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Fatigue Characteristics of Steel Plate Decks for Steel Bridges

Caractéristiques de fatigue des tabliers métalliques pour les ponts en acier

Ermüdungseigenschaften von Stahlfahrbahnplatten für Stahlbrücken

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SUMMARY
This paper presents the results and a discussion of full scale model tests to study the initiation and propagation of fatigue cracks in steel plate bridge decks. The observed fatigue cracks are then classified according to pattern and stress condition. Factors affecting fatigue crack initiation are identified by detailed examination of the stress conditions. Finally the reduction of fatigue strength in the welded deck joints is discussed in relation to weld defects.

RESUME
Cet article présente les résultats et une discussion d'essais sur modèle en grandeur nature pour étudier l'initiation et la propagation de fissures dues à la fatigue dans les tabliers métalliques de pont. Les fissures observées, dues à la fatigue, sont classées selon leur type et leur condition de contraintes. Les facteurs affectant l'initiation d'une fissure de fatigue sont identifiés par l'examen détaillé des conditions de contrainte. Finalement la résistance à la fatigue dans les joints soudés du tablier est discutée en relation avec des défauts de soudure.

ZUSAMMENFASSUNG
Der Beitrag stellt die Ergebnisse von Versuchen an Fahrbahnplatten aus Stahl vor. Die Versuche hatten das Studium des Rissbeginns und der Rissfortpflanzung zum Ziel. Die beobachteten Ermüdungsrisse sind gemäss ihrem Typ und dem zugehörigen Spannungszustand klassiert. Aufgrund einer detaillierten Untersuchung des Spannungszustandes werden Faktoren, die den Rissbeginn beeinflussen, identifiziert. Schliesslich wird die Reduktion der Ermüdungsfestigkeit geschweisster Verbindungen in Fahrbahnplatten im Zusammenhang mit Schweissfehlern diskutiert.

1. INTRODUCTION

A steel plate deck for a steel bridge consisting of longitudinal ribs, transverse floor beams and a deck plate, is an assembled welded structure subjected directly to repeated vehicle loads. The fact that fine fatigue cracks were found out in the longitudinal stiffeners below the deck plate of some of existing bridge, was reported [1]. Therefore, it is necessary to study on the fatigue behavior of the steel deck. Fatigue strengths of some models of welded joints to be used at the deck have been obtained for small coupon-type specimens under repeated axial tensile stresses. In practical problems, however, each element of such a structure will be in complicated stress conditions.

To study on the initiation and propagation of fatigue cracks of steel plate decks, the authors have been carrying out fatigue tests of their full-sized models such as orthotropic decks with open-shaped longitudinal ribs and hollow decks with V-shaped longitudinal ribs. The fatigue test results of the orthotropic deck panels were reported [2]. It was also reported that the hollow deck tested had the great fatigue strength because of no observation of fatigue crackings [3]. Furthermore, for a hollow deck panel with a smaller thickness than that of such a test deck as mentioned above, a fatigue test was conducted, assuming that the traffic direction was perpendicular to the V-shaped longitudinal ribs.

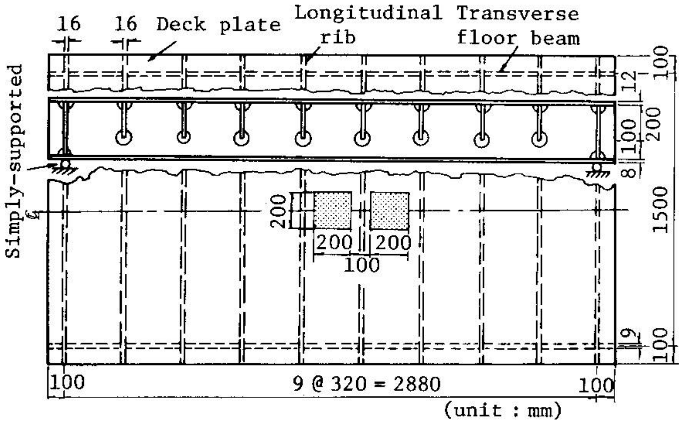


Fig. 1 Orthotropic deck panel

In this paper, the fatigue test results of the orthotropic deck panels and the hollow deck panel with a smaller thickness are presented and discussed. The observed fatigue cracks could be classified into several patterns in accordance with the stress condition. Then, the authors will discuss the pattern of fatigue cracks in combination with stress analysis around the cracks by the finite element method.

