Experimental Study on Repair Welding to Steel Bridges under Loading

Kohsuke HORIKAWA*, Hiroyuki SUZUKI and Masato TANAKA*****

Abstract

Welding is used more or less in almost all case in repair or strengthening works. One of the characteristic features of repair or strengthening welding is to be performed under loading. Load carrying capacity of structures decreases temporarily during welding because of welding heat. So, safety during welding under loading should be examined. Also welding under loading may reduce ultimate strength after repair or strengthening work because large deformation and additional residual stress are introduced in the members.

In this paper, fillet welds between bearing stiffeners and web plate are repaired using welding under loading and safety during welding and ultimate strength after welding are studied.

KEY WORDS: (Repair Welding) (Ultimate Strength) (Deformation) (Correction)

1. Introduction

Recently, it has been reported that fatigue cracks have initiated in considerable numbers of welded bridges. There are some procedures on repairing of these cracks, but in almost all case these cracks are repaired by welding. Repair welding is characterized by being performed under loading. These researches are not enough, so, at present many fatigue cracks are repaired without loading using temporary supports.

This paper describes experimental study on repair welding to concentrated loading point, such as bearing stiffener of main girders.

1.1 Previous Studies

Previous researches on repair welding are classified into two types, the one is procedure qualification tests of the repair welding on bridges in service conditions, the other is fundamental study on plates under loading. The latter is summarized as follows;

1) Mechanical properties, such as yield strength, tensile strength and charpy absorbed energy, are not deteriorated by welding.
2) Residual stress is reduced by the same amount of applied stress in case of welding to tensile members, but in compressive members it is not reduced.
3) Yielded part enlarges by transient stress redistribution in case of welding to tensile members, but in compressive members it is not made clear now.
4) Deformation are arranged with the ratio (1/b) of weld length (1) to plate width (b). In case of welding to tensile members, with $1/b \leqq 0.5$ weld cracks and large deformation don't occur. In compressive members, when 1/b is larger than 0.1, buckling occurs at some cases.

1.2 Aims of This Experiment

In the structures, fatigue cracks initiate at the point where the stress doesn't transmit smoothly. If the stress transmits smoothly, fatigue cracks may not initiate in the high stress level over fatigue limit. In bridges, fatigue cracks particularly initiate at the concentrated loading point, such as bearing stiffener plates of main girders and stiffener plates with lateral bracing.

This paper investigates fundamental repair welding conditions for these members under bending, compressive and shearing stresses.

In this experiment, the bearing stiffener plates in existing bridges are modeled and repaired by welding under loading. The effects of repair welding on the structures are considered as follows.

* Associate Professor
** Research Associate
*** Tokyo Steel Rib & Bridge Const. Co. Ltd. HŌFU Plant

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(Step 1) Heat of welding, gouging etc. are induced to the structures.
(Step 2) The part of high temperature are extended, thereby Young's modulus and yield point reduce.
(Step 3) The deformation occurs during and/or after the welding, and residual stresses are introduced.
(Step 4) As a result of step 1 ~ 3, ultimate strength of the structures reduces.

The general procedures of step 1 are shown as follows.
(Step 1-1) Cracks are removed by gouging.
(Step 1-2) Gouging slots are filled up by welding.
(Step 1-3) The new reinforcing members are attached by welding if necessary.
(Step 1-4) If necessary, deformation caused by welding is corrected by heating of gas flame.

The difference of total heat input and heated part by welding and gouging are considered to influence on the temperature distribution and ultimate strength of the structures. In this experiment, the same conditions as the practical works were used.

There are three fracture modes near the bearing stiffener plates of main girders.
(Mode 1) Buckling of a web plate under shearing stress.
(Mode 2) Buckling of a flange plate under compressive stress.
(Mode 3) Buckling of a column (combined a web plate and stiffener plates) under axial compressive stress.

The aim of this experiment is fracture mode 1.

2. Experimental Procedure

2.1 Experimental Conditions

In this experiment, repair welding of the fillet weld that connects stiffener plates to a web plate was performed. Its procedure was that the weld metal was removed by gouging and was filled up by a new fillet weld. Two specimens, called S-1 and S-2, were prepared. Rectangular panels of these specimens were named A panel and B panel (Fig. 1). A and B panel were experimented in the different conditions. These conditions are shown as follows.

Case 1; As fabricated; S-1; B panel
Case 2; Repair without loading; S-2; B panel
Case 3; Repair with loading; S-2; A panel
Case 4; Repair and correction with loading; S-1; A panel

In repair and correction of cases 3 and 4, works were performed under loading corresponding to allowable shearing stress. Table 1 shows experimental conditions and procedures in each specimen.

