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Maintaining and Extending the Lifespan of Steel Bridges in Japan

Maintenance et réhabilitation des ponts métalliques au Japon

Wartungsarbeiten und lebensverlängernde Massnahmen an Stahlbrücken in Japan

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SUMMARY

A review is made of fatigue problems related to maintaining and extending the lifespan of steel bridges in Japan, mainly on the Tokaido Shinkansen bullet train system opened in 1963, Tomei Expressway opened in 1969 and the Honshu-Shikoku bridge project which is under construction.

RÉSUMÉ

Le rapport traite des problèmes de fatigue concernant la maintenance et la durée de vie des ponts métalliques au Japon, en particulier sur la ligne ferroviaire à grande vitesse Shinkansen Tokaido inaugurée en 1963, sur l'autoroute Tomei ouverte au trafic en 1969 et pour le projet des ponts de Honshu-Shikoku en cours de construction.

ZUSAMMENFASSUNG

Diese Arbeit ist ein Bericht über Ermüdungserscheinungen in Bezug auf Wartungsarbeiten und lebensverlängernde Massnahmen an Stahlbrücken in Japan. Es werden dabei Schwerpunkte gelegt, nämlich auf das Tokaido Shinkansen Eisenbahnsystem (1963 eröffnet), die Tomei Autobahn (1969 eröffnet) und die Honshu-Shikoku Brücke, die zur Zeit im Bau ist.

1. INTRODUCTION

A review is made here centered on the problems attributable especially to fatigue, in regard to maintenance of steel bridges in Japan mainly on the Tokaido Shinkansen bullet train system, Tomei Expressway, and Honshu-Shikoku bridge project. The Tokaido Shinkansen and Tomei Expressway were constructed as the forerunners of high-speed railways and automobile expressways of Japan and can be considered as infrastructures which had brought about the high-level economic growth of Japan. It may be said that the problems entailed by steel bridges in Japan are more or less covered by taking up these two. The Honshu-Shikoku bridge project, which make up a large-scale bridge project with construction now in progress, include the world longest suspension bridge, Akashikaikyo Bridge, and cable-stayed bridge, Tatara Bridge, in the world. The newest bridge technology of Japan is concentrated in this project.

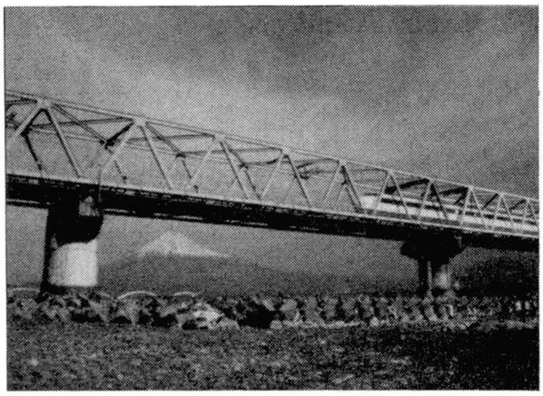
2. BRIDGES OF TOKAIDO SHINKANSEN

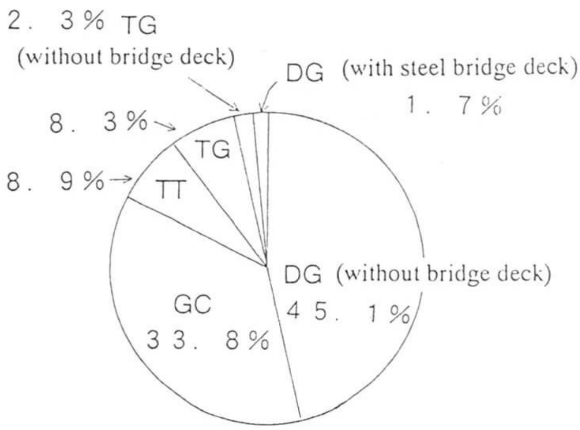
2.1 Description of bridges

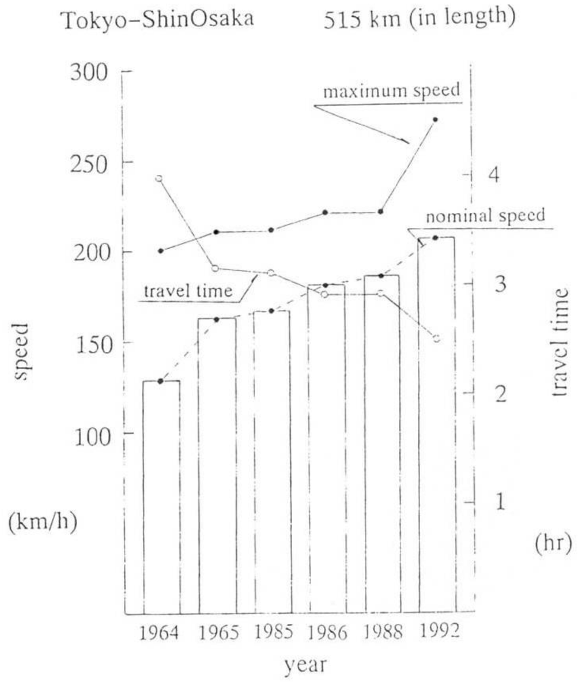
The outline of steel bridges in Tokaido Shinkansen are given in Table 1. Fig.1 shows the change of train speeds, travel time and the number of trains in one day from the opening to the present state. These have all changed in the direction of severity for structures. Only, the weight of train changes for the lighter.

Table 1. Outline of steel bridges in Tokaido Shinkansen

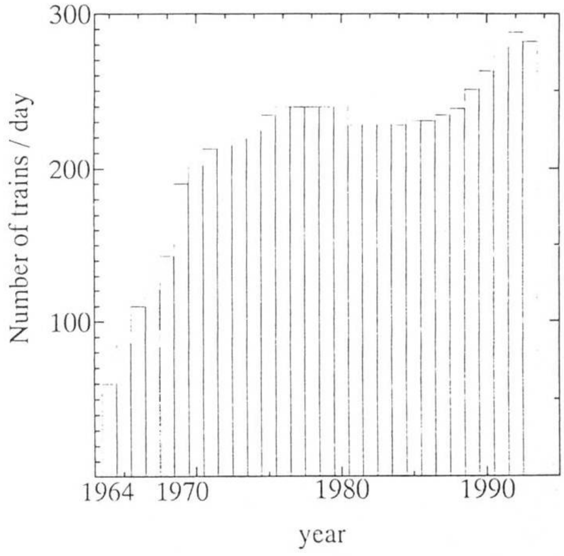
Type of Steel Bridge	Ratio	Number of girders	Total Length
Deck Plate Girder (without bridge deck)	45.1%	682	12.17
Composite Girder	33.8%	510	9.12
Through Truss	8.9%	135	2.40
Through Plate Girder (with steel bridge deck)	8.3%	125	2.24
Through Plate Girder (without bridge deck)	2.3%	34	0.62
Deck Plate Girder (with steel bridge deck)	1.7%	25	0.46
Total	100%	1511	27Km





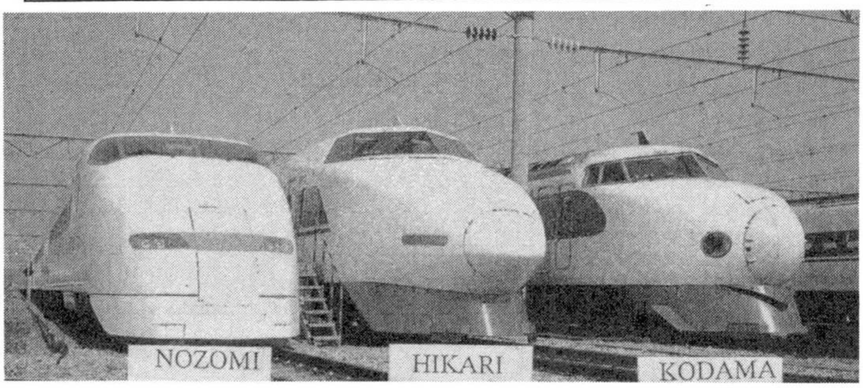


(a) speed and travel time



(b) number of trains

Name	Car Series	Weight(t/train(16cars))	Capacity	Max Speed(km/h)
KODAMA	0	970	1391	220
HIKARI	100	925 ▲45	1321	220
NOZOMI	300	710 ▲215	1323	270