2. OUTLINE OF TESTS

2.1 Test Panels

Test panels are two kinds of orthotropic decks with open-shaped longitudinal ribs as shown in Fig. 1 and a hollow deck with V-shaped longitudinal ribs as shown in Fig. 2.

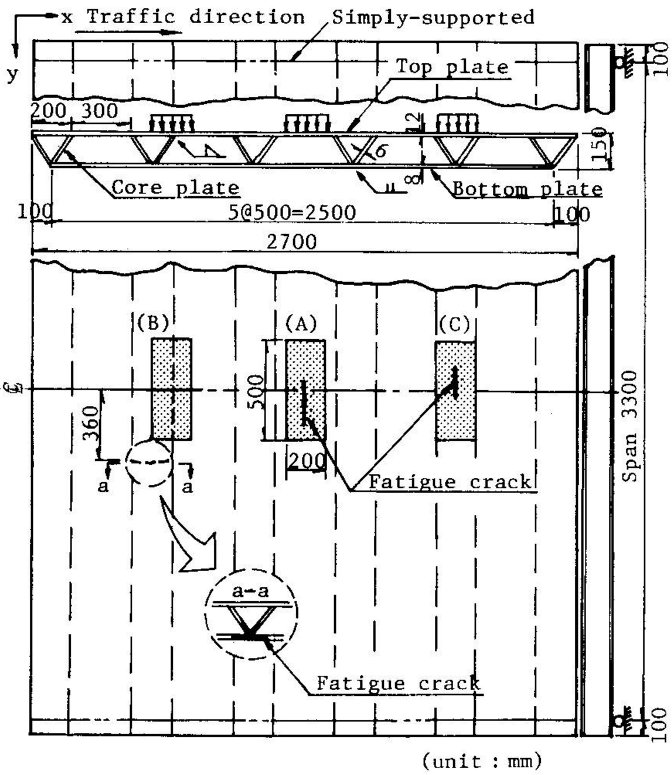


Fig. 2 Hollow deck panel

Details of the test panels are given as follows:
(a) The steel material is structural steel of SS41 designated at the Japanese Industrial Standards (JIS). Mechanical properties of the plates

of all of the panels are given in Table 1.
(b) The longitudinal ribs of the orthotropic deck panel were welded to the floor beam webs on the both sides or one side only as shown in Fig. 3. The former is called Type-1 joint and the latter Type-2 joint. The panel as shown in Fig. 5(a) has Type-1 joints in two floor beams and the panel as shown in Fig. 5(b) has Type-1 joints in a floor beam and Type-2 joints in another one.
(c) Fabrication process for the hollow steel deck is shown in Fig. 4. At first, core plates forming evenly-spaced triangles were welded to the top plate by fillet welding. Next, the bottom plates were welded strip by strip to the core plates by butt welding.

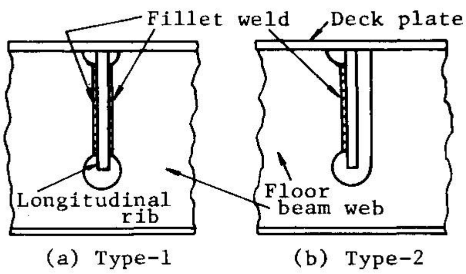


Fig. 3 Details of intersection

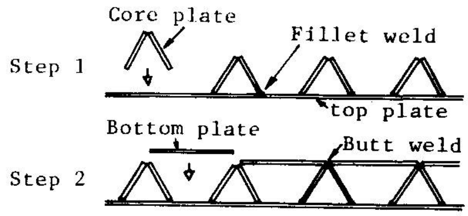


Fig. 4 Fabrication of hollow deck

2.2 Test Procedures

All panels have two opposite simply-supported edges and two free edges. The supported line is indicated in Figs. 1 and 2.

