Non-destructive inspection system for welded portions of the Honshu-Shikoku Bridges

Non-Destructive Inspection System for Welded Portions of the Honshu-Shikoku Bridges

Système de contrôle non-destructif des parties soudées dans les Ponts Honshu-Shikoku

Zerstörungsfreie Prüfung von Schweissverbindungen in den Honshu-Shikoku-Brücken

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SUMMARY

The Kojima-Sakaide route of the Honshu-Shikoku Bridges consists of the world's first large-scale combination of highway and railway bridges. Design and fabrication were conducted with consideration for fatigue based surveys in truss members subjected to railway loads. This report outlines the non-destructive inspection system developed for prompt detection of any fatigue cracks that may be generated in the bridge during usage, and also for evaluation of the cracks based on fatigue analysis.

RÉSUMÉ

L'itinéraire Kojima-Sakaide des ponts entre Honshu et Shikoku est la première véritable grande liaison au monde combinant le rail et la route. Le comportement à la fatigue des treillis soumis à la charge des trains a été prise en due considération tant au stade de la conception qu'au stade de la construction. La Honshu-Shikoku Bridge Authority a mis au point un système de contrôle non-destructif des soudures visant à déceler le plus tôt possible les fissures de fatigue et à évaluer leur évolution par une analyse de la fatigue.

ZUSAMMENFASSUNG

Der Kojima-Sakaide-Abschnitt des Honshu-Shikoku-Brückensystems besteht aus der ersten grossen Kombination aus Strassen- und Bahnbrücken der Welt. Überlegungen zur Ermüdung von Fachwerkstäben unter Eisenbahnlast werden in Planung und Ausführung berücksichtigt. Es wurde ein Verfahren zur zerstörungsfreien Prüfung von Schweissarbeiten entwickelt, um eine rasche Erkennung von Ermüdungsrissen in der Brücke, eine Auswertung von Rissen basierend auf Ermüdungsanalyse sowie geeignete Wartungs- und Instandsetzungsarbeiten zu ermöglichen.

1. INTRODUCTION

The Kojima-Sakaide route, often called the Seto Ohashi Bridges, of the Honshu-Shikoku Bridges, consists of the world's first large-scale combination of highway and railway bridges. Design and fabrication were conducted with consideration for fatigue based on years of surveys of fatigue in truss members subject to railway loads. A record of inspections during the fabrication process has been kept.

Since the Seto Ohashi Bridge was opened for service in April 1988, advanced maintenance for its important role has been required. The maintenance of fatigue cracking in welded portions is especially important to ensure the soundness of the bridge.

This report outlines the "Non-destructive Inspection System for Welding on the Seto Ohashi Bridges," which was developed for prompt detection through non-destructive inspection of any fatigue cracks that may be generated in the bridge during usage, and also for the evaluation of the cracks based on fatigue analysis. The report covers not only considerations for fatigue in the design and fabrication stages, but follow up and evaluation of fatigue strength during usage.

2. DESIGN, FABRICATION, AND INSPECTION OF TRUSS MEMBERS BASED ON EVALUATION OF FATIGUE

The fatigue design of the Honshu-Shikoku Bridge is based on how fatigue cracks advance. By preventing fatigue cracks from penetrating the steel plate, during the durable years (100 years) of a bridge established in the design, serious damage to it can be avoided. When fabricating members, fatigue of the main chord members is given primary consideration. With corner welds on the main chord members, for example, design and fabrication is based on the following ideas:

① Fatigue cracks are generated from welding failure in the blow holes of the root portion.

② Fatigue cracks are generated in the early stages of repeated stress and fatigue life is almost the same as crack advancement life.

③ The number of repetitions of fatigue cracks advancing 80% the distance from the root to the surface of the plate is considered to be a measure of the end of fatigue life.

④ Welding failure of blow holes that generate fatigue cracks cannot be completely avoided, so allowable values of initial failure in fabrication should be set and places where failure exceeds these values should be repaired.

As Table 1 shows, based on these ideas, in fabricating members of thermal refined high strength steel, members are classified according to the ratio of their working stress range and their allowable stress range, and allowable dimensions of failure are determined for each member. For detection of failure in corner welds, ultrasonic flaw examinations, in which blow holes as small as about 1 mm can be detected, are done. In fabrications in use, all failures exceeding allowable values are repaired and those within allowable values are recorded for future maintenance management servicing.