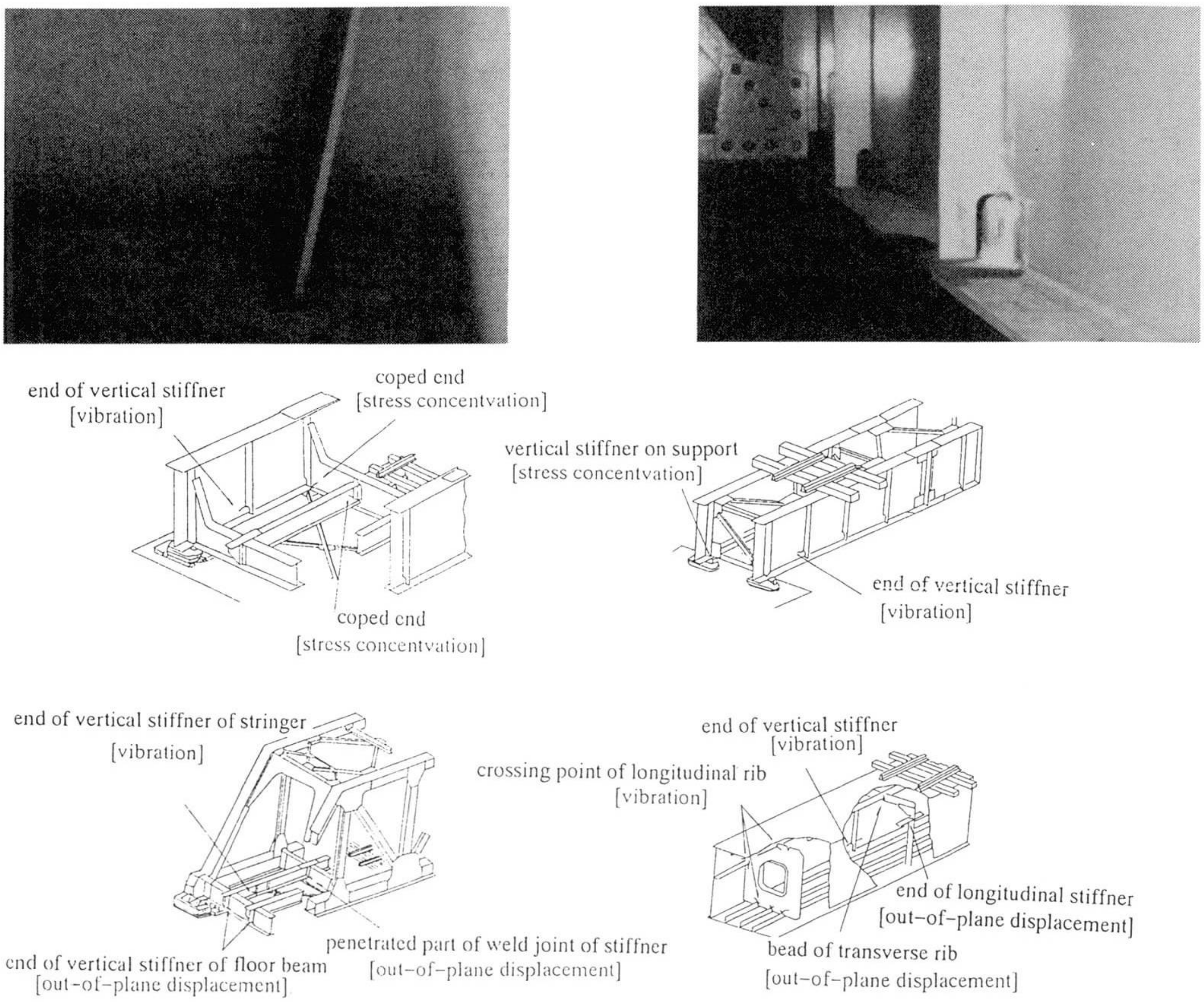
(c) train cars

Fig.1 Changes of service conditions

Fatigue design of steel bridges had done based on design specifications established in 1960. These specifications were strongly influenced by DIN, but especially with regard to welded joints, the results of fatigue tests which were carried out in Japan were taken up in the establishment. The fatigue design standards had set up allowable fatigue stresses based on fatigue strengths at two million cycles which were considered as fatigue limits, but considerations such as to take design fatigue train load as 18 tons against design train load of 16 tons with the aim of reflecting difference in influence line length on number of design stress repetitions are given.

2.2 History of fatigue cracking

Occurrences of fatigue damage began to be reported concerning bridges of the Tokaido Shinkansen from around 10 years after having been put into service. An outline is given in Fig. 2, with cases of damage being those resulting from stress concentrations due to structural details of members, those due to out of plane displacements occurring between perpendicularly crossing members such as main girders and cross beams or cross beams and stringers, and those due to vibration induced distortion by high-speed operation of trains peculiar to Shinkansen[1].



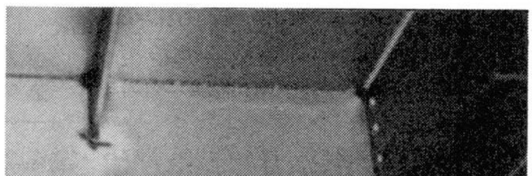


Fig.2 Fatigue damage in steel bridges of Tokaido Shinkansen

2.3 Maintenance inspection

Inspections of Shinkansen consist of periodic regular inspections have been arrived out every two years and individual special investigations have been formed when any damage is found during a periodic regular inspection. Inspections of structures are made by engineers of Central Japan Railway Co. which manages and operates this line. These engineers have thorough knowledge about fatigue and corrosion which occur in bridge structures, and possess the capability of carrying out stress measurements, nondestructive test, etc. They also periodically undergo training in skills concerning these technologies.

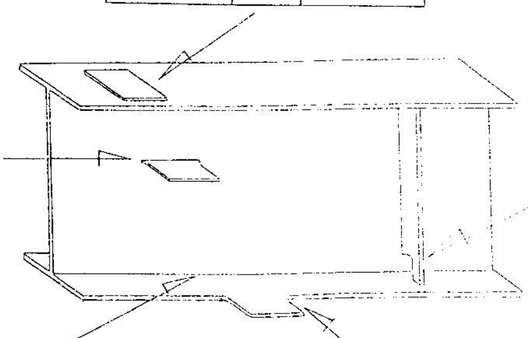
Selection of contents of special individual special investigations and evaluations are made by specialists consisting of engineers of the Railway Technical Research Institute and university professors, including the author. The necessary retrofitting measures are discussed by the above mentioned group, upon which recommendations are made to Central Japan Railway Co..

2.4 Damage prevention works

When what had been assumed at the time of designing and the subsequent condition of use are considered, certain parts in bridge structures are approaching the ends of their design service lives. Therefore, a number of preventive and protective set-ups against fatigue damage have been established. What have great differences in allowable fatigue strengths between the time when Shinkansen was designed and the current design standards are longitudinal weld between flanges and webs, and ends of gusset plates welded to webs (Fig.3). They are the points in damage prevention work.

