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Fatigue Evaluation of Existing Steel Highway Bridges

Evaluation de la fatigue dans les ponts-routes existants en acier

Abschätzung der Ermüdungsfestigkeit bestehender Strassenbrücken aus Stahl

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SUMMARY
In 1978 numerous fatigue cracks were found in various components of a major interchange structure carrying expressway traffic in the Metropolitan Chicago Area. As a result of these findings, a project dealing with an evaluation of accumulated fatigue damage and predictions of fatigue life expectancy of all steel bridges within this system was initiated.

RESUME
En 1978 de nombreuses fissures de fatigue furent trouvées dans différents éléments de la structure d'un important échangeur de trafic de la région de Chicago. Conséquence de ces découvertes, une étude fut entreprise afin de permettre l'évaluation des dommages cumulés de fatigue ainsi que l'espérance de vie de tous les ponts réalisés selon ce système.

ZUSAMMENFASSUNG
Im Jahre1978 wurden an verschiedenen Teilen einer wichtigen Brückenkonstruktion über eine Autobahn im Gebiet von Chicago Ermüdungsrisse festgestellt. Diese Feststellung führte zu einem Forschungsprojekt, welches den akkumulierten Schaden und die zu erwartende Lebensdauer aller Stahlbrücken des Autobahnsystems Illinois untersucht.

INTRODUCTION

Thirty-three cracks in bent connection plates and brackets supporting expansion bearings were found during inspection of Bridge Structures No. 209 and 210, carrying the Tri-State over the East-West Illinois State Toll Highway. The useful life of these original components was exhausted after 20 years in service, and the safety of these structures was questioned.

Detailed analysis and field testing have identified most of the cracks as having been caused by fatigue.

As a result of these findings, a project dealing with evaluation of accumulated fatigue damage and prediction of fatigue life expectancy of all steel bridges owned and maintained by Illinois State Toll Highway Authority was initiated.

This project consisted of the following: review of drawings, preparation of inventory sheets for each structure, design stress range calculation, research of loading history of these structures, instrumentation of selected details, evaluation of actual stress ranges, calculations of accumulated fatigue damage and fatigue life expectancy, field inspection of selected details, and recommendations of retrofitting methods.

Relatively inexpensive retrofitting is possible when the early discovery of fatigue cracks is made.

2. FATIGUE EVALUATION OF 82 STEEL HIGHWAY BRIDGE

2.1 Preliminary Review

The 82 steel bridges at 50 different sites on the Tollroad System were reviewed and analyzed according to current AASHTO Specifications. The findings were presented in one or two-page reports called "Fatigue Location Inventory."

The fatigue stress category and its allowable stress range for each location were determined according to the design detail and the applicable repetitive loading and compared with the design stress range determined by preliminary analysis.

As a final step in this phase, a table was prepared which summarizes the findings of the "Fatigue Location Inventory" and which lists all reviewed steel bridges with the following information:

a) Structure number and location of structure;
b) Loading case - number of cycles;
c) Stress range due to the design load;
d) Category of allowable fatigue stress range at the section where the stress range was calculated;
e) Allowable stress range for the particular category;
f) Overstress, based on the design load, expressed in percentage of allowable stress range; and
g) Remarks.

2.2 Detailed Analysis of Ten Structures

Only ten structures were selected for detailed analysis due to the limited scope of this project. Overstress based on the design load, expressed in percentage of allowable unit stress, and a location of the details in respect to the positive or negative moment region were the only criteria used in selection of these structures. It is known that continuous span structures, consisting of steel stringers and concrete decks which were designed as non-composite, do actually act as a composite section provided the bond between concrete and steel beam is not destroyed. Therefore, the structures with details susceptible to fatigue crack located in negative moment region were not selected for further detailed analysis because the actual stresses would be only a fraction of design stresses calculated on assumption of non-composite section.

Only the structures with highest overstress and with the details susceptible to fatigue cracks located in positive moment region were selected (Table 1).

