FATIGUE DESIGN, EVALUATION AND INSPECTOION FOR ORTHOTROPIC STEEL DECKS ON LONG-SPAN BRIDGES

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Abstract

Recently, fatigue damages have been reported on steel bridges in Japan. On long-span bridges of the Honshu-Shikoku Bridges (HSB, Figure 1), the specification for fatigue design was applied during construction and the structural details were improved, carrying out the fatigue tests with full-scale specimens. However, there is a possibility that fatigue damages will occur on the HSB in the future, since the HSB have the similar types of orthotropic steel decks with trough ribs as the steel bridges. Therefore, the possibility of fatigue damages on the HSB was verified through field measurements and structural analysis. In order to inspect a large number of details efficiently, "fatigue hazard figures for bridge inspection" were proposed. Important inspection details, where fatigue damages will occur in a relatively high possibility, are indicated in the figure. This paper describes a new challenge for the bridge inspection against fatigue damages on the HSB.

1. Introduction

Fatigue damages in the steel bridge have been reported in recent years [1]. Especially, more than 1,000 fatigue damages on steel bridges in urban expressways are reported [2]. The steel bridges in urban expressways have orthotropic steel decks with longitudinal flat rib. There is a possibility of fatigue damages in the orthotropic steel deck with longitudinal trough rib in the HSB.

In the design for the HSB, the fatigue tests with full-scale specimens were conducted (Photo.1). Based on test results, the specifications for fatigue durability were made and applied to the design of orthotropic steel decks. Moreover, because the operation period is comparatively short and the traffic is not heavy, the fatigue damage has not yet reported. However, many fatigue damages are reported in similar structure details in other operators, the future safety is not necessarily ensured just because no fatigue damage occurs at present. Therefore, it is necessary to review the inspection methods against fatigue damage.

The early detection of fatigue damage is required for structural safety although the curtailment of the inspection expense is also required. Consequently, the efficient inspection is indispensable. Under such a background, the maintenance effort for detection of fatigue damages on the HSB is described in this paper.

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2. Fatigue Design for Honshu-Shikoku Bridges

2.1 fatigue design

Since the several HSB are designed for combined bridges for highway and railway, the fatigue damage by railway load was one of the important problems in design. As for the fatigue design in highway bridges, the fatigue allowable stress was conventionally defined for the steel deck design. However, the fatigue evaluation was not conducted. It was common to improve the fatigue durability by changing a structure detail, etc.

Therefore, the fatigue tests for the HSB, using large-sized specimen, were conducted to obtain the characteristic of fatigue. The test results yielded to the design criteria [3] and the fabrication standard [4]. The criteria and standard were applied to design and construction of the Seto-Ohashi Bridge, completed in 1988. Then, fatigue damages in the highway bridges were reported in 1980s. Since the Seto-Ohashi Bridge and the Ohnaruto Bridge also had similar detailed structures, the fatigue tests of orthotropic steel deck were carried out and the detailed structures were improved.

The Design Standard for Highway Bridges in 2002, considering the fatigue design, was published to take the influence of fatigue into consideration in a steel highway bridge. At the same time, a new book was published, named the Fatigue Design Manual for Steel Highway Bridge [5] as the reference data of the fatigue design(Figure.2). In addition, in the fatigue design manual, since the quantitative evaluation of generating stress is difficult for the orthotropic steel deck, the high-fatigue-durability details are basically selected instead of stress examination. On the other hand, the fatigue design for the main structure in the plate girder bridge is basically carried out by checking the generating stress.

2.2 Steel Deck

The HSB, which have steel deck structures, are shown in Table 1, excluding ramp viaducts in interchanges. The details of orthotropic steel decks in the HSB, can be roughly classified into three types, as shown in Table 1. Type A is used in the Innoshima Bridge, the Ohnaruto Bridge, and the Seto-Ohashi Bridge. The welding joint is mainly adopted in trough rib joints except close to longitudinal girder, where the filed welding is difficult in construction. Type B is a new type by improving the fatigue durability of Type A, and is later adopted as the Fatigue Design Manual for Steel Highway Bridges. It is used in the Akashi Kaikyo Bridge and the Kurushima Kaikyo Bridges, and the high-tension bolted (HTB) joint is basically adopted in trough rib joints. Moreover, the scallop in the trough rib joint is changed in size as small as possible, as shown in Figure 3. Type C is used in steel bridges constructed by the Ministry of Land, Infrastructure and Transport, and operated by the Honshu-Shikoku Bridge Expressway Co., Ltd. The HTB joint is adopted in the deck plate joints and in the trough rib joints, and there is a difference between the scallop in the lateral rib of Type A and that of Type C. The attention shall be paid to Type A and Type C in the following fatigue evaluation.