Joint	Sleeper pad	
Code	Class	2×10^6 Fatigue Strength
Old code '60	$\bar{D}$	120MPa
Current code '92	F	65MPa

Joint	Out-planegusset(r=20mm)	
Code	Class	2×10^6 Fatigue Strength
Old code '60	D	100MPa
Current code '92	F	65MPa



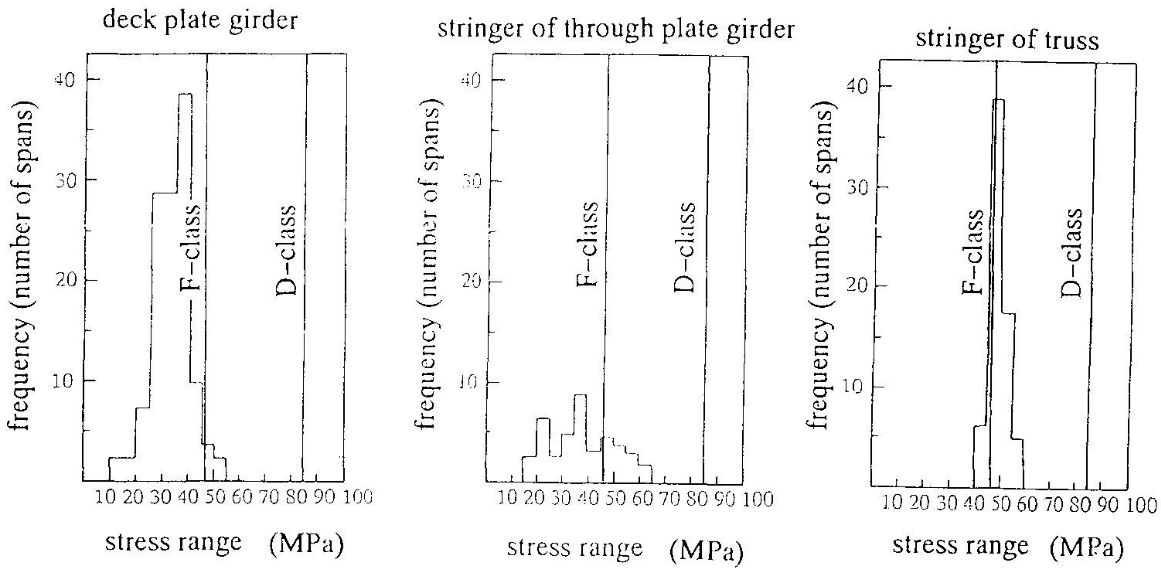
Joint	Cruciform weld	
Code	Class	2×10^6 Fatigue Strength
Old code '60	D	100MPa
Current code '92	E	80MPa

Joint	Longitudinal weld	
Code	Class	2×10^6 Fatigue Strength
Old code '60	B	150MPa
Current code '92	C	125MPa

Joint	In-plane gusset(r=20mm)	
Code	Class	2×10^6 Fatigue Strength
Old code '60	C	126MPa
Current code '92	F	65MPa

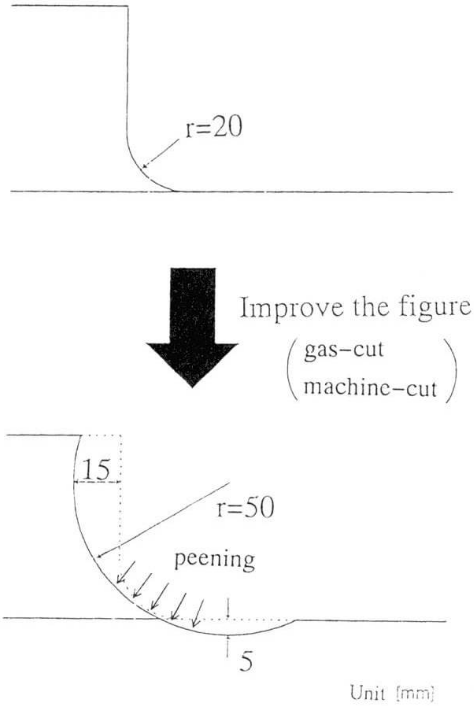
Fig.3 Changes of allowable fatigue stress from '60 code to '92 code

One of damage prevention works is measurement of actual stresses. This is done regarding plate girders and the stringers of truss girders. To elaborate, since stresses in bridge members actually occurring are normally low compared with those in design calculations, it is thought to consider maintenance based on stresses actually occurring. Stress measurements for this purpose consist of grasping the bending stress on average occurring in the bottom flange and the location of the neutral axis. The reason for actual stresses being low compared with calculated stress in case of railway bridges, lies in the load distribution due to rails and secondary members. The results of stress measurements are illustrated in Fig. 4, in which it is clearly shown that the possibility of fatigue damage in a fairly large number of members is high on the basis of design calculated stress, however, there is hardly any cause for concern when actual stress is observed. Regarding longitudinal welds joining flanges and web (categorized into C class), it was learned that there was ample allowance from measurements of actual stresses, but the degrees of allowance at the ends of gussets attached to flanges (categorized into F class) were slightly small. Hence, remedial measures regarding fatigue strength are presently under study for this gusset detail. Methods being considered are to increase the radius of the fillet at the end of the gusset and, further, to add residual compressive stress by peening, and the effectivenesses are being examined through fatigue tests (Fig.5).



Fatigue category	longitudinal joint	: C
	vertical stiffener end	: E
	flange gusset detail	: F

Fig.4 Variation of measured maximum stress range and fatigue assessments



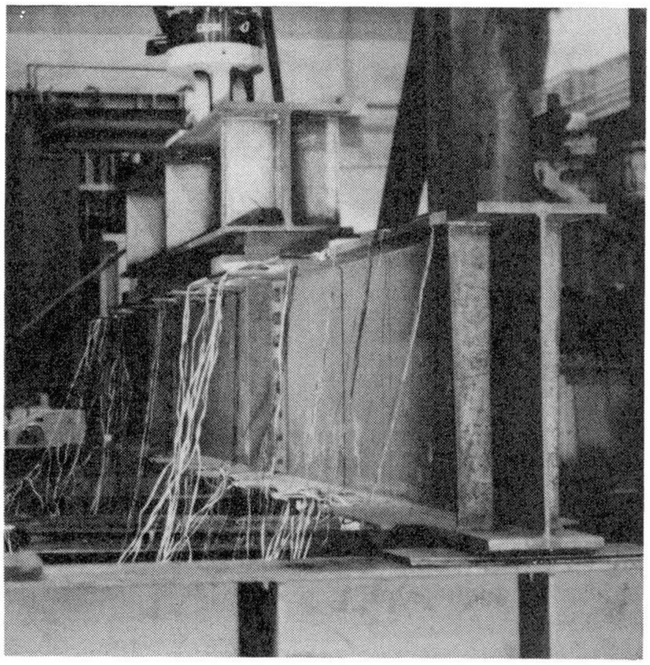


Fig.5 Improving work of flange gusset detail and fatigue test

3. TOMEI EXPRESSWAY

3.1 Description and history of bridges

The numbers highway bridges constructed in Japan by year are shown in Fig.6. It can be seen that construction of infrastructure facilities in Japan has been concentrated in a certain period. As a consequence, an enormous number of bridges will become antiquated at once, and measures to cope with such a situation will be of grave importance.

Tomei Expressway is the first expressway in Japan, which was constructed in 1965-1968. There are 112 plate-girder bridges (composite and non-composite) on the part of the Tomei Expressway under the Tokyo First Operation Bureau of the Japan Highway Public Corporation which operates about 85% of Tomei Expressway. Of these, approximately 58 percent are quadruple-main-girder bridges, 37 percent are triple-main-girder bridges, and the remainder small numbers of quintuple-main-girder and sextuple-main-girder bridges. The thicknesses concrete deck slabs are 180 to 200 mm for triple-main- girder bridges while 170 to 190 mm for quadruple-main-girder bridges. Besides plate girder bridges, there are some truss girder bridges and arch type bridges on Tomei Expressway. In all of the bridges damage began to occur in the reinforced concrete deck slabs four to five years after being put into service, and stringers for supporting deck slabs are being added starting in order from bridges in the poorest condition. The transitions in the states of service of the Tomei Expressway are shown in Fig.7. Traffic volume has increased sevenfold in 30 years. A feature is the high proportion of large vehicles such as trucks and trailers. Vehicle scales are installed in main traffic lanes at Nihondaira on the Tomei Expressway. According to records kept since opening of service, the maximum weights of automobiles passing have been constant with the times (Fig.8).