A load is applied at the locations as shown in Figs. 1 and 2 by a hydraulic jack of a Losenhausen type fatigue testing machine.
A size of loading pads was determined by considering rear double tires of a design truck. Firstly, each panel was loaded statically in order to investigate the elastic behavior of the test panel. Then, a dynamic repeated load was applied to the panel at the rate of about 5 Hz.

During the fatigue test, a repeated loading was interrupted to measure deflections and strains at various points. Since it was difficult to find out fatigue cracks visually, two inspection methods were used together to determine the fatigue life. One was a liquid penetrant inspection and the other was an estimation method of picking up changing points of dynamic strin range histories at the points where crack initiation was expected.

Table 1. Mechanical properties of plates

Specimens	Yielding point σ_y (MPa)	Tensile strength σ_t (MPa)	Elongation (%)	Young's modulus E_s (GPa)
SO	311	445	27.6	196
SV	278	419	28.7	201
JIS-SS41	≥245	402 - 510	≥17.0	—

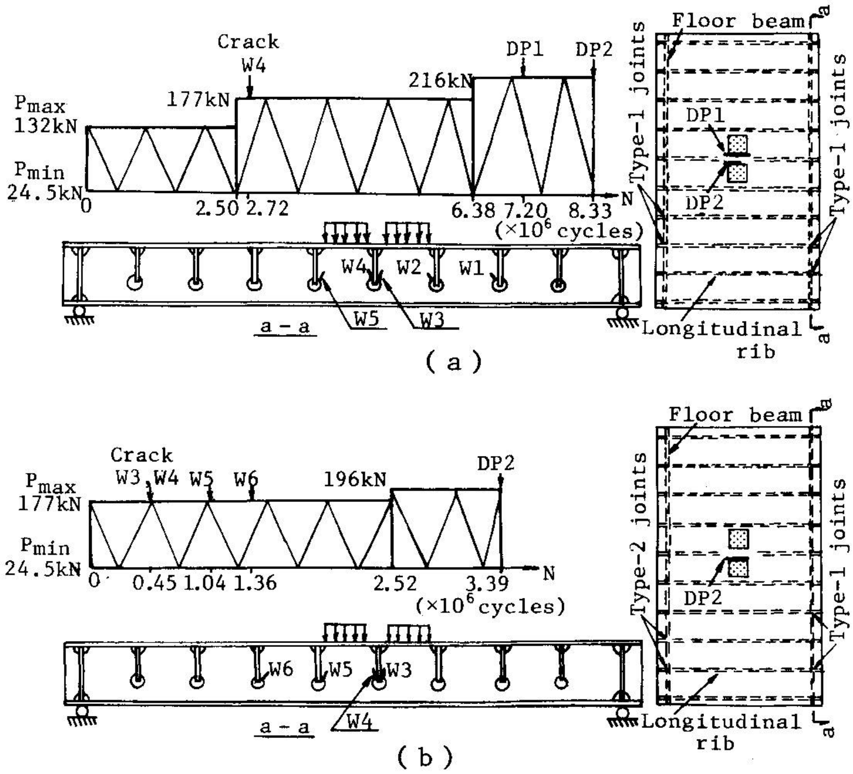


Fig. 5 Testing records and locations of cracks

2.3 Test Results

2.3.1 Orthotropic Deck Panel

Fatigue testing records and locations of fatigue cracks are shown in Figs. 5(a) and (b). In the both panels, the first crack 'W4' occurred at the intersection of a longitudinal rib and a floor beam web. Next, the fatigue cracks 'W2' and 'W5' were observed during the fatigue test.