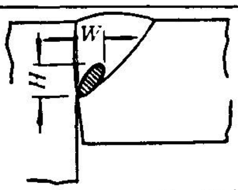
Member class	Working stress range (σ_r) / allowable stress range (σ_{fa})	Allowable dimensions	Notes
Special A	$0.7 \leq \frac{\sigma_r}{\sigma_{fa}}$	$W \leq 1.5$mm $H \leq 4$mm	
A	$0.5 \leq \frac{\sigma_r}{\sigma_{fa}} < 0.7$	$W \leq 3$mm $H \leq 6$mm	
B	$\frac{\sigma_r}{\sigma_{fa}} < 0.5$	$W \leq 3$mm $H \leq 6$mm	

Table 1 Classification of inspection standards of members using thermal refined high strength steel (corner welds)

Compared to inspections done during fabrication at the factory, however, the following problems exist with non-destructive inspections of actual bridges:

① Crack locations are difficult to determine.

② Means of approaching members closer are inadequate.

③ Inspections are done from all angles.

④ Inspections are done from above the coating.

To deal with these problems, a committee for examining the non-destructive inspection system being used was established and investigations related to the above problems were done over a period of four years as the bridge was built.

3. EXAMINATIONS ON ACTUAL BRIDGES

3.1 Confirmation of automatic ultrasonic flaw detection technology

3.1.1 Improvement of ultrasonic flaw detectors

Equipment was developed featuring the improvements listed below and no performance sacrifices over equipment used in inspections during fabrication.

① As Figure 1 shows the main unit has the following components: ultrasonic flaw detector, computer, controller, and plotter.

② The probe scanner is small and light, and the device has a new structure that enables inspections to be done above and to the sides.

③ Data is stored on floppy disks so it can be reexamined, which heightens the accuracy of flaw detection evaluation.

④ In addition to corner joints, the automatic flaw detection function can now be used on butt joints and T-joints.

Figure 2 shows the probe arrangement for inspecting corner joints with the equipment. As with the equipment used for doing inspections during fabrication, penetration depth is measured with the point focusing vertical probe P, and failure inspections are done with the point focusing beveled probes (reflection angle of 45°) F-AF and F-AB and the point focusing vertical probe F-N. The results are output as shown in Figure 3. Results of inspection with the three probes for flaw inspection are shown in columns FLAW-N, FLAW-AF, and FLAW-AB. LEVEL shows the peak echo values of each scan line, and PLAN VIEW shows the shapes of penetration lines and flaws (marked in white) as observed from the surface of the detected flaw.