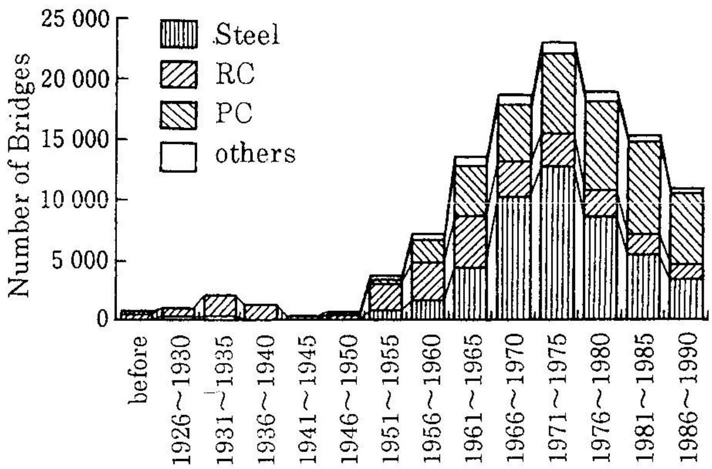


Fig.6 History of bridge construction

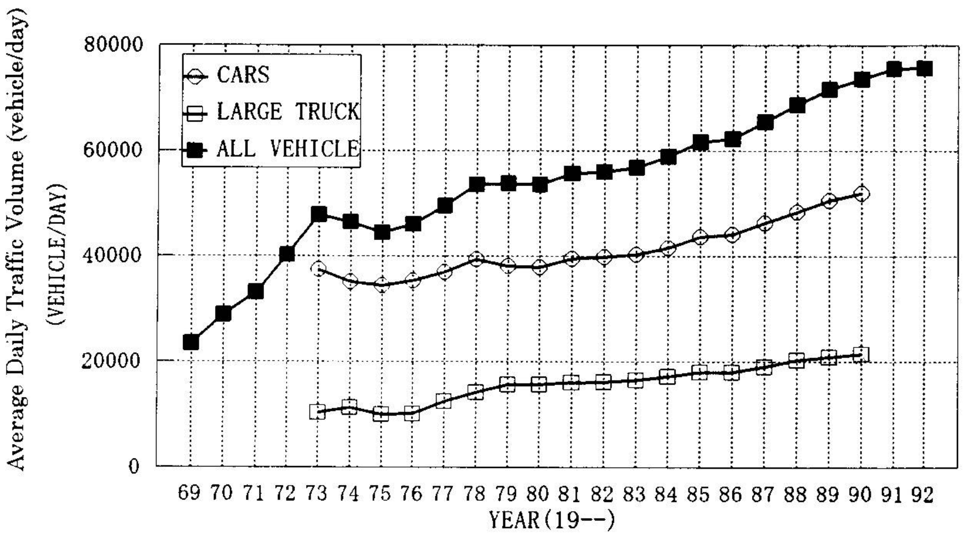


Fig.7 Change of daily traffic volume

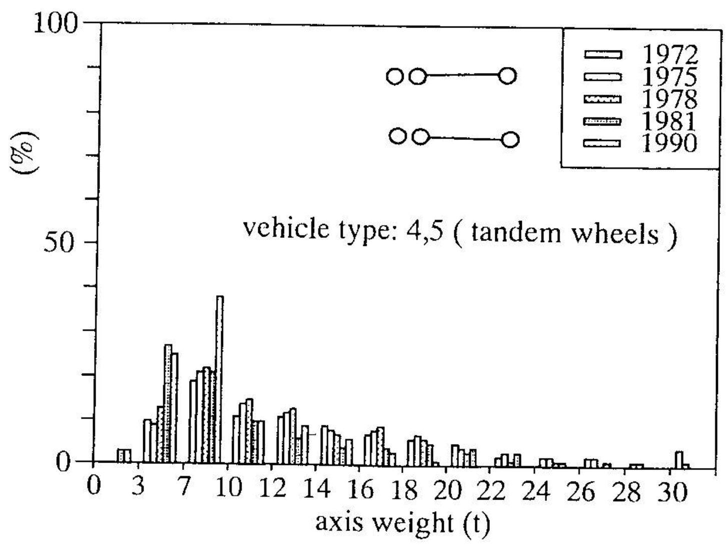


Fig.8 Measured axis weight

3.2 History of cracking and retrofitting works

The types of fatigue damage in steel plate girder bridges of the Tomei Expressway are shown in Fig. 9 [2]. Various types of fatigue damage have been observed. The percentage of occurrence is highest for fatigue cracks at the ends of vertical stiffeners with sway bracing attached. and detailed studies have been made on this fatigue. It has been found to be due to force acting so that displacement will occur orthogonally to the web from differences in deflections between girders and deformations of deck slabs.