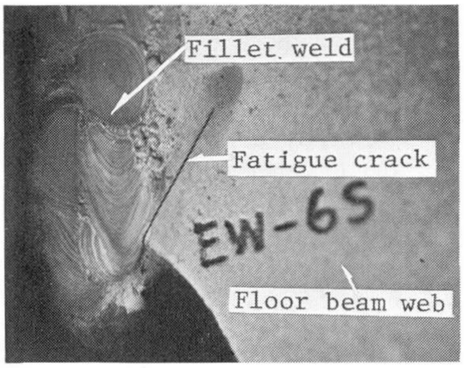


Fig. 6 Fatigue crack in floor beam web

All of the fatigue cracks in the floor beam web were initiated at the fillet weld toes at the upper part of circular cutouts in the web. The fatigue cracks 'W3' and 'W4' propagated upward along the fillet weld toe. The fatigue cracks 'W5' and 'W6' developed toward the center of loading in the floor beam web as shown in Fig. 6. At the final stage, a fatigue crack 'DP1' occurred in the deck plate between loads as shown in Fig. 5(a).

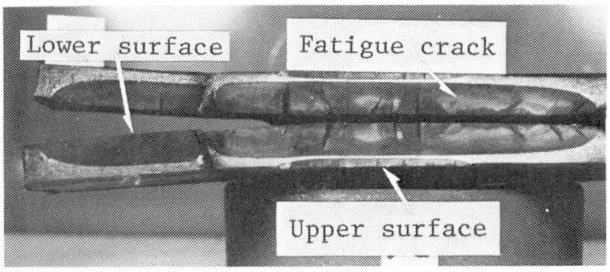
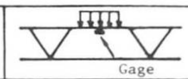
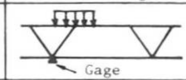
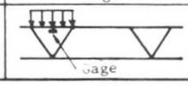


Fig. 7 Fracture surface of top plate

2.3.2 Hollow Deck Panel

Fatigue tests were conducted for three loading cases which could be considered as independent each other. Loadings at the fatigue tests are summarized in Table 2. The locations of the fatigue cracks are indicated in Fig. 2. Fatigue cracks at the loading cases A and C were initiated at a top plate below a loading pad. A typical fracture surface of these cracks is shown in Fig. 7. A fatigue crack at the loading case B was initiated at a longitudinal butt welded joint at which core plates were connected to a bottom plate. The fatigue crack propagated into both the bottom and core plates perpendicular to the longitudinal butt weld line. The fracture surface of this crack is shown in Fig. 8.

Table 2. Testing records of hollow deck panel

Loading conditions		Load (kN) P_{max}	Load (kN) P_{min}	No. of cycles ($\times 10^6$)	Stress range (MPa)
A		147	19.6	0 - 3.00	212
		235	19.6	3.00 - 3.42	297
B		177	19.6	0 - 3.00	82
		245	19.6	3.00 - 4.01	117
C		147	19.6	0 - 3.00	210
		196	19.6	3.00 - 3.65	278

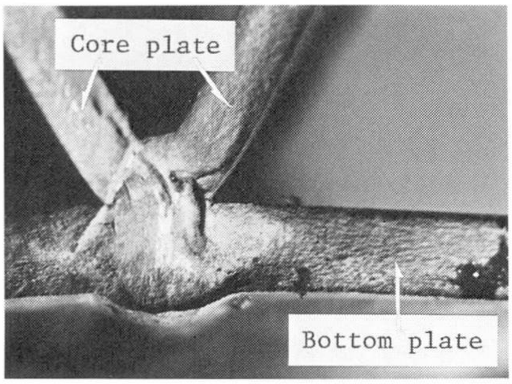


Fig. 8 Fracture surface of butt weld

3. FATIGUE BEHAVIOR

3.1 Pattern of Fatigue Cracks and Stress Conditions

Fatigue cracks observed at the tests are classified into the following patterns:

(a) Cracks in base metals such as a deck plate and a top plate,
(b) Cracks in continuous longitudinal butt welded joints to connect bottom plates to core plates,
(c) Cracks at the intersection of longitudinal ribs and transverse floor beam webs.