3. Fatigue Evaluations for Honshu-Shikoku Bridges

3.1 Stress measurement in orthotropic steel deck

In general, the analysis of local stress in orthotropic steel deck is difficult in accuracy because the orthotropic steel deck is a complex structure and wheel loads have variations in weight and location. Therefore, the local stress measurement in the orthotropic steel deck was carried out on the Ohnaruto Bridge, which was completed in 1985 as a suspension bridge with the main span of 876 meters. The bridge has a large traffic volume and an orthotropic steel deck with details of Type A in Table 1.

The measurement points were selected just under wheel loads in the left lane for slow traffics, as shown in Figure 4. Stress gauges were attached to the 5 mm-distance point from toes of welded joints. The 24 hour-measurement was carried out for a weekday from 2:00 p.m., Thursday, February 27 through 2:00 p.m., Friday, February 28, 2003. In order to investigate kinds of vehicles or running locations of vehicles, the traffic flow was monitored by a video recorder in 3 hours in the daytime and a special vehicle with the weight of 200 kN passed through the bridge several times during the monitoring. Numbers of stress amplitudes was counted by the rain-flow method and the result was shown in Figure 5.

The aim of local stress measurement, however, is not to evaluate the fatigue lives for details, but to select severe details against fatigue damage in orthotropic steel deck and to reduce the maintenance costs. Figure 5 shows that large stress amplitudes occur in the scallop of the bolt joints for trough ribs (Gauge a and d) as well as in the slit between trough rib and cross rib (Gauge p and q), which means a severe condition against fatigue.

3.2 Cumulative fatigue damage in orthotropic steel deck

Based on the result of the local stress measurement on the Ohnaruto Bridge, the fatigue life for the scallop of the on-site bolt joints for trough ribs in the orthotropic steel deck were estimated [6]. The result of estimation is shown in Figure 6. The procedure of estimation is outlined as follows.

1) The numbers of stress amplitudes, counted by the rain-flow method, is used for fatigue damage estimation.
2) Fatigue strength grade for the above-mentioned detail is assumed to be Grade G, which has the allowable fatigue stress range of 65 N/mm^2 against 2 million repetitions.
3) Cumulative fatigue damage on the measurement day can be calculated, considering the low amplitude limit of 15 kN against variable stress amplitude for Grade G.
4) Cumulative fatigue damage from 1985 to 2005 can be given by multiplying the measurement-day cumulative fatigue damage and the ratio of the cumulative traffic volume of large vehicles to the measurement-day traffic volume of large vehicles.
5) Cumulative fatigue damage from 2006 to the future can be given so that the future traffic volume is assumed to be the same as the traffic volume in 2005.

The estimation for the orthotropic steel deck reveled that the cumulative fatigue damage for the scallop of the on-site bolt joints for trough ribs will be equal to 1.0 after 45-year operations, i.e., in 2030. The estimation result of the fatigue life of 45 years has a possibility of several variations, because uncertain factors are assumed in the estimation. For example, the pavement stiffness is relatively large on the measurement day on winter, and the fatigue strength grade for the detail is assumed to be Grade G nevertheless welding qualities. The estimation for the orthotropic steel deck, however, yields to a certain possibility of fatigue damage for evaluation of the structural safety against fatigue damage.

4. Preventive Maintenance for Honshu-Shikoku Bridges

4.1 Fatigue hazard figure for bridge inspection

In inspections, fatigue cracks need difficult and careful observations to be detected since they are very small defections. The visual inspection from inspection ways is not necessarily effective to detect fatigue cracks since steel structures are covered by coatings. The visual inspection from close positions or the touch inspection is effective to detect fatigue cracks. In visual inspections, paint cracks or rusts are primary signs for fatigue cracks. In order to detect fatigue cracks in their early stages and carry out the inspection efficiently, high possibility points against fatigue damages shall be selected and inspected intensively, considering the difficulty of inspection for fatigue cracks.