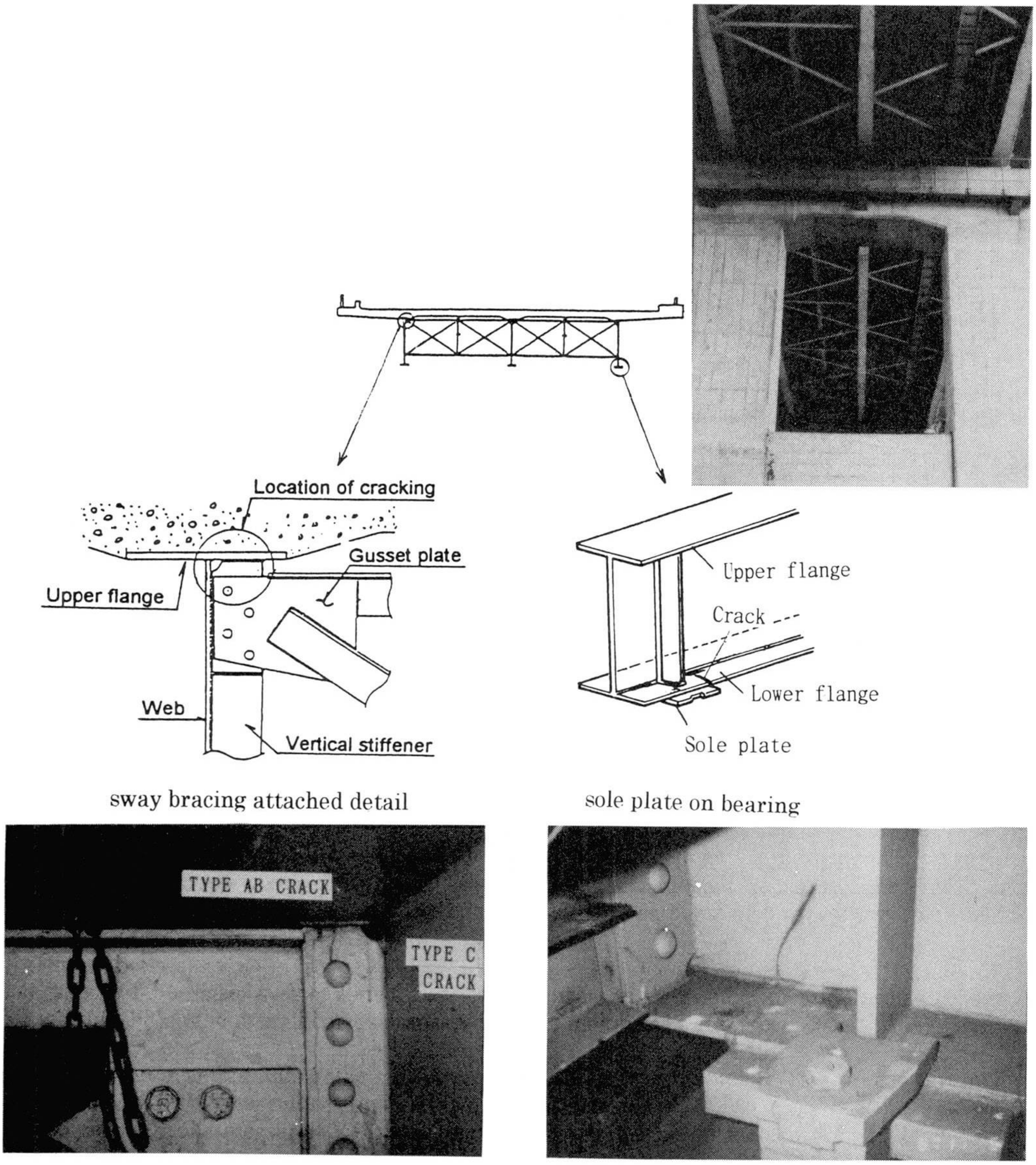


Fig.9 Typical fatigue damage in plate girder bridge

The measures taken against these fatigue cracks are differed according to the levels of cracking (Fig.10). For cracks with lengths at the surface not more than 20 mm, the basic measure applied is to add one pass of welding on top and then remelting with TIG dressing (Fig.11). For fatigue damage longer than that, damaged parts are all removed by gouging, and after rewelding, the surface is simultaneously treated with TIG dressing. The procedure of gouging, rewelding, and TIG dressing is predetermined in details. As a result of inspection approximately 5 years after such a measure had been taken, most parts were sound, but cracks were found again, although few in number, at repaired parts where fatigue cracks had been large.
At bridges with prominent damage, the load applied in the lateral direction by existing sway bracing is to be alleviated by adding sway bracing in improved joint details (Fig.12). The joint details between the sway bracing and main girder at this time was proven by fatigue tests to have been improved. The stresses at fatigue crack occurrence points were reduced approximately 20 percent by providing this measure, while further, stresses were reduced approximately 30 percent by detaching the horizontal members of existing sway bracing.

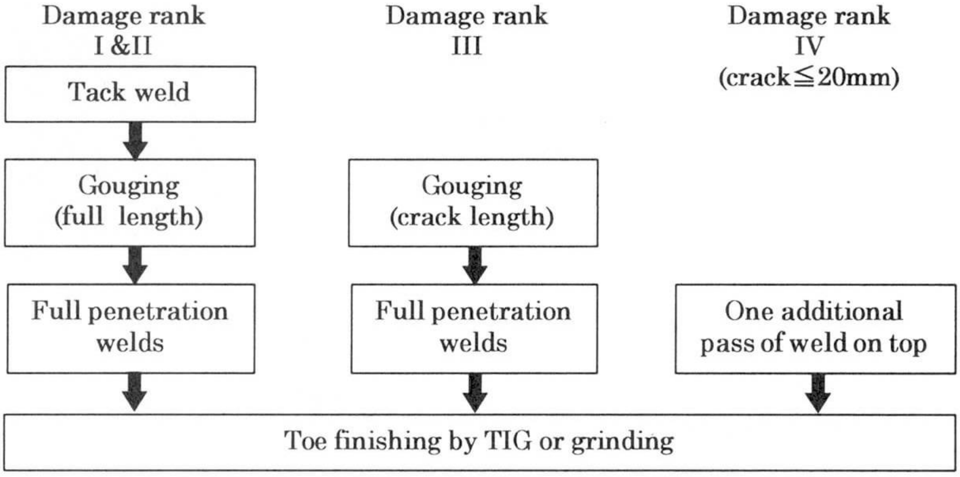
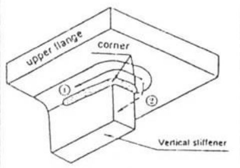


Fig.10 Retrofit methods depend on damage ranks

TIG-dressing conditions

position aimed at by TIG arc	the toe of weld bead
electrod	thoriated tungsten 3.2mm in diameter
current	240 A
flow rate of argon	10 ℓ /min
TIG arc movement	10~20 cm/min 

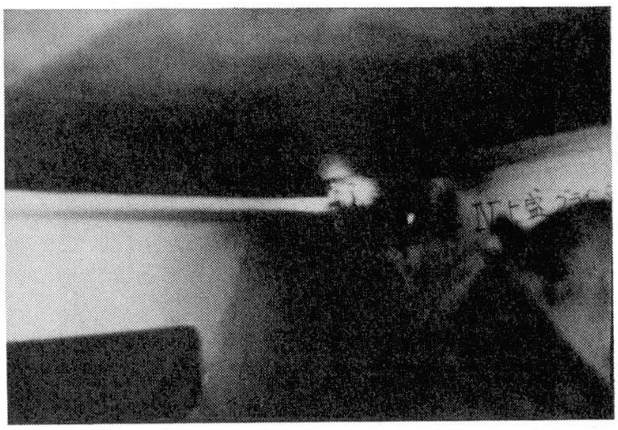


Fig.11 Finishing by applying TIG dressing

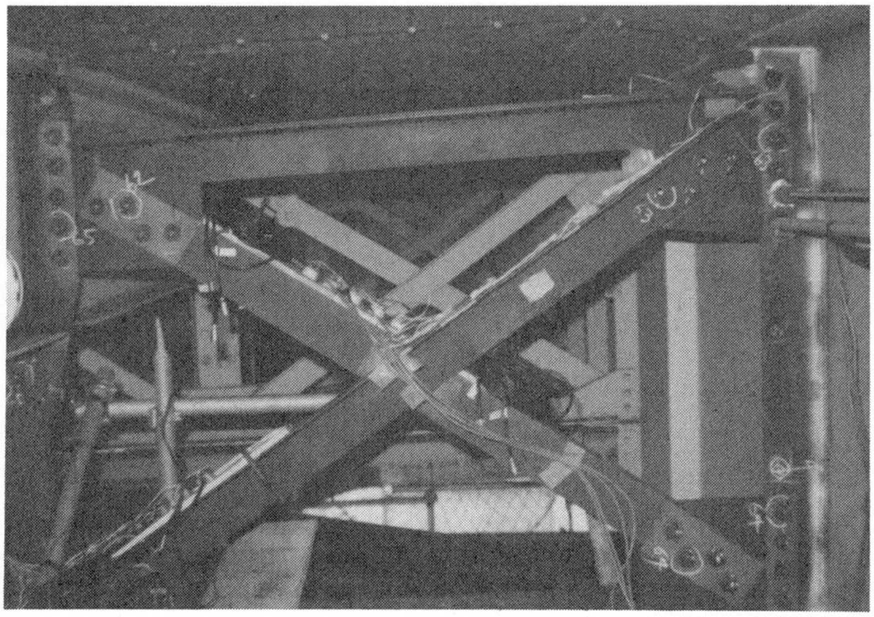


Fig.12 Adding work of sway bracing

What have become conspicuous recently are cracks around sole plates of bearing points of main girders (Fig.13).Fatigue cracks have occurred in fillet welds for attaching sole plates to main girders and fillet welds between main girders and webs The feature of this damage is that it occurs in a girder which has impairment of the rotating function of its support. The bearing point is the point where loading concentration is the severest in a bridge, while structurally , since this location is at a distance from the neutral axis, the stress is different from that according to the beam theory, and the deterioration of the support function causes such a condition to come about. Regarding this damage, the sole plate is exchanged for a larger one, attaching it with high-strength bolts, while further, structural improvements such as to add vertical stiffeners are provided (Fig.14).