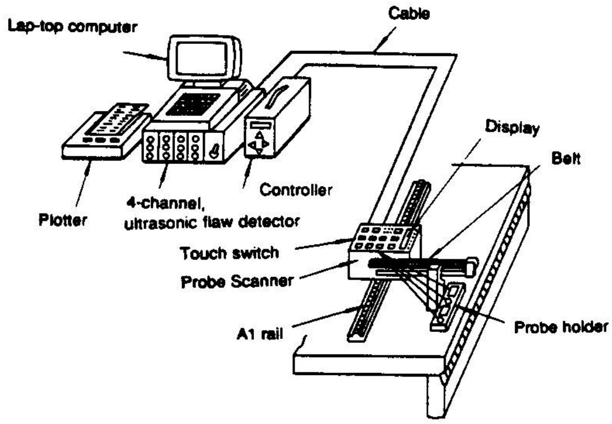


Fig. 1 Configuration of the small, automatic, ultrasonic flaw detector

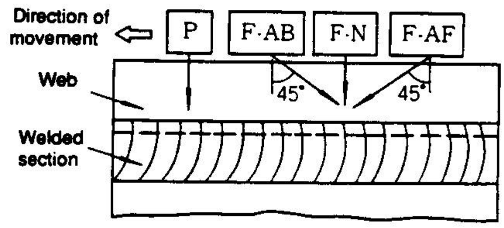


Fig. 2 Probe arrangement for flow inspection of corner joints

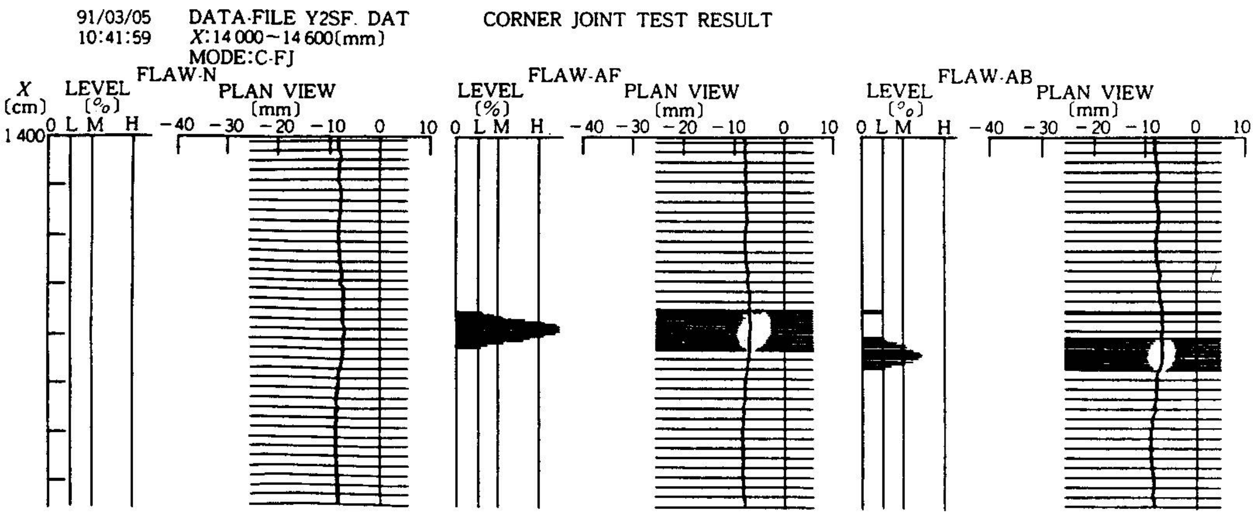


Fig. 3 Example of results of an inspection conducted with the equipment developed

3.1.2 Confirmation of the applicability of the equipment to field inspections

Field flaw detection tests were done on the Kitabisan Seto Ohashi Bridge to examine the applicability of the equipment developed. The primary objects of the tests were as follows:
1) Ability to reach inspection points
2) Effects of equipment positioning
3) Effects of coating

Automatic ultrasonic flaw detection was done during fabrication and before coating; each member of bridges in use was coated to a thickness of 255 μm. Therefore, places where blow holes of less than the allowable value remained were field inspected and the effects of coating on flaw detection was examined. The results are shown in Table 2. Surfaces of detected flaws were coated to a thickness of 288-307 μm, but the results were the same as in tests conducted during fabrication. It was confirmed that there were no problems in detecting flaws through the coating.

Field tests showed that, by using the equipment developed, the same inspections done during fabrication can be done on bridges in use, inspection data collected during fabrication can be followed up on in field inspections, and new data can be accumulated.

Flaw No.	Result of inspection during fabrication		Result of field inspection		
	Estimated flaw dimensions		Coating thickness	Estimated flaw dimensions (mm)	
	Width	Height	(μm)	Width	Height
79	0.8	1.5	279-288	0.7	1.6
80	0.8	1.4	295-307	0.8	1.2

Note) The same probes and sensitive standard test pieces were used to set sensitivities at the same levels.

Table 2 Comparison of inspection during fabrication and field inspection

3.1.3 Examination of the method for measuring the frequency of fatigue stress

To rationally determine inspection frequency and the need for repairs by analyzing fatigue life with a non-destructive inspection system, it is important to accurately estimate the degree and frequency of stress on evaluation points. Therefore, to predict the frequency of stress on actual bridges by using data collected in stress analysis in the design phase, the frequency of fatigue stress on each member of the Kitabisan Seto Ohashi Bridge was measured and analyzed.

4. CONSTRUCTION OF A NON-DESTRUCTIVE INSPECTION SYSTEM

Based on the results of the above examination and measurements from field tests, a non-destructive inspection system was designed and an interactive system featuring personal computers with user-friendly menus was developed.

