge on which poor welds had been applied, and (2) construct a system for measurement of strains on an in-service highway bridge. The second part of the project includes demonstrating a procedure for using the measured strains to estimate remaining fatigue life and establish inspection intervals.

Results of the first part of the project have been implemented to reduce the cost of repairs on the evaluated bridge, and results of the second part will be implemented to improve the accuracy of future bridge assessments. The data acquisition system constructed in the second part has been turned over to the Oklahoma Department of Transportation (ODOT) for operation by ODOT personnel. ODOT personnel worked with the researchers to install and operate the system for three load tests on in-service bridges. ODOT personnel also worked with the researchers to evaluate the remaining fatigue life for one of the tested bridges. Using the data acquisition system and the data evaluation procedures developed in this project, ODOT personnel will be better able to manage bridge repair and replacement for the future.

EVALUATION OF U.S. HIGHWAY 69 BRIDGE

In 1993, the U.S. Highway 69 bridge over the South Canadian River was widened by closing the existing gap between the north- and southbound spans and by extending the deck outward on both spans. To close the gap between spans, it was necessary to add crossframes between existing interior girders. As a result of difficult working conditions and procedural errors by the welders, the quality of the field welds used to install the crossframes was very poor. The problem with weld quality was compounded by the fact that these welds, contrary to the designer's intentions, were regularly applied to the tension flanges of longitudinal plate girders.

According to design specifications [American Association of State Highway and Transportation Officials (AASHTO), 1992], the transverse weld used to attach the crossframe to the plate girder qualifies as a category C fatigue detail. However, in establishing fatigue lives for the detail categories in the specification it is assumed that proper welding procedures are used to construct the detail. If poor welding reduces the detail to a category D, calculated stress ranges exceed allowable stress ranges at 136 locations along the bridge, resulting in a projected fatigue life below the design life. If no additional information had been obtainable, it would have been necessary to grind out and replace the welds at all 136 questionable locations. Such a procedure would be very costly and possibly result in additional damage to the bridge.

To reduce repair costs and minimize the risk of additional damage during repairs, it was decided to perform a more detailed study of the bridge. The primary components of this study included load tests on the bridge, fatigue tests on laboratory specimens containing poor quality welds similar to those on the bridge, and a three dimensional analysis of the bridge.

Investigative Procedure

In preparation for the load tests, the bridge was visually inspected and a simple grid model of the bridge was analyzed under a moving truck load. Based on the results of the inspection and analysis, critical locations on the bridge were selected for strain gage installation. Eight gages were installed at three locations on the bridge, for a total of 24 gages.

Strain gages and monitoring equipment were installed and operated by two engineers on loan from the Texas Department of Transportation (TxDOT), working off a Snooper truck provided by (ODOT). The monitoring equipment was developed for and owned by TxDOT, and the two engineers assisting with the load test had performed this same function numerous times on Texas bridges. Personnel and equipment were occupied for two days installing strain gages and one day performing tests. The same personnel and equipment were required for one-half day at the test site approximately two weeks later to download data and remove equipment.

Load tests were conducted in two parts. In the first part, strains were recorded versus time while a 47,000 lb dump truck was driven over the bridge at four different speeds and three different transverse locations (referred to as a truck test). Data collected from these tests provided information on impact and load distribution, and were used to calibrate the analytical model. The second part of the load test involved leaving the data acquisition equipment in place and unattended for approximately two weeks while data on the number and range of stress cycles (referred to as a rainflow count) were recorded. Data from both parts of the load tests were used to develop an estimate of the remaining fatigue life of the bridge.

Following the load tests, detailed analytical models of the bridge were constructed so that a variety of loads could be applied to the bridge and stresses could be determined at locations other than strain gage locations. These detailed models included a refinement of the grid model developed in advance of the load tests and a three dimensional finite element model. The grid model was constructed in approximately one day; the finite element model was constructed using a general purpose finite element program, and several weeks were required to prepare an accurate model. If a finite element program developed specifically for three dimensional bridge analysis had been used (such as BRUFEM), it is estimated that the model could have been constructed in less than one week.

The load tests and analyses provide information with regard to the stresses applied to the bridge, but no information is provided on the capacity of the bridge to support these stresses. Under normal circumstances, the capacity of the bridge would be determined from AASHTO specifications. Unfortunately, the AASHTO specifications do not apply to the welded details on this bridge because of the very poor weld quality. To determine capacity, laboratory fatigue tests were conducted on specimens with poor welds similar to those on the actual bridge. Results of these tests were used to construct a plot of stress range versus number of cycles to failure. A line fit to this data (S-N curve) was used to estimate the fatigue life of the bridge girders under the measured and computed applied stresses.