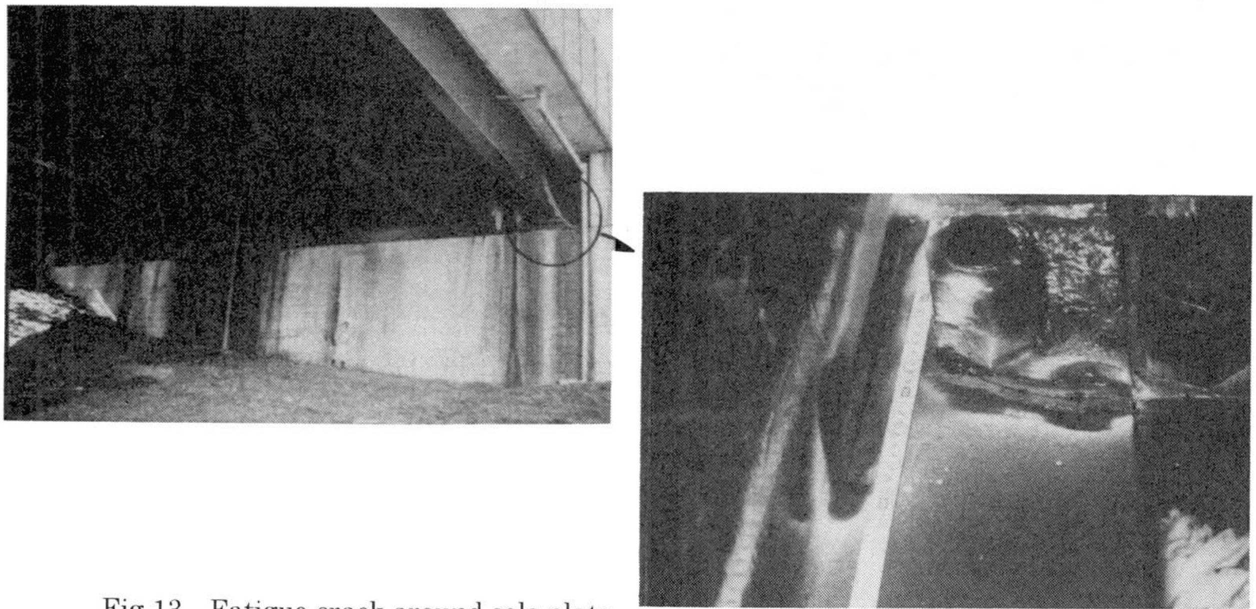


Fig.13 Fatigue crack around sole plate

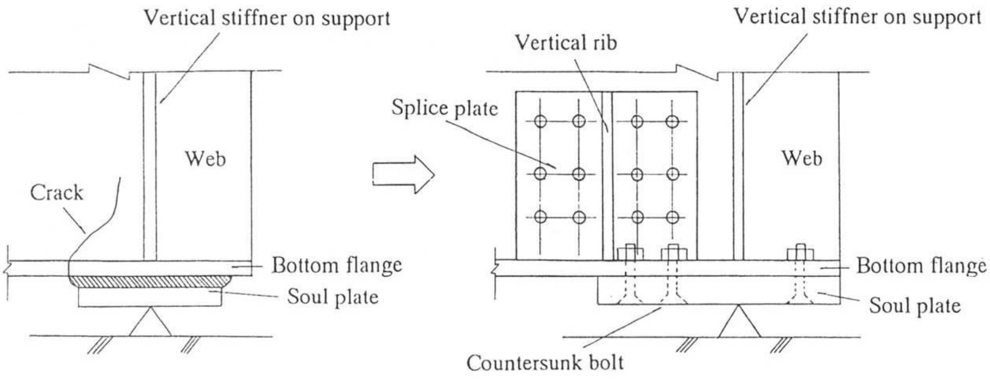


Fig.14 Retrofit detail for cracks at sole plate

3.3 Damage prevention works

Damage to reinforced concrete deck slabs is a general type of damage in highway bridges constructed in Japan around that time. On the Tomei Expressway stringers were added between main girders as a measure against such damage to reinforced concrete slabs. Recently, work to increase thicknesses of deck slabs is also being performed(Fig.15). It has been ascertained that there works also has effect in alleviating stresses at the sway bracing attachment portion.
Work to add an extra lane is going on at the Tomei Expressway to increase its capacity. This work has been taken as an opportunity to improve fatigue strengths of existing parts by changing structural details. Damaged reinforced concrete deck slabs have been changed for thicker reinforced concrete deck slabs or composite deck slabs or steel bridge decks (Fig.16).
The Design live load for throughway bridges in Japan was changed on Nov., 25 1993, The maximum weight of design truck 25 ton varied with the length of truck and the distribution of axes in the new rules, as against the weight of design truck was 20 ton in old rules. The studies on the influence of this change on the existing structures has been proceeding by many institutions and committees.

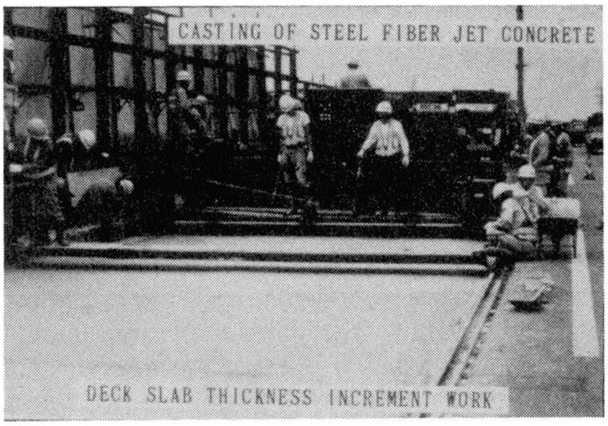


Fig.15 RC deck slab thickness increment work

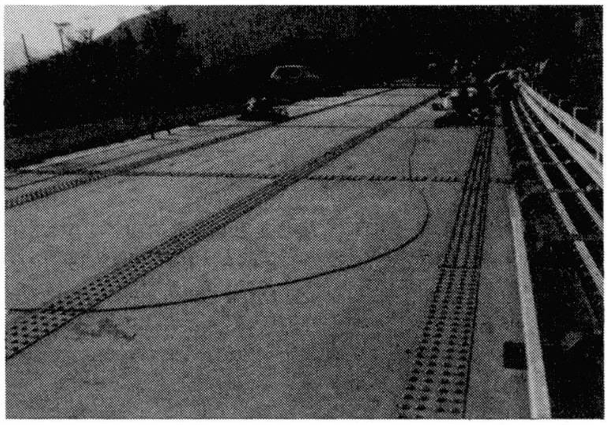


Fig.16 Replacement works of damaged RC decks to prefabricated steel bridge deck

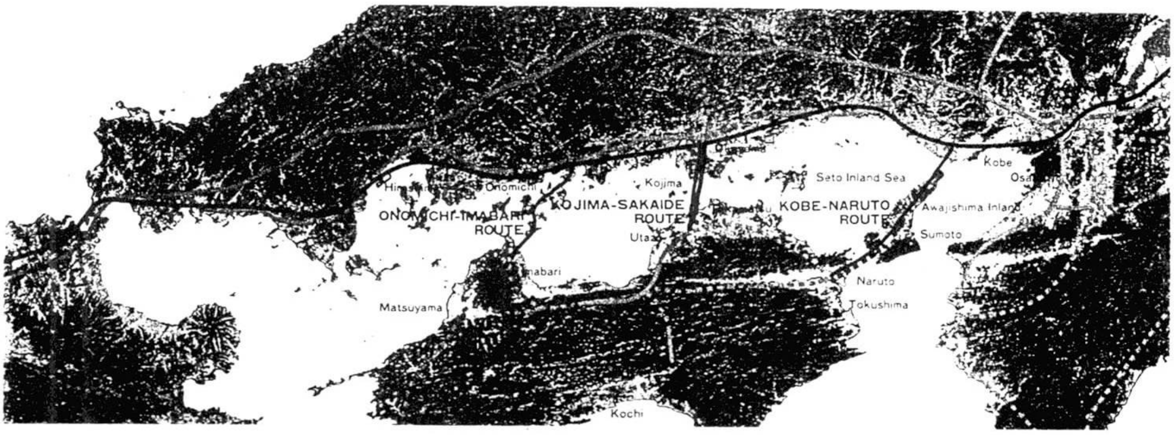
4. HONSHU-SHIKOKU BRIDGES

4.1 Fatigue design and quality control

Of the three routes of the Honshu-Shikoku Bridge project (Fig.17), the central route consists of combined highway and railway bridges with fatigue design made a priority item along with wind-resistant design from the beginning. Since high-strength steels of 800-MPa class were used in large quantities, large-scale fatigue tests were started from 1970(Fig.18), and these tests have made great contributions to the fatigue design in Japan of today. Numerous tests of full-size or large-scale models (Fig. 19) were carried out for investigation and ascertainment of plate thickness effect on fatigue strengths of various welds and fatigue behaviors due to secondary stresses attributable to structural details. Test specimens about 15 mm in plate thickness and 100 mm in plate width had been mainly used in past fatigue tests, but specimens with plate thickness of 45 to 75 mm were used in this case.