4.1 System functions

Figure 4 is a flow chart of the system, which has the following five primary functions:

1) Retrieving and updating flaw data
   All data on flaws detected through non-destructive inspection during fabrication which are less than the allowable value are input into a table. Data can be retrieved, and new data obtained during inspections can be input.
2) Display of the distribution of flaw data
   Data on blow hole size, which constitutes most of the detected failure data, were classified into classes A to D. The distribution of the frequency of flaws on each member is displayed as shown in Figure 5. In addition, for members with Class A or B flaws, data detailing the location and dimensions of each flaw are displayed as shown in Figure 6.
3) Display of fatigue design data
   The class of each member according to the required quality and fatigue design stress range are displayed.
4) Fatigue analysis
   Fatigue crack advancement analysis using flaw data collected through non-destructive inspection and fatigue strength analysis of welded joints where the generation of fatigue cracks is a concern were done to rationally determine inspection frequency and the need for repairs.

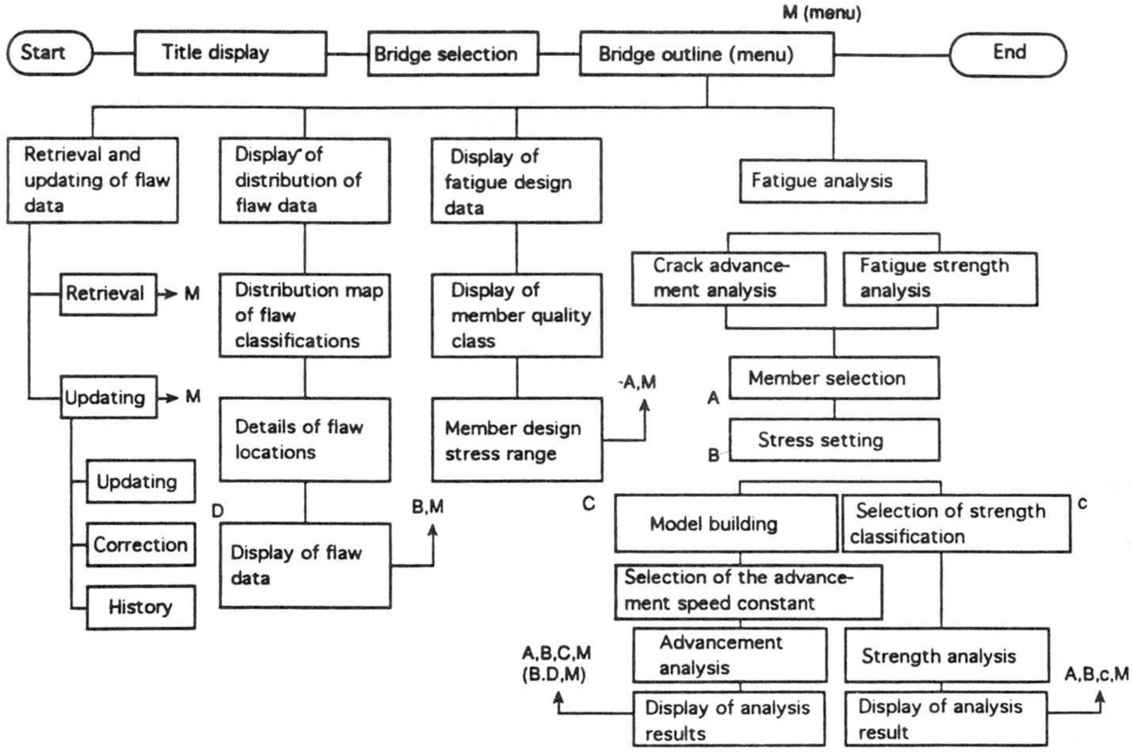


Fig. 4 System flow chart

The contents of the crack advancement analysis are shown below. In the equations of fatigue crack advancement speed, numerical integration is repeated from the initial crack dimensions a_i to the crack dimension limit a_f.

$$da/dN = C(\Delta K^n - \Delta K_{th}{}^n) \qquad \ldots\ldots\ldots\ldots\ldots\ (1)$$

$$da_i = C(\Delta K^n - \Delta K_{th}) \cdot dN_i$$

where, da/dN: fatigue crack advancement speed
ΔK: range of the stress expansion coefficient
C, n: constant
ΔK_{th}: range of lower limit of stress expansion coefficient

With this system, 11 analytical models, including a root blow hole model, are used in accordance with the characteristics of the members of the Honshu-Shikoku Bridges. When selecting which evaluation model to use, the stress expansion coefficient ΔK in the equation (1) is automatically determined. ΔK is expressed below.