“Fatigue hazard figures for bridge inspection,” which indicate possibilities of fatigue cracks, were examined for orthotropic steel decks, based on the above-mentioned estimation results and fatigue damage examples in other operators. The fatigue hazard figures can be used in inspection efficiently and economically.

Considering the above-mentioned estimation results and the cumulative traffic volumes of Honshu-Shikoku Highways (Figure 7), important inspection details in orthotropic steel decks (Table 2) were selected in term of bridges, locations, and detailed structures. The Akashi Kaikyo Bridge, which has a large traffic volume, is excluded because the details of the orthotropic steel decks are partly improved during construction. The fatigue hazard figure for orthotropic steel deck (Figure 8) was made for the Ohnaruto Bridge, which has a large traffic volume and Type-A details in orthotropic steel deck.

The important inspection details in the fatigue hazard figure can be classified as follows,

1) Rank A of importance inspection detail, which has a fatigue life of 25-50 years, is referred to be a high possibility of fatigue damage.
2) Rank B of importance inspection detail, which has a fatigue life of 50-100 years, is referred to be a middle possibility of fatigue damage.
3) Rank C of importance inspection detail, which has a fatigue life of more than 100 years, is referred to be a low possibility of fatigue damage.

4.2 Inspections against fatigue damage

Inspections are mainly carried out by the visual inspection for general steel bridges.

On the other hand, inspections for the HSB shall be carried out efficiently by the visual inspection with help of the fatigue hazard figure.

Since inspection ways and inspection vehicles are equipped on the long-span bridges of the HSB, the visual inspection can be easily done from close positions under the orthotropic steel decks. The visual inspection from close positions is usually carried out at the basic inspection at each 1-2 years.

Several examples of the relation between the steel deck damage and the pavement damage are reported from other operators. Considering these examples and technical information, the inspections for HSB shall be done more efficiently and effectively.

5. Conclusion

The conclusions are summarized as follows,

1) The fatigue examination was performed in the orthotropic steel deck of the HSB, and the fatigue damage were evaluated

2) The "fatigue hazard figures for bridge inspection," which indicate the important inspection details in typical bridges were proposed.

The further examinations shall be done as follows,

1) The fatigue hazard figures for other bridges are scheduled in order to reduce maintenance costs.

2) The application of the sensing technology to the fatigue damage, including the fatigue censors, is examined for the preventive maintenance.

3) More information on the fatigue damages in other operators or the latest technology shall be collected.

References

[1] For example,

(a) Japan Society of Civil Engineering: *Fatigue in orthotropic steel deck* (in Japanese), September1990

(b) Japan Road Association: *Fatigue in steel highway bridges* (in Japanese), May 1997

(c) National Institute for land and infrastructure management: *Reference data of periodical inspection for highway bridges-photographs of bridge damage examples* (in Japanese), No.196, December 2004

[2] Bridge newspaper: Fatigue damages of steel decks on urban expressways bridges (in Japanese), No.919 and 920, May21, 2006

[3] Honshu-Shikoku Bridge Authority: *Design standard for superstructure* (in Japanese), June 1980

[4] Honshu-Shikoku Bridge Authority: Fabrication specifications for steel bridges (in Japanese), March 1977

[5] Japan Road Association: *Fatigue design manual for steel highway bridges* (in Japanese), March 2002

[6] Moriyama and Usui: *Investigation and examination of fatigue on orthotropic steel deck* (in Japanese), Honshi Technical Report, No.103, September 2004