Table 1 Experimental Conditions and Procedures

Specimen	S - 1		S - 2	
	A-Panel	B-Panel	A-Panel	B-Panel
Repair Condition	Case 4: Repair and Correction with Loading	Case 1: As Fabricated	Case 3: Repair with Loading	Case 2: Repair without Loading
Experimental Procedure	① After loading 109 tons, repair welding in A-panel ② Keep load in two hours for cooling, and unload. (End of Case 1) ③ Again loading 109 tons, correcting in A-panel. ④ After cooling, unload. (End of Case 4) ⑤ Loading test		① After loading 109 tons, repair welding in A-panel. ② Keep load in two hours for cooling, and unload. (End of Case 3) ③ Repair welding in B-panel without loading. (End of Case 2) ④ Loading test	

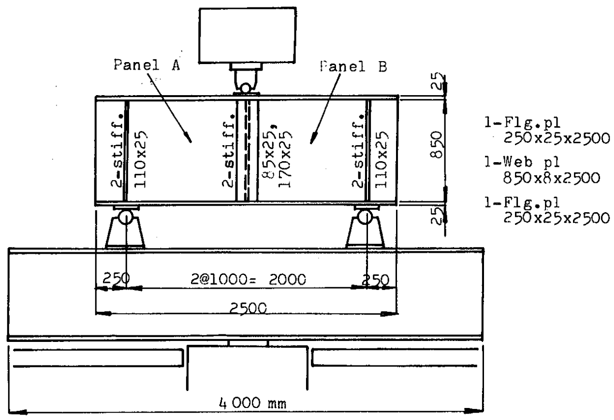


Fig. 1 Specimen's Configuration and Loading Condition

2.2 Specimens

Specimen's configuration is shown in Fig. 1. The span and web height are 2000mm and 850mm, respectively. Thickness of web plate is 8mm, which is nearly equal to that of existing bridges. As a result, it is considered that size effect in welding can be neglected. Stiffening plate's width and thickness are 100mm and 25mm. Because buckling of web plates was aimed, stiffening plate became higher rigidity than that of existing bridges supported the same reaction. Specimens were fabricated by the same method and the same procedure. Prebending and correction by gas flame were not used in fabrication. Material is the mild steel of $41 kg/mm^2$ in the tensile strength (called SS41 in JIS G 3101). Mechanical properties are shown in Table 2.

Table 3 shows the reference of load carrying capacities in this specimen. In table 3;

1) P=109tons; load which shearing stress of web plate becomes equal to allowable stress $\tau_a = 800 kg/cm^2$ (in Standard Specifications for High-

Table 2 Mechanical Properties

	Thickness (mm)	Yield Point (kg/mm^2)	Tensile Strengh (kg/mm^2)	Elongation (%)
Web	7.5	31	47	29
Flange & Stiffener	24.3	25	43	32

Table 3 Reference Loads of Load Carrying Capacities

	Allowable Shear Stress Load	Combined Stress of Bending Moment & Shear	Elastic Buckling Load	Plastic Buckling Load
Load (t)	109	176	188	243
Bending Momwnt (t-m)	54	88	94	122
Shearing Force (t)	54	88	94	122
σ (kg/cm²)	874	1413	1510	1951
τ (kg/cm²)	800	1294	1383	1790
$(\sigma/\sigma_{cr})^2+(\tau/\tau_{cr})^2$	0.38	1.00	1.14	1.68

$\sigma_{cr} = k\sigma_e = 23.9 \times 168 = 4015$ kg/cm²

$\tau_{cr} = k\sigma_e = 8.23 \times 168 = 1383$ kg/cm²

$\tau_y = \sigma_y / \sqrt{3} = 3100 / \sqrt{3} = 1790$ kg/cm²

way Bridges of Japan Road Association).

2) P=176tons; load which combined stress by bending moment and shearing force becomes equal to 1:

$$(\sigma/\sigma_{cr}) + (\tau/\tau_{cr}) = 1$$

3) P=188tons; elastic buckling load.

4) P=243tons; plastic buckling load.

2.3 Loading Condition

Loading was done by three points bending. Thus, A and B panel were under bending moment and shearing force. After a specimen was set on the bearing shoe, a gap between the crosshead and the base plate on the upper flange plate was adjusted by the tapered filler plate. In order to prevent lateral buckling, bearing stiffener plates were restrained for out-of-plane displacement by jigs with roller.

2.4 Repair Welding

Repair work was performed to four welded joints that connects web plate to bearing stiffener plates shown as Fig. 2. For one welded joint, weld metal was removed by gouging all over the repair length, then repair welding was performed to fill up gouging slot. Welding conditions are shown in Table 4. Finishing all work to one welded joint, next welded joint was done after some rest time as practical work. Each specimen's repairing process is shown in Fig. 3.