Test Results

The results of the load tests indicated that stress ranges applied to the bridge are very low. The test truck produced a maximum stress range of 1.9 ksi at the most highly stressed strain gage location. The maximum effective stress range (weighted average stress range) at a gage location was determined to be 0.95 ksi with an average cycle count of 12,312 per day. Although these values seem low, they are comparable to values reported by other researchers conducting measurements on highway bridges [Moses et al., 1987].

Both the grid and the three dimensional finite element models provided results which closely matched field measurements. The grid analyses indicated a maximum stress range of 2.1 ksi at the critical location on the bridge while the finite element analyses indicated a maximum stress range of 1.4 ksi at the same location. The critical location from the analyses matches the location of the gage reporting the maximum stress range of 1.9 ksi, as discussed above.

The laboratory fatigue tests showed that the poor quality welds decreased the fatigue life of the detail below that of a category C detail, and, for high stress ranges, below that of a category D detail. In addition, fatigue failures occurred at stress ranges below the infinite life fatigue limit for the category C detail.

The results of the field measurements, analyses, and laboratory tests were combined to arrive at the conclusion that the remaining fatigue life of the bridge is infinite. This long fatigue life comes as a result of the very low stress ranges applied to the bridge, and in spite of the poor performance of the welded detail. This conclusion is not intended to promote or excuse the poor welding practice employed on the U.S. Highway 69 bridge. It should be understood that the same conclusion does not extend to all bridges. If the lateral load distribution system had been less effective on this bridge, it would have been necessary to undertake extensive repairs.

DATA ACQUISITION SYSTEM

As a second phase of the project, researchers were given the task of constructing a data acquisition system similar to the system owned and operated by TxDOT. When the ODOT system is made operational, researchers are to provide users' manuals and training to ODOT personnel so that the system can be used by ODOT personnel without the involvement of the researchers.

The hardware components making up the system include a datalogger, an interface box, a portable computer, and a variety of cables. The datalogger used in the system is a Campbell Scientific model 21X. The model 21X is a general purpose datalogger with four excitation channels capable of supplying (5 volts DC and 8 differential input channels. In the field, the datalogger is powered by a 12V marine battery allowing at least 3 weeks of continuous operation without recharging. The interface box, constructed by the researchers, is built to accommodate up to eight input channels. The input channels can be strain gages or full bridge transducers. If the input channels are strain gages, bridge completion modules inside the interface box are activated. Wiring of cables connecting strain gages or transducers to the interface box determines whether or not bridge completion modules are activated. Cables for strain gages have been provided with the system, as well as cables to connect the interface box to the datalogger and the datalogger to the computer. Cables for transducers are not provided. Wiring diagrams for all cables, including transducer cables, are provided in the interim report. All of the hardware required to construct the system, including the portable computer, can be purchased for $10,000.00.

In addition to constructing a hardware system, it was necessary to develop a software system to allow the system user to communicate with the datalogger through a personal computer. The primary software component is a compiled QBASIC program which translates user input parameters into datalogger downloadable files. By selecting items from a menu, the user can input strain gage factors, command the datalogger to collect strain versus time data, or command the datalogger to undertake a rainflow count. The interim report contains both a flowchart and a listing of the system software.

The interim report serves not only as a maintenance and operation manual for the system, but also contains guidelines for conducting a test and evaluating the data. It is recommended that a complete bridge evaluation include a thorough visual inspection, an analysis of the structure, and a load test. The load test should include both a series of short-term tests in which stresses are recorded as truck of known weight passes over the bridge (truck test), and at least one long-term test in which the number and magnitude of stress cycles are recorded under normal traffic (rainflow test). The recommended procedure for estimating remaining fatigue life follows NCHRP Report 299 [Moses et al., 1987], taking full advantage of the fact that stresses are measured rather than computed. The procedure for setting inspection intervals is based on a fracture mechanics estimate of the time required for a crack of an assumed initial length to grow to a critical length when driven by the measured stress cycles.

The system has been evaluated in three field tests, with the level of involvement by ODOT personnel increasing in each test. The first field test was conducted in June 1996 on the elevated portion of Interstate Highway 40 in Oklahoma City. Working from a fixed scaffold and a bucket truck, eight strain gages were applied to the cross beam at pier 29 north. Gages were installed by both OSU and ODOT personnel; the time required to install the eight gages was approximately 6 hours. Data acquisition equipment was operated by OSU personnel. The test truck portion of the program worked properly, but the rainflow portion did not. Data collected were not used for bridge evaluation.

The second field test was conducted on the Interstate Highway 35 southbound bridge over the Chickaskia River in northern Oklahoma. In preparation for the field tests, visual inspections and independent analyses of the bridge were completed by OSU and ODOT personnel. On the basis of these inspections and analyses, locations were selected for 27 strain gages. Working from a Snooper, these 27 gages were installed by OSU and ODOT personnel in approximately 12 hours over a two-day period. On the third day truck tests were conducted for approximately 6 hours. The system was left in place for approximately three weeks for collection of rainflow data. At the end of the three-week period, the system was removed from the bridge with the assistance of the Snooper in approximately 3 hours.