Figure 1: Location of Honshu-Shikoku Bridges

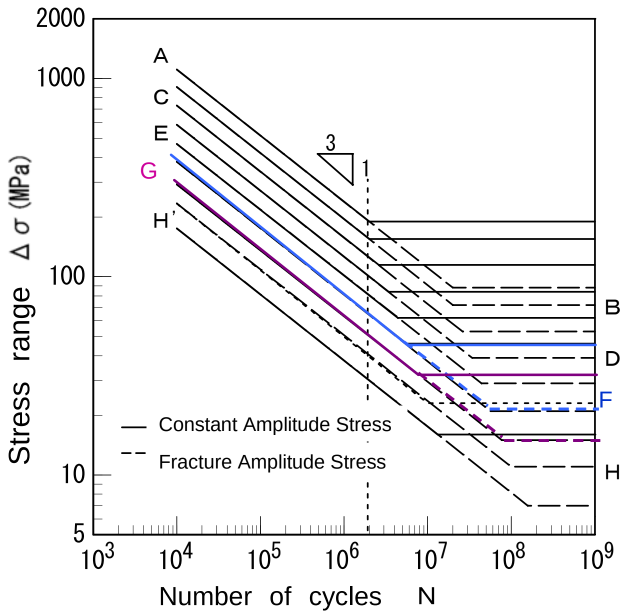
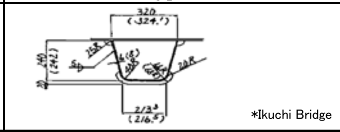
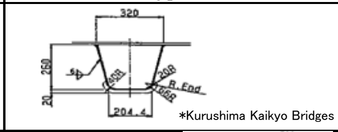
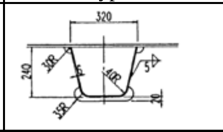
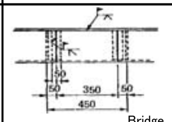
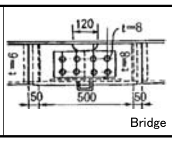
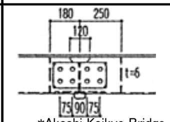
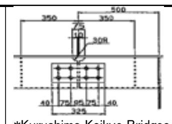
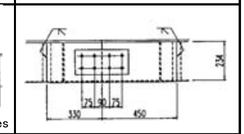
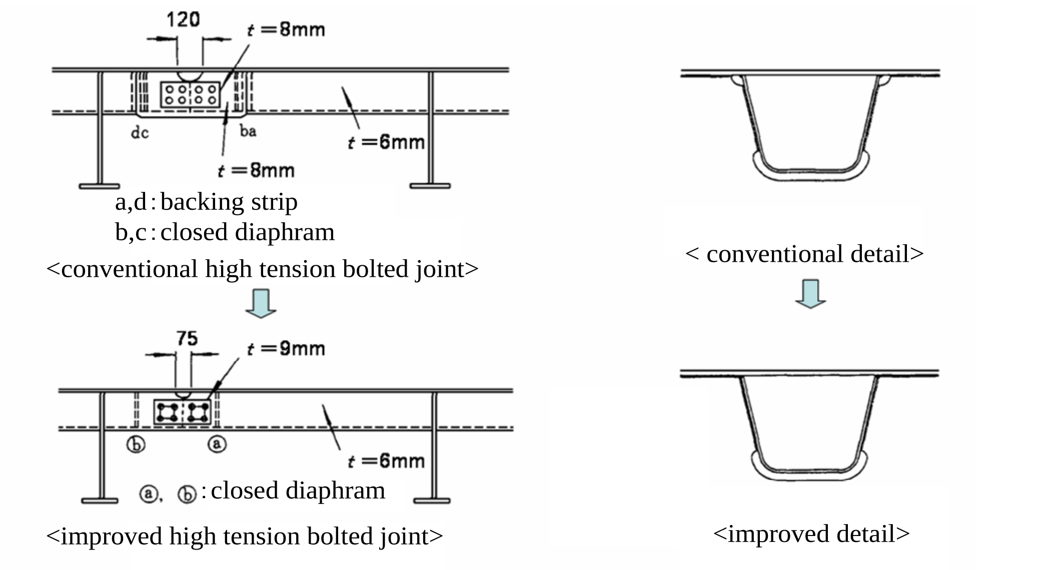


Figure 2: Stress Range versus Number of Cycle

Photo 1: Fatigue test with full-scale specimen of Honshu-Shikoku Bridges

Table 1: Orthotropic steel decks of Honshu-Shikoku Bridges

Detail/Bridges		Type A		Type B		Type C
Scallop of intersection between trough rib and lateral rib		 *Ikuchi Bridge		 *Kurushima Kaikyo Bridges		
Field joint of trough ribs		 Bridge	 Bridge	 *Akashi Kaikyo Bridge	 *Kurushima Kaikyo Bridges	
Bridges	Kobe-Awaji-Naruto Expressway	Ohnaruto Bridge		Akashi Kaikyo Bridge		
	Seto-Chuo Expressway	Shimotsui-Seto Bridge、Hitsuishijima Bridge、Iwakurojima Bridge、Kita Bisan-Seto Bridge、Minami Bisan-Seto Bridge	Yoshima Bridge			
	Nishi-Seto Expressway	Innoshima Bridge、Ikuchi Bridge; Ohshima Bridge			Shin-Onomichi Bridge、Tatara Bridge、Kurushima Kaikyo	



field joint of trough ribs by high tension bolt　　cross section of trough rib and transverse rib