$$\Delta K = \Delta\sigma\sqrt{\pi a} \cdot F$$

where, Δσ: stress range
a: crack dimensions

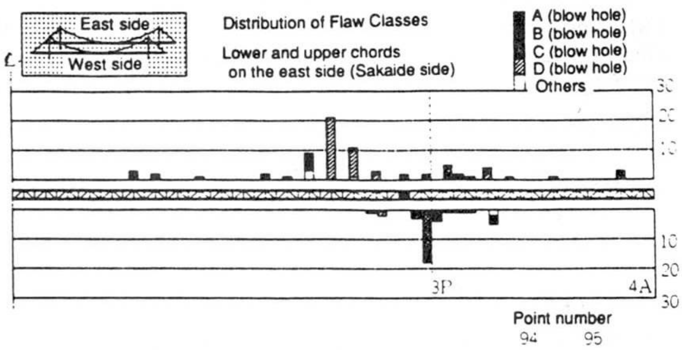


Fig. 5 Distribution of flaw class

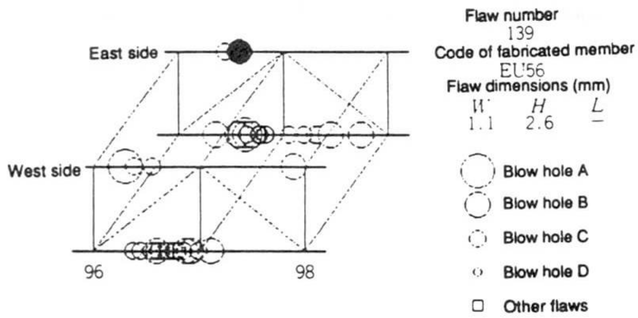


Fig. 6 Details of flaw cocations

F: correction factor for concentrated stress on and crack shapes of joints

The first step in the analysis is to input the initial flaw dimensions a_i Then, based on the examination results derived with the method in Section 3.1.3 for predicting fatigue stress frequency, fatigue loads preset for each member are set. (Since the secular change of traffic load conditions can be input in the form of a coefficient, analysis incorporating changes in traffic volume after the bridge is in use and predictions can be conducted.) When crack advancement speed data C, n, and ΔK_{th} are set from data obtained by the Honshu-Shikoku Bridge Authority, the system automatically analyzes crack advancement and the results are displayed in the form of a crack dimension curve and a crack shape diagram, as shown in Figure 7. Fatigue strength analysis can also be done with the system.

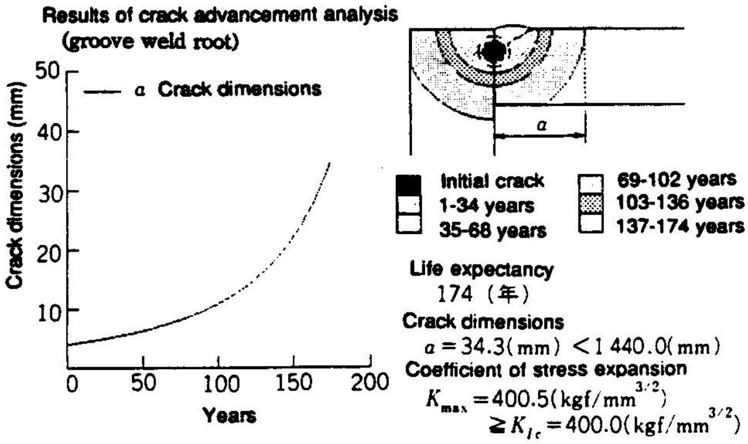


Fig. 7 Example of results of crack advancement analysis

4.2 Configuration of system hardware

The system has a 32-bit IBM personal computer (40MB hard disk, built-in 2-drive floppy disk, and an additional 6MB of extended memory) and a color printer.

5. CONCLUSION

Based on studies of fatigue on the Honshu-Shikoku Bridge and tests on actual bridges for verification of conditions for systematizing technologies, a comprehensive non-destructive inspection system was developed. The system enables the following: retrieval and distribution display of flaw data obtained in ultrasonic flaw inspections of the Kitabisan Seto Ohashi Bridge; and, with consideration for stress frequency and member characteristics, fatigue crack advancement analysis and fatigue strength analysis.

There are many cases in which accurate surveys and analyses must be urgently done to evaluate the soundness of a large bridge. However, with this system, these types of survey and analysis can be performed in daily inspections. Therefore, this system is very useful for proper maintenance management of the Seto Ohashi Bridges. In the future, we are planning to extend use of the system to other bridges.

6. REFERENCES

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