STR. NO.	LOADING CASE	DESIGN STRESS RANGE N/mm2	FATIGUE STRESS CATEGORY	ALLOWABLE STRESS RANGE N/mm2	% OVERSTRESS	REMARKS
1147,	I	131	D	48	272	Low Traffic
1148		80	E'	18	444	Volume
367,	I	83	D	48	172	(+) Moment
368		80	E'	18	444	Region
355,	I	84	D	48	175	
356		46	E	34	135	Intermittent
		61	E'	18	339	Fillet Welds
209,	I	52	E'	18	289	(+) Moment
210						Region
191,	I	102	D	48	212	(+) Moment
192		50	E'	18	277	Region
		83	E'	18	461	(-) Moment
						Region

TABLE 1

All of these bridges were built between the years 1958 and 1971. The typical cross section is shown in Figure 1. The stringers were from wide flange rolled sections. The simple or continuous spans were from 18.9 m to 31.4 m.

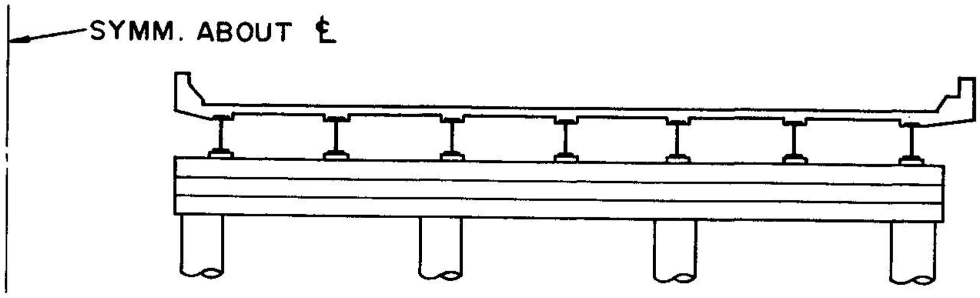

Figure 1 -- Typical Section

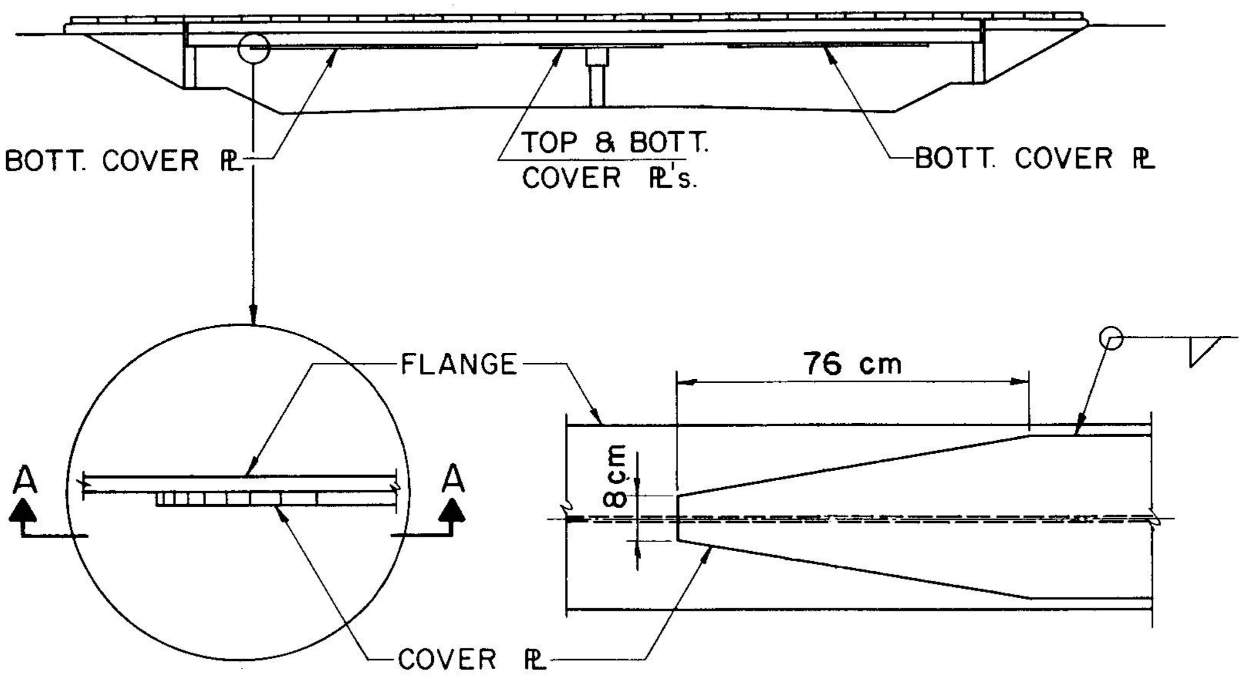

Figure 2 -- Typical End Detail of Welded Cover Plate

All structures selected for detailed analysis have welded cover plates. Their end details belong to Category E' with allowable 18 N/mm^2 stress range for over 2,000,000 cycles.

The typical end detail of welded cover plate is shown on the Figure 2.

Stress ranges for these structures were analyzed by the computer at various desired locations. The overstress, based on the design load and expressed in percentage of allowable unit stress, ranges from 444 percent on structures No. 1147 and 1148 to 277 percent on structures No. 191 and 192.

2.3 Strain Measurement