Figure 3: Improvement in structural details of orthotropic steel decks

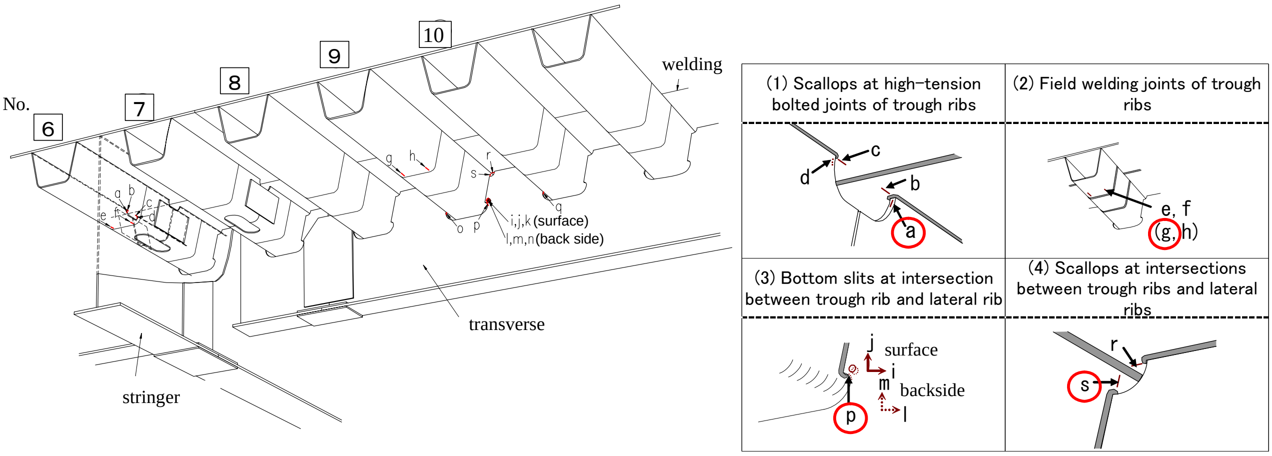


Figure 4: Stress measurement locations in the Ohnaruto Bridge

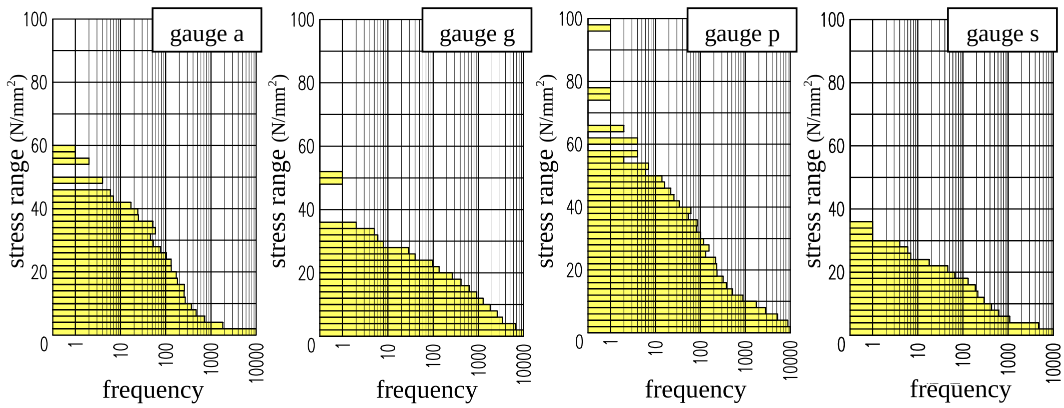


Figure 5: Stress measurement result in the Ohnaruto Bridge

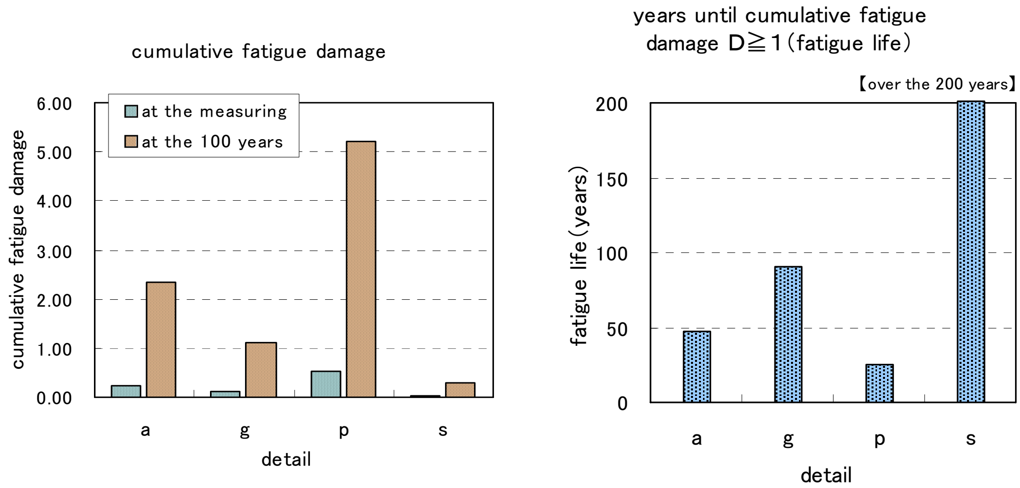


Figure 6: Evaluation of Fatigue damage and fatigue life in the Ohnaruto Bridge

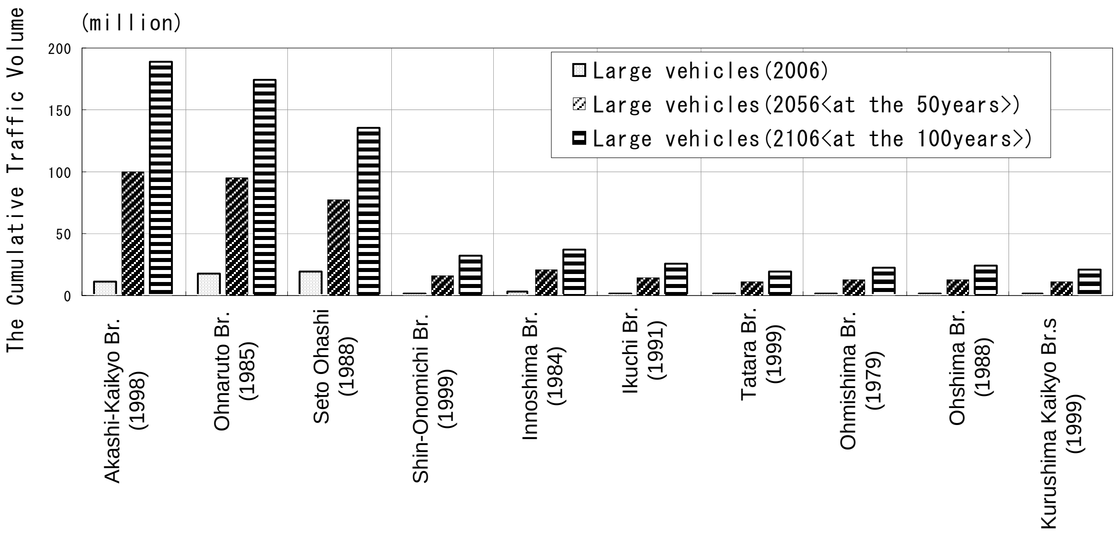


Figure 7: Cumulative traffic volume （completed year） of Honshu-Shikoku Bridges

Table 2: Important inspection details in orthotropic steel decks

Structures	Criteria	Selected bridges/locations/Details
Bridges	Cumulative traffic volume	○Ohnaruto Bridge ○Tozaki viaduct ○Seto Ohashi Bridges
Location of lateral direction	Location of wheel load	○Under wheel loads of heavy traffic lane
Details of orthotropic steel deck	Result of stress measurement (Note: ● is selected, considering fatigue damage examples in other operators.)	○Scallops at high-tension bolted joints of trough ribs ○Field welding joints of trough ribs ○Bottom slits at intersection between trough rib and lateral rib ●Welds between deck plate and trough rib ●Welds between deck plate and vertical stiffener