Temperature distributions were measured by thermopaint and contact thermometer.

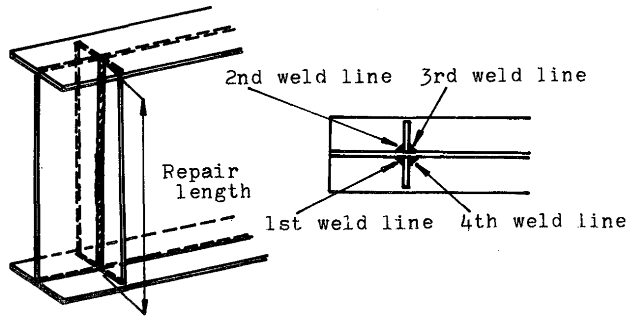


Fig. 2 Extent and Procedure of Repair Work

Table 4 Repair Welding Conditions

No.	Works	Welding	Welding Conditions	Heat Input (kj/cm)
1	Gouging	Arc Gouging Rot	Vertical up Gouging	
2	1st Layer	LB-47 3.2φ	Vertical up Welding 125A, 25V, 8.5cm/min	22
3	2nd Layer	ZERODE-6V 4.0φ	Vertical down Welding 225A, 31V, 41cm/min	10
4	3rd Layer	ZERODE-6V 4.0φ	Vertical down Welding 225A, 31V, 41cm/min	10

2.5 Correction

As a result of repair welding, not a little deformation occurred in web plate. Particularly large deformation occurred in the edge of specimen because this part was not restrained more than the other part. Considering that this

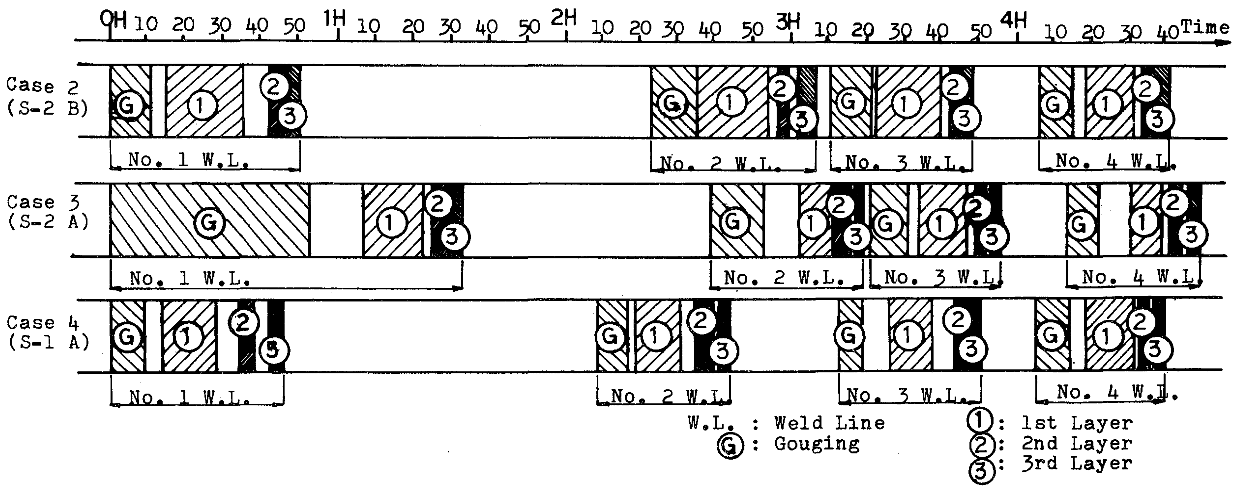


Fig. 3 Each Specimen's Repairing Process

large deformation occurred in repair welding of existing bridges, it was examined by this specimen whether or not deformation in the edge of specimen can be corrected under loading.

The correction was performed by two methods as follows.

1) Heating of flange plate by gas flame.
   Two jacks were set between upper and lower flange and the interval of both flanges was expanded. Afterward, lower surface of flange near the base plate was heated in transverse direction by gas flame. As a result of angular deformation of lower flange, the distance between upper and lower flange was expanded and the deformation of web plate was corrected.
2) Heating of web plate by gas flame.
   The web plate in cantilever panel was pressured by clamps and angle bar. Afterward, the web plate was heated by gas flame. Attention was paid to heating temperature not to reach red heat. Water cooling was not performed because it was considered that water cooling couldn't use in practical works for special characteristics of repair works.

2.6 Loading Test

Specimens had been unloaded after cooling to room temperature after repair welding and correction by heating under loading. Then, loading test was performed by three-points bending.