Strain distributions of the hollow deck in x- and y-directions on the upper surface of the top plate at three loading cases A, B and C as shown in Fig. 2, are indicated in Fig. 9 and those on the lower surface of the bottom plate are shown in Fig. 10.

In Fig. 9, the highest strain in x-direction on the top plate occurred below the applied load, and diminished rapidly close outside the region. Since it is evident that the top plate is subjected to a large local out-of-plane bending, the fatigue cracks will be initiated at the surface of the tension side of the top plate. The fatigue fracture surface as seen in Fig. 7 indicates developing process of this crack. The bottom plate is subjected to axial forces in the direction parallel to the longitudinal weld line to connect a bottom plate to core plates, due to overall bending as the whole structure.

Then, in order to obtain stress conditions at the intersections of longitudinal ribs and transverse floor beam webs, the orthotropic deck structure was replaced by a three-dimensional model as assemblage of thin plates for analysis by the finite element method.

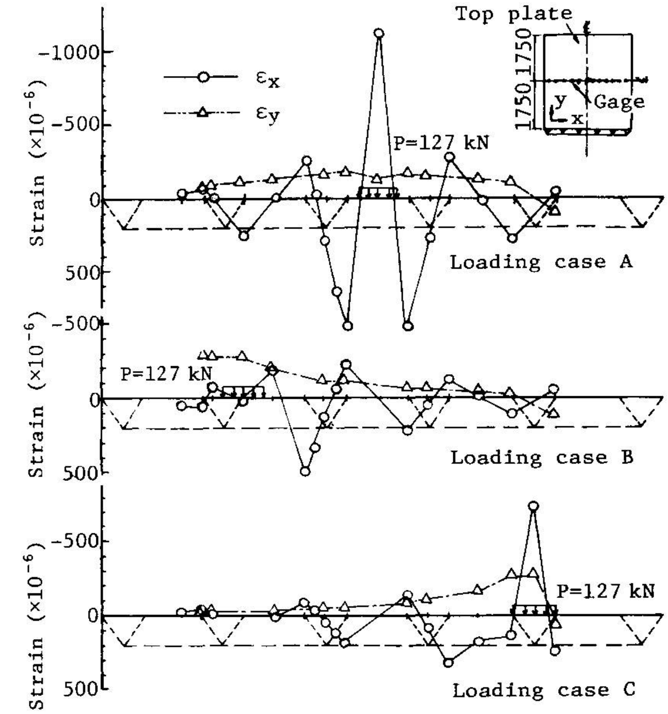


Fig. 9 Strain distributions in top plate