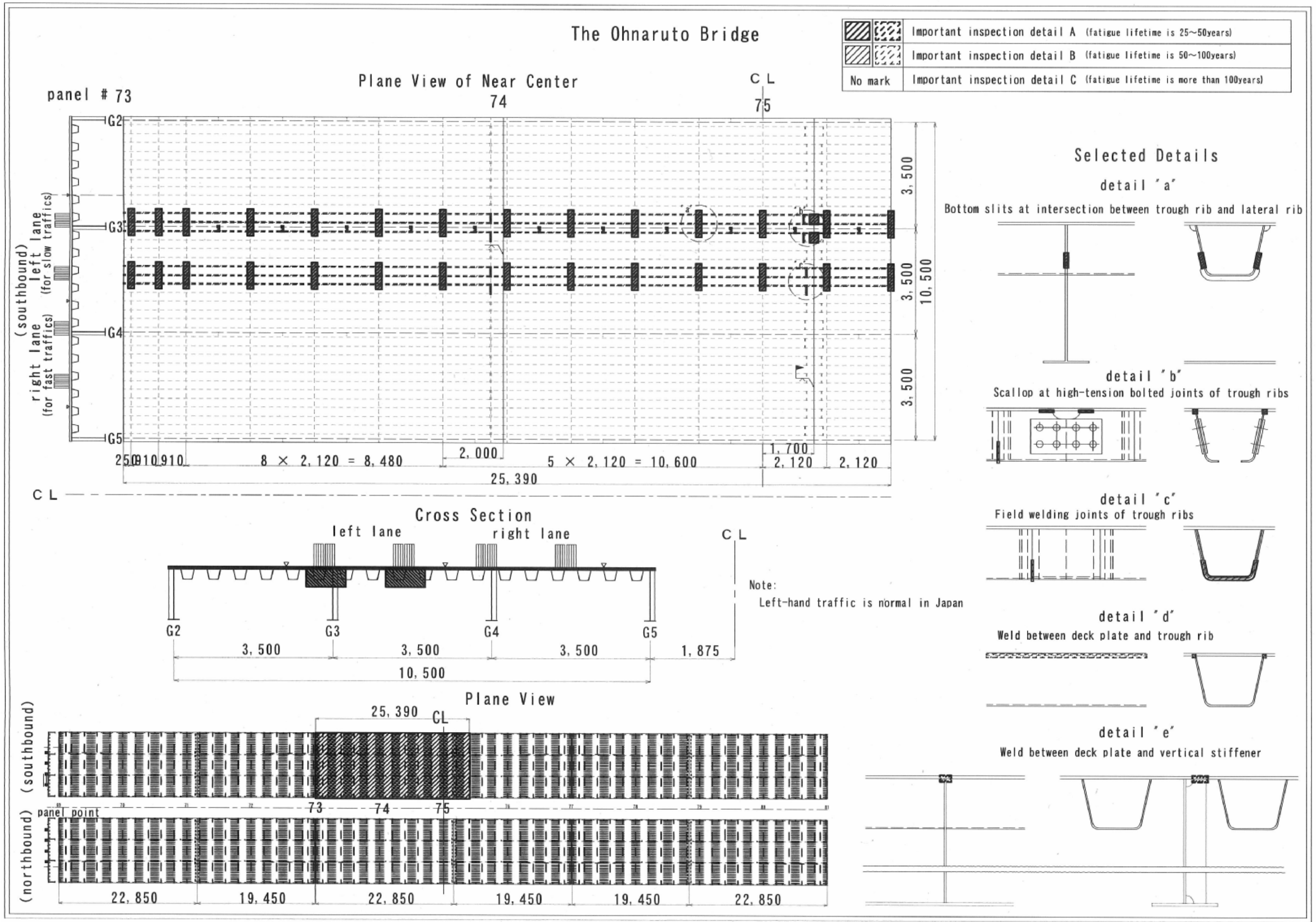


Figure 8: Example of fatigue hazard figure for orthotropic steel deck