Various new and useful things have been learned from these fatigue tests, typical of which may be cited fatigue of longitudinal-bead welds of box section members (Fig.20). Such joints play almost no role in transmitting load, and simply are for assembly of members, but if defects such as blowholes exist at root portions, fatigue strength will be extremely reduced. The relationship between defect size and fatigue strength has been ascertained from the results of experiments on many large-sized models and from fracture mechanics models (Fig.21), based on which design allowable fatigue stress and corresponding allowable defect size have been determined (Fig.22).

Fabrication methods have been improved so that all truss members will have defects not more than the allowable limits. Joint portions are inspected using a newly developed automatic ultrasonic flaw detection system, and defects exceeding allowable values are repaired. These nondestructive inspection results have been organized as a data base, and play an important role in the maintenance plan.



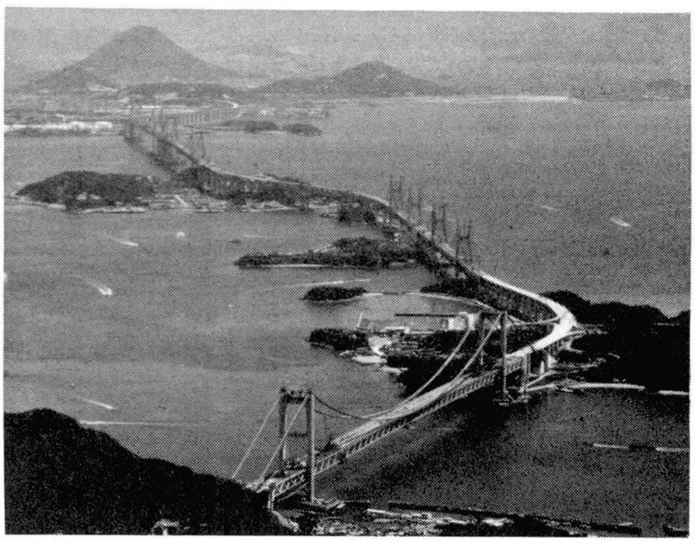


Fig.17 Honshu-Shikoku Bridge Project and general view of Seto-Ohashi (Kojima-Sakaide route)

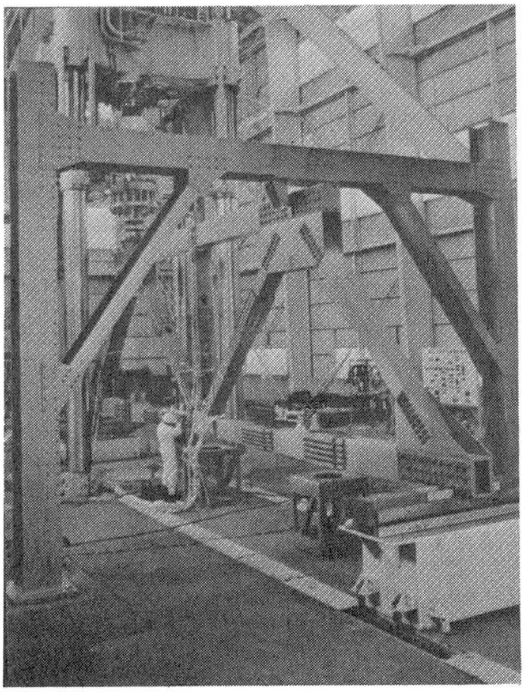
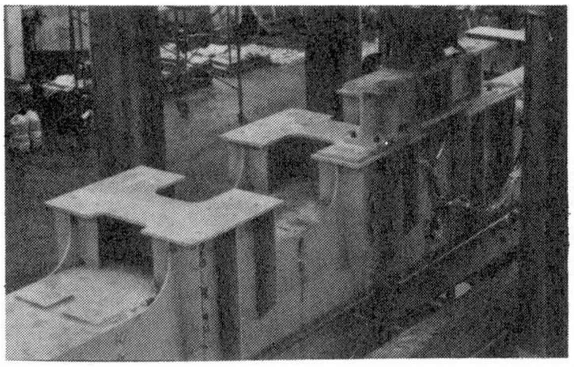
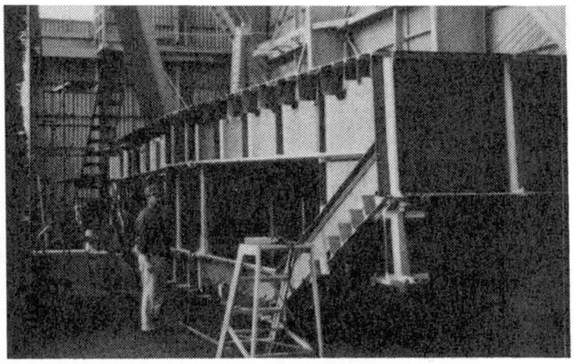


Fig.18 Large scale fatigue test
(truss panel joint)