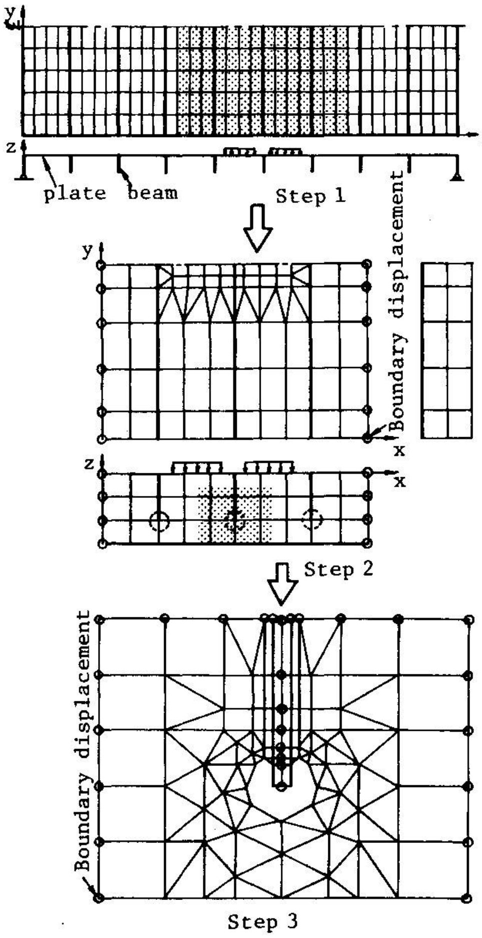


Fig. 11 Finite mesh divisions at zooming step

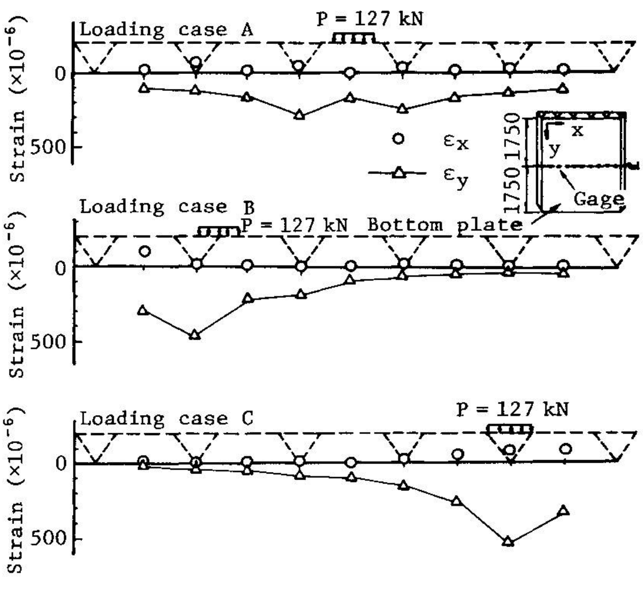


Fig. 10 Strain distributions in bottom plate

The finite mesh divisions in each step in the analytical procedure by a zooming method are shown in Fig. 11.
A plate element in which out-of-plane and in-plane deformations were considered, and a beam element in which an eccentricity between the middle surface of the plate and the neutral axis of the beam was considered, were used for finite elements in a computer program developed by the authors [4].

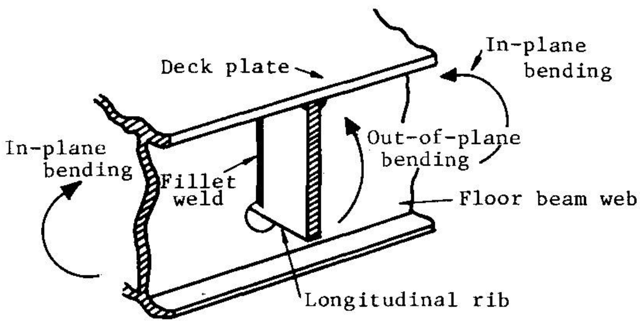


Fig. 12 Bending condition in floor beam web

The analytical results indicate that the floor beam web is subjected to not only in-plane forces due to beam actions, but also out-of-plane forces due to flexural deformations of the longitudinal ribs as shown in Fig. 12. Principal stress distributions on the outer surface of the floor beam web are shown in Fig. 13. It is evident that there are high stress concentrations at the upper part of a circular cutout where a fatigue crack was initiated.

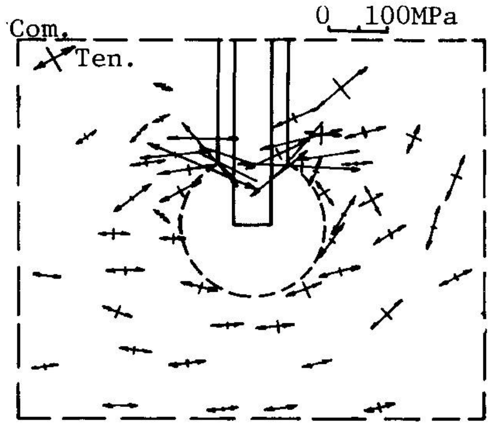
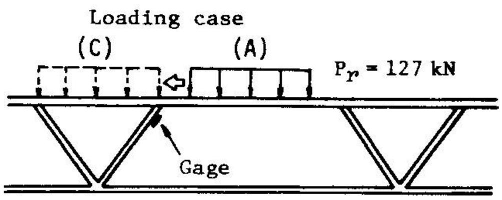