Similar to the first field test, the test truck portion of the system worked properly but the rainflow portion did not. The results of the test truck measurements compared very favorably with the results of analyses performed independently by ODOT and OSU personnel. The test truck data combined with weigh-in-motion data collected at a nearby site provided adequate information to estimate the remaining fatigue life of the bridge. It was determined that even though the stress range is expected to be low at approximately 3 ksi, the category E' fatigue detail in the bridge reduces even the most optimistic remaining safe life estimate to less than 5 years.

Following the second field test, the system was taken back to the OSU laboratories and programming modifications were made to improve the reliability of the rainflow counting portion of the system. The modified program was tested on a laboratory specimen and determined to function properly.

In early May 1997, the complete system was transferred to ODOT, along with a strain gaged bar for practice with the system in the office. The engineers working with the system were able to successfully conduct both test truck and rainflow tests using the practice specimen. Unfortunately, the engineers were also unsuccessful in at least two practice rainflow tests run over a several-week period. An intermittent error occurs in downloading information from the datalogger which results in an attempt to read past end of file.

In early June 1997, a third field test was conducted at the same location, using the same gages as the first field test. Upon arrival at the test site, it was determined that only five of the original eight gages were still functioning. The instrumentation was installed and the five functioning gages were connected in approximately 2 hours. Several stress-time histories were recorded under normal traffic and data were successfully collected for rainflow tests run for intervals of several minutes. Instrumentation was left in place for approximately two weeks to collect rainflow data. At the end of the two-week period, an attempt to download the data resulted in an attempt to read past end of file error. Subsequent rainflow tests run for intervals of several minutes were successful.

SUMMARY AND CONCLUSIONS

Load tests conducted on the U.S. Highway 69 bridge over the South Canadian River clearly demonstrate the usefulness of the test approach for fatigue evaluation of bridges. Evaluation of load test results and finite element analyses led to the determination that repair of poor field welds on the bridge was not necessary. The applied stresses are so low that infinite fatigue life can be expected from the bridge, even with the poor quality welds. As a result, the expense associated with field repairs of 136 welds was eliminated, as well as the potential for additional damage during repairs.

The data acquisition system constructed for ODOT provides the potential for cost savings through improved fatigue evaluations, as well as through other bridge evaluation needs. Strain data acquired during load tests can be used to calibrate analytical models, which can then be more accurately analyzed for proposed future loads, such as those imposed by international (North American Free Trade Agreement) or regional (Western Association of State Highway and Transportation Officials) traffic. These analyses can help to identify upgrade requirements and project future maintenance needs. The strain data can also be used to re-evaluate bridges which have been closed to heavy local traffic. Rated capacities limited by calculated stresses in superstructure members can generally be upgraded on the basis of load test results.

Cost savings can also result from increasing inspection intervals on bridges with fracture critical members. The second interim report includes a procedure for using the data to set inspection intervals. Low stresses in fracture critical members may allow inspection intervals to be increased to the 2-year maximum mandated by the National Bridge Inspection Standards.

To organize, conduct, and evaluate the results of a load test requires approximately three weeks by one engineer. The first week is spent visually inspecting the bridge and performing a preliminary analysis to establish a basis for strain gage placement. In the second week, two days are required to install strain gages and one day is required to perform truck tests. To install strain gages, the engineer will require the assistance of a Snooper or bucket truck. It would also be helpful to have available a second individual trained to install strain gages, to provide relief to the primary installer. To conduct load tests, a dump truck with driver and assistance with traffic control will be needed. Approximately two weeks after the truck tests are performed, the engineer will again require the assistance of a Snooper or bucket truck to remove the instrumentation. The data from the truck and rainflow tests can be plotted and evaluated in approximately one week.

A minor amount of supplies are consumed during a load test. It is necessary to purchase approximately $300.00 worth of strain gages and installation supplies for a complete load test. Complete lists of consumable and nonconsumable supplies are provided in the second interim report.

Although a substantial time commitment is required by at least one engineer for each bridge tested, the cost of this commitment is small compared to the benefits available. If one bridge replacement is avoided, the savings would offset many years of evaluation and inspection costs. Even the cost of a minor retrofit will exceed the cost of the bridge test, considering the engineering plus the cost of labor, materials, and equipment required for installation. More difficult to quantify, but no less real, are the benefits derived from opening a bridge to heavy local traffic rather than limiting loads as a result of a low rating. The data acquisition system and evaluation procedures developed in this research project have the potential to provide benefits far above the cost of development and implementation.

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