Based on the detailed analysis, structures No. 355, 356, 367, and 368 were selected for instrumentation. The purpose of such testing was to measure strains due to the actual live load and to determine actual stress ranges in the detail under investigation. These actual stress ranges and estimated number of their occurrences were used to determine the cumulative fatigue damage of these structures and to estimate their useful life expectancy. The strains were recorded continuously for 24 hours; field data from the gages was conditioned and recorded on a Sangamo 3500 magnetic tape recorder. The recorded analog data was replayed on an Analog-to-Digital conversion system.

During processing time, the time history data of the strains which enter as analog values is converted to digital values and written on a digital magnetic tape. At the start of processing of any given vehicle traversal, a special identifying data block is written which includes, among other parameters, a count of the particular vehicle. This block labels and separates the data representing individual vehicle crossings. Thus, a compressed reel of data written in digital form is produced which contains only the crossing information and which has been stripped of the vast amount of zero traffic time.

This data is then further processed by Peak-to-Peak Method. The individual groups of data for each specific crossing are checked to obtain the strain range values. The initial values of all gages are used as an arbitrary zero, and succeeding strain values are checked for the maximum and minimum values which are retained. The strain range is then the algebraic difference of these two values.

The range of strain so determined for each gage then is used to add one count to a table of the number of occurrences at given levels of strain for each gage.