Fig. 13 Principal stresses in floor beam web

Figure 14 shows a comparison between stress ranges for the cases A and C at a gage point on a core plate. It is seen from this figure that the core plate is subjected to stress reversal as a load on the top plate moves from the center of a V-shaped rib to the part between two V-shaped ribs. When the vehicle load moves in the direction perpendicular to the longitudinal V-shaped rib as illustrated in Fig. 12, the stress range in the fillet welded joint between core plate and a top plate due to such stress reversals becomes larger than that caused by loading only at single position in the laboratory. Therefore, this part may become a weak point for fatigue failure under actual vehicles.



σ_r = -154 MPa at case (A) (Compression)

σ_r = 102 MPa at case (C) (Tension)

Fig. 14 Reversal of stress

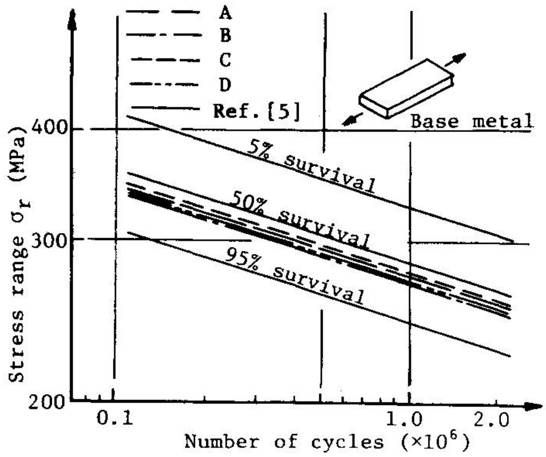


Fig. 15 S-N curves for base metal

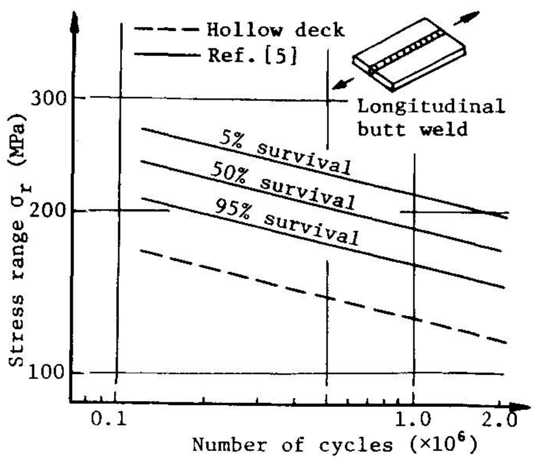


Fig. 16 S-N curves for butt welded joint

3.2 Comparison of Fatigue Strength

The present test results are compared with the fatigue test data given by other investigators for small coupon-type specimens subjected to axial tensile stresses. Comparison of S-N curves for the base metal is shown in Fig. 15. In this figure, the solid line indicates the P-S-N curves given by other investigators [5], and the lines A and B indicate S-N curves for orthotropic deck panels and the lines C and D for a hollow deck panel, which have been obtained on the basis of the present test results. Because the present test data were insufficient to draw S-N curves, these S-N curves were estimated on the assumption that the slope is equal to that of the P-S-N curves given by the other investigators and cumulative fatigue damages for a step loading can be evaluated by the Miner's rule. It may be said that the fatigue strength of the deck plate could be estimated from the fatigue test data of the base metal obtained by other investigators on coupon-type specimens.