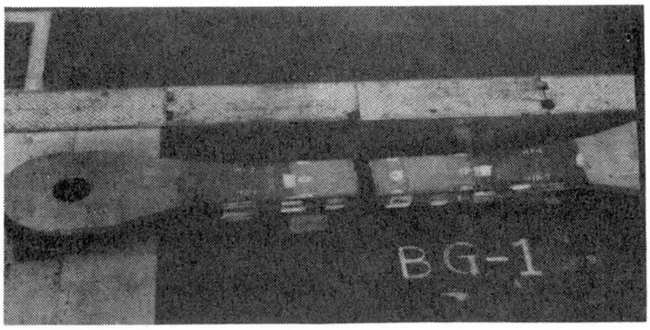


(a) floor beam of stiffening truss

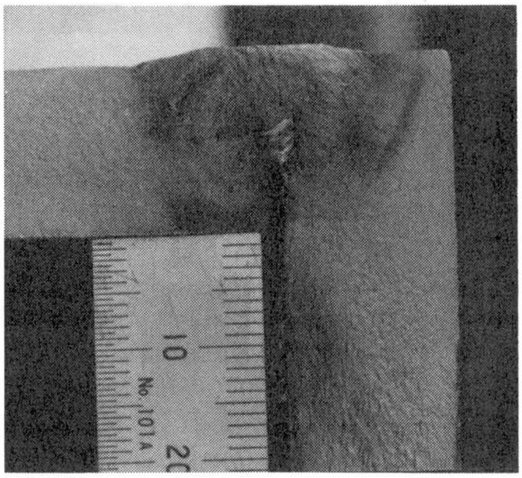


(b) box section stiffening girder

Fig.19 Examples of fatigue test



specimen



crack initiated from blowhole

Fig.20 Box section members

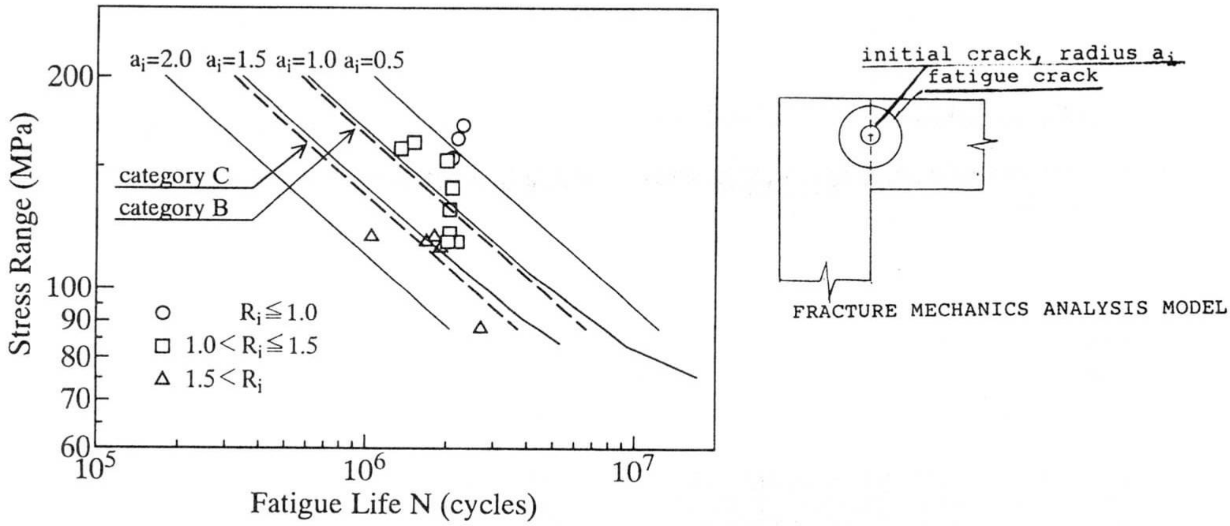


Fig.21 Results of fatigue test and fracture mechanics analysis

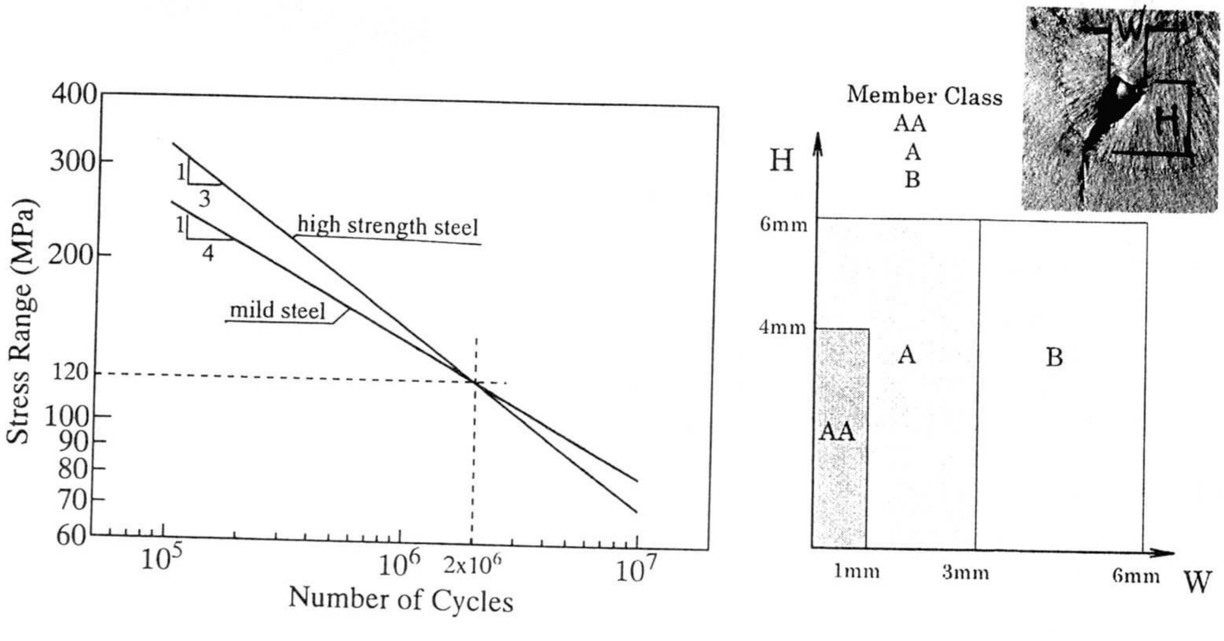
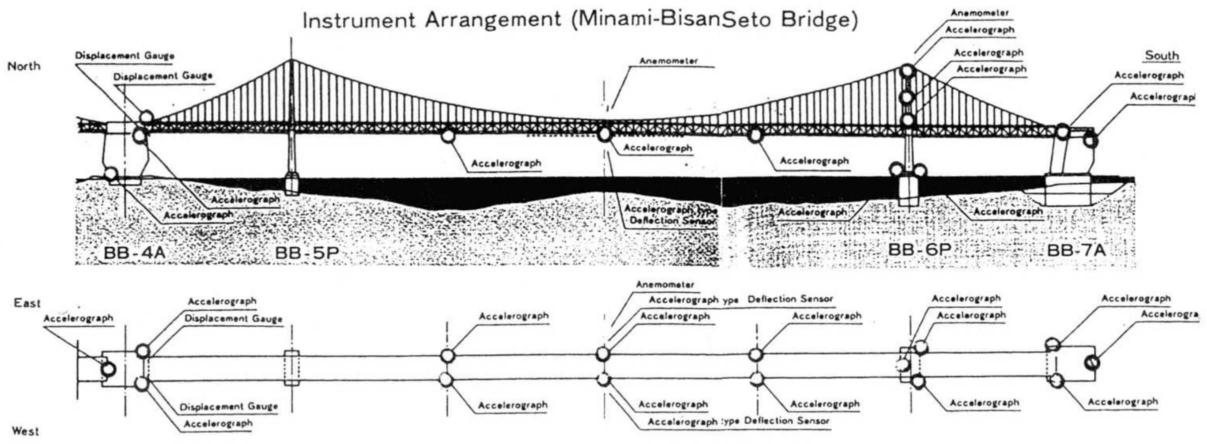
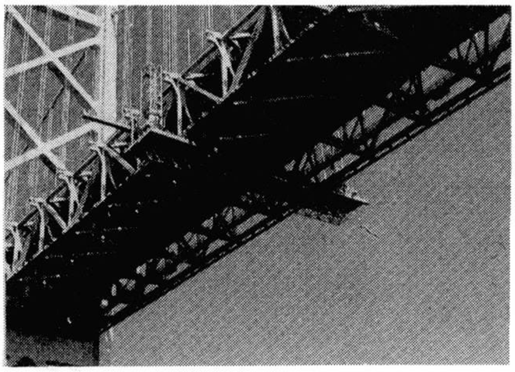


Fig.22 Allowable stress for corner joint and permissible size of blowhole in corner joint

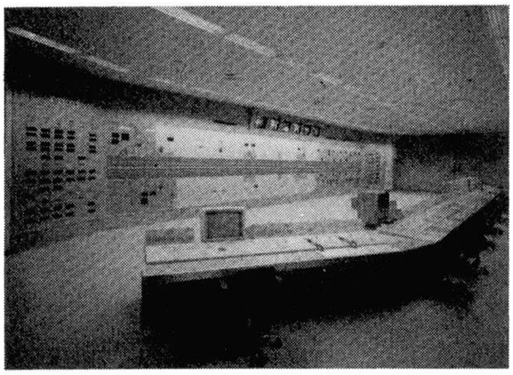
4.2 Maintenance

Various new technologies have been applied in maintenance also. Honshu-Shikoku bridges are equipped with inspection cars making it possible for on-hand inspections to be made of all members. And as shown in Fig. 23, various types of sensors such as accelerometers and displacement meters are installed and the behaviors of bridges are monitored at all times at a central control room. Besides these data being used for operations, the records comprise a base for formulating maintenance plans.





inspection car



control room

Fig.23 Instruments for monitoring of bridge behavior

5. CONCLUSIONS

The service environment of a bridge, such as loading, often differs greatly from what had been assumed at the time of designing. To evaluate the degrees of soundness of bridges from both the aspects of function and load bearing power taking such situations into account to set up maintenance plans including proper retrofitting and replacement is a matter of extreme importance.

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