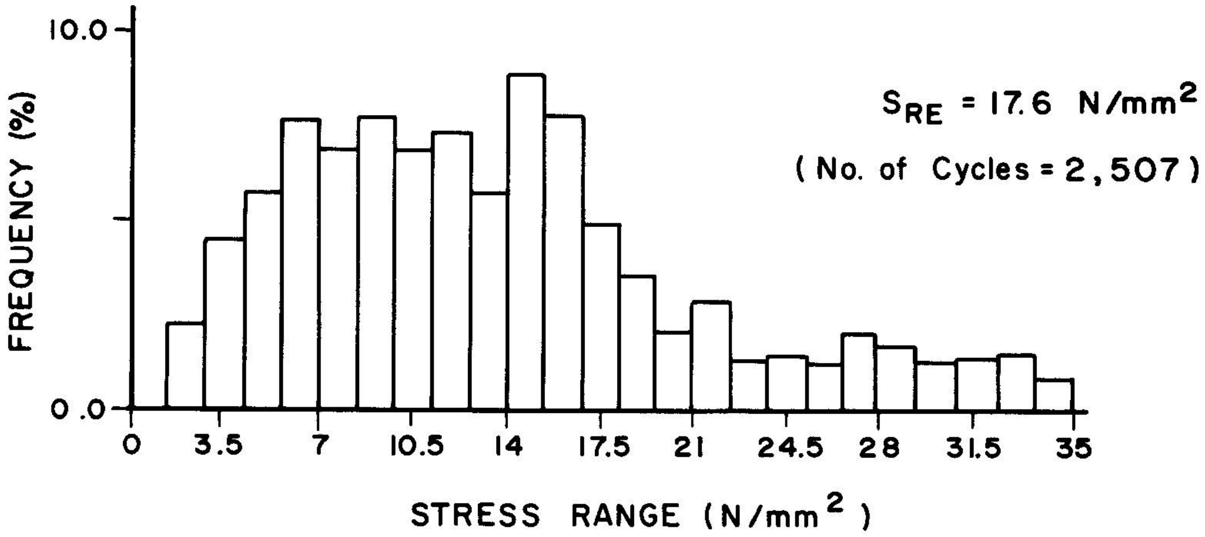

Figure 3 -- Histogram of Stress Range Spectrum for Gage No. 6

The processed strain data was used in preparation of stress range histograms. Figure 3 shows the stress range histogram for stresses recorded at gage No. 6, recorded on the Bridge No. 367.

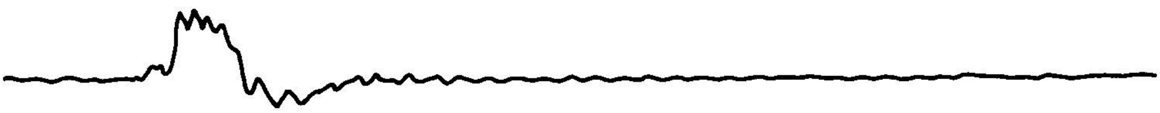

Figure 4 -- Typical Strain Response at Gage No. 6

Figure 4 shows a typical record of strain measured on gage No. 6. A certain percentage of the recorded strains on gage No. 6 were observed to look like those shown on Figure 5.

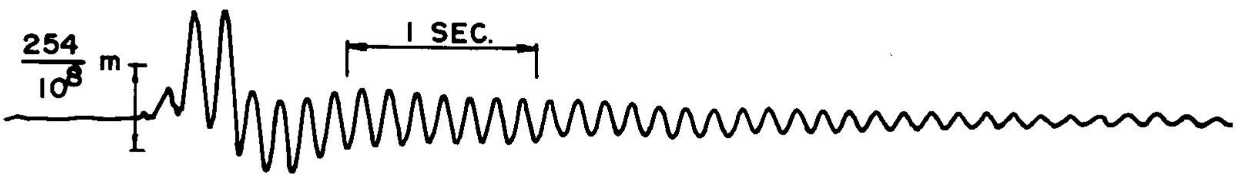

Figure 5 -- Strain Response on Gage No. 6

Additional field inspection revealed that the open expansion joint at the south end of the bridge has the following deficiencies:

a) excessive opening;
b) vertical misalignment; and
c) depression at the adjacent approach slab.

These deficiencies cause a truck's axles to become airborne, landing with considerable impact at various points of the span, depending on the speed of the truck. Such type of loading causes the structure to get excited and to be stressed approximately 40 percent more than the adjacent structure whose expansion joint is in good condition and, therefore, does not experience such loading.

Once the structure becomes excited with a relatively low damping, it is possible for one passing truck to cause approximately 15 cycles of relatively high stress ranges as shown in Figure 5. Thus, the fatigue life expectancy of such structures is dramatically reduced due to the higher stress and additional stress range cycles.

It is obvious that maintenance of the bridge and approach slab surfaces as well as the alignment of expansion joints are extremely important factors in the determination of the structure's fatigue life expectancy.