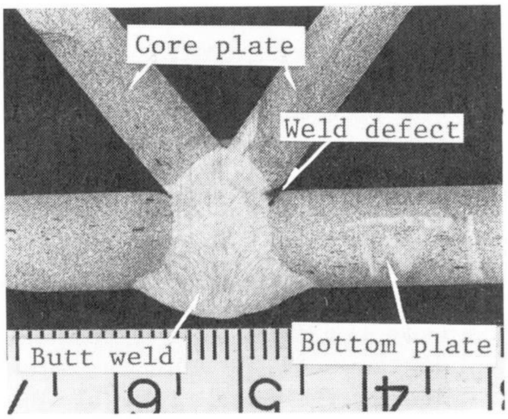


Fig. 17 Macrosection of butt weld

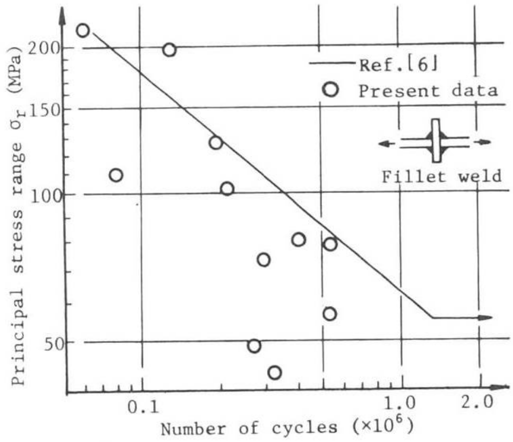


Fig. 18 S-N relations of fillet welded joint

Figure 16 shows S-N diagram for longitudinal butt welded joints. The S-N curve for the hollow deck panel was estimated in the same manner as the case of the base metal. It is observed that the fatigue strength of the hollow deck panel is lower than that given by other investigators [5]. From the observation of the fracture surface as shown in Fig. 8, it is recognized obviously that this fatigue crack was initiated due to the lack of penetration as seen in Fig. 17. Therefore, it may be implied that the fatigue strength of these butt welded joints is decreased by the existing lack of penetration in the joint.

The fillet welded joints at the intersections of longitudinal ribs and floor beam webs can be regarded as the transverse load-carrying ones by considering the stress conditions of the floor beam web. S-N relations between principal stress ranges which were measured at an upper part of the circular cutout on the outer surface of the floor beam web by using rosette strain gages and estimated number of cycles to crack initiation, are indicated in Fig. 18. The solid line in this figure is a S-N curve for transverse load-carrying fillet welded joints [6]. The plotted data are remarkably scattered mainly because of inaccurate estimation of crack initiation. The fatigue strength of this joint may be at the most lower than that of the S-N curve for coupon-type specimens due to the effect of imperfect shape of welding.

4. CONCLUSIONS

Main conclusions for fatigue characteristics of the test panels at the present study are summarized as follows:

(a) The deck plate subjected directly to repeated vehicle loads has a high fatigue strength similar to that of the base metal. Since, in practical traffic, the deck plate would not be used under severe loading conditions such as

laboratory fatigue tests, this plate will not be sustained critical fatigue damages.
(b) A fatigue crack at the longitudinal butt welded joint of the hollow deck was initiated from an 'internal' weld defect such as lack of penetration, while a fatigue crack at the transverse load-carrying fillet welded joint of the orthotropic deck was initiated from an 'external' weld defect such as imperfect shape of welding. Since the fatigue strengths of these welded joints are decreased due to weld defects, it will be necessary to take into account the reduction of fatigue strength at a detailed design. As a matter of general policy it should always be one of the aims for the fabrication of welded structures, to produce welds that are free from defects.
(c) When this hollow deck is placed in the traffic direction perpendicular to the longitudinal V-shaped ribs, the fillet welded joints between core plates and a top plate are always subjected to stress reversals. Since those joints will become a weak point for fatigue failures under actual vehicle loadings, it is necessary to examine the fatigue strength of those joints subjected to the stress reversal.

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