2.4 Traffic Data

The next step in this project was to determine the traffic volume and the axle loadings which have occurred on the sections of the tollway system since its opening to the traffic and to predict the future traffic magnitude to which the bridges in these sections will be subjected. This data is then used to calculate accumulated fatigue damage and predict fatigue life expectancy off steel bridges under investigation. Traffic volume figures were obtained from the study based on traffic data obtained from the Illinois Tollway's annual traffic reports. This data was used to prepare a table of actual traffic growth of commercial vehicles using Illinois Tollway system between the years 1959 and 1990.

Of next importance was to find statistics on cross vehicle weight and axle load. Weight measurements were conducted on over 10,000 vehicles of rural interstate truck traffic in the state of Illinois during the period 1968 through 1976 by the University of Illinois.

This data of traffic volume and axle load was used to determine fatigue life expectancy of any tollroad bridge.

2.5 Accumulation of Fatigue Damage

The accumulated damage to any structure could be determined if the loading history and spectrum of actual stress ranges these loads are inducing into this structure are known.

The spectrum of stress ranges caused by the actual traffic was measured on four structures. The measurements were taken in the vicinity of the details which are susceptible to fatigue cracks. These measurements and loading history data were used in the detailed evaluation of accumulated fatigue damage and prediction of fatigue life expectancy of these structures.

As a final result of this evaluation, the number of trucks required to cross the bridge in order to initiate a fatigue crack at the end of welded cover plate has been calculated. This calculated number of trucks was then compared with the table of annual and accumulated transactions, and the year during which the first fatigue cracks on this detail will appear was provided.

2.6 Field Inspections

All ten structures which were selected for detailed analysis have the critical areas susceptible for fatigue cracking at toes of welds of cover plate termination. Thus, the areas needing examination are relatively small.

Two methods were used during the course of this field inspection to detect cracks, the visual examination with a 10X magnifying glass and the dye penetration examinations.

According to accumlation of fatigue damage calculations, the fatigue cracks alaready should have started at the end of cover plates on structures No. 367 and 368. All those details were sandblasted and examined by 10X magnifying glass. Approximately 2 mm long fatigue cracks were found on every one of them.

2.7 Suggested Repair Procedure

The following three methods were considered for improving the fatigue life and for arresting the progress of fatigue damage:

a) Grinding the weld toe to remove the slag intrusions and reduce the stress concentration;

b) Air-hammer peening the weld toe to introduce compression residual stresses; and

c) Remelting the weld toe using the gas tungsten arc process (GTA), also commonly referred to as the TIG or tungsten inert gas process.

Out of these three methods, only peening is considered an effective retrofitting method which improves the fatigue life expectancy of the detail. The other effective method of retrofitting is splicing with A-490 high strength bolt.

3. SUMMARY AND CONCLUSION

Findings of serious fatigue cracks in structures, described in the INTRODUCTION of this paper, were instrumental factors in the initiation of the fatigue evaluation program of all steel bridges owned and maintained by Illinois State Toll Highway Authority. There are 82 steel bridges within this system, all of which were built between the years 1958 and 1971.

Required fatigue inventory documentation for all these bridges was prepared based on the review of drawings, calculations, and field inspection.

Ten structures with E' category detail were selected for detailed fatigue evaluation.

Preliminary field inspection did not uncover any fatigue cracks of such magnitude as those described in the INTRODUCTION of this paper.

The actual stress ranges were obtained from the measured strains. The existing traffic studies were used to determine the loading history of each structure.

The fatigue life expectancy for each structure was calculated based on the actual stress ranges and loading history of the structure.

The analysis of structures No. 367 and 368 revealed that the fatigue cracks already should have started at the end of welded cover plates.

During the detailed field inspection of these structures, approximately 2 mm long fatigue cracks were found at the weld toes of the cover plate ends. This confirmed the theoretical findings.

As a final step on this project, repair procedures were proposed to arrest the progress of fatigue damage and to improve the fatigue life of the structure.

4. ACKNOWLEDGEMENT

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