The deflection of specimen, the longitudinal strain at the lower flange plate of the span center and out-of-plane displacement at the panel center were measured during loading. When out-of-plane displacement increased rapidly and was over the web thickness, it was defined as buckling occurred in this panel. With increasing of the out-of-plane displacement at panel center, it became difficult to keep load constant during measurement. After the displacement increased largely, load was controlled during measurement to keep deformation constant.

As a result of keeping deformation constant, load was decreased. Therefore, load was read when measurements of deformation and strain were finished. Because two panels of one specimen were the different experimental conditions, loading was stopped for strengthening before the deformation of the buckled panel became too large. And the specimen was once unloaded and strengthened using H.T. bolts and angle bars. Then, the specimen was loaded again to measure the other panel's ultimate strength.

3. Experimental Results and Discussions

3.1 Temperature Distributions in Repair Works

Figure 4 shows examples of the temperature with time

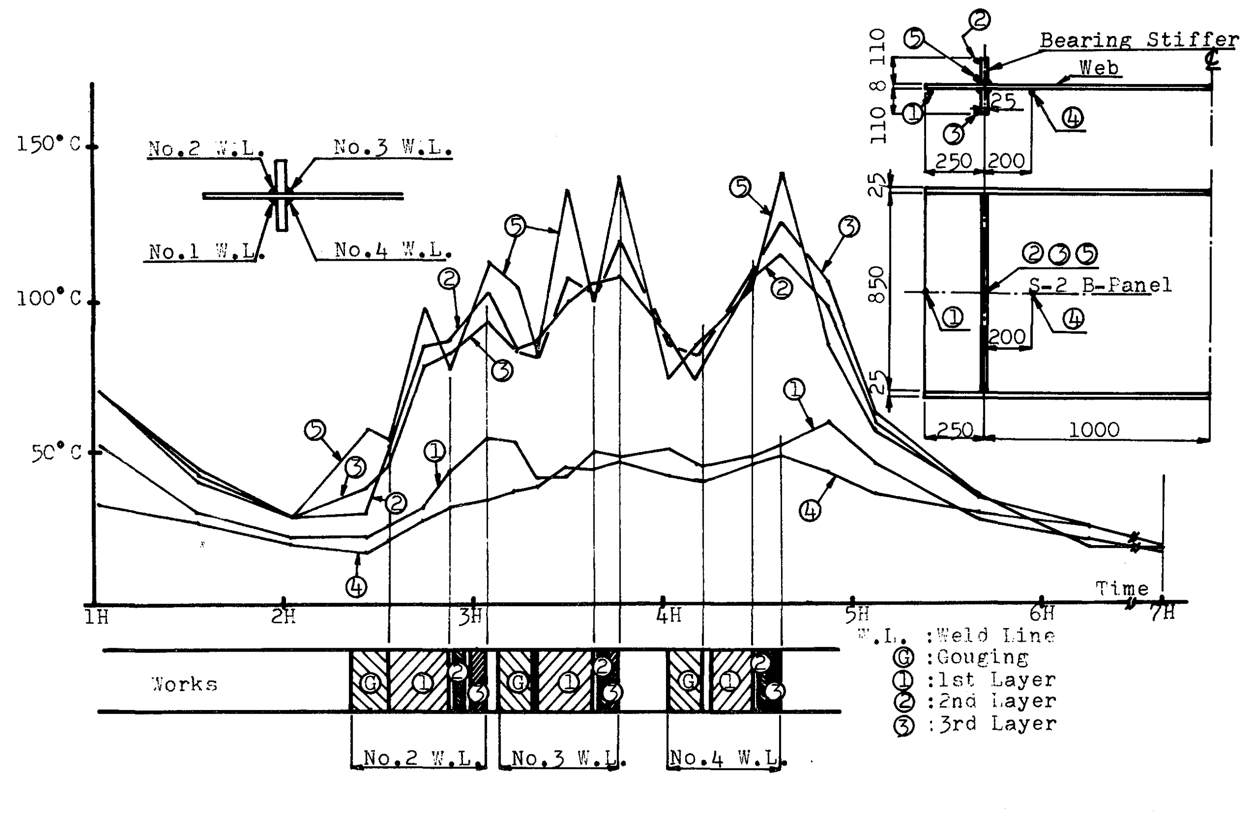


Fig. 4 Temperature with Time at Each Welding Work in Case 2

at each welding work at some points on web plate and bearing stiffener plates. The horizontal axis is time and repair works are also shown.

The measurement was started after finishing of works to No. 1 welded joint and was performed during or after works by the contact thermometer.

The temperature with time can be classified two groups; one is ① and ④, the other is ②, ③ and ⑤. The temperature of ① and ④ rose to about 60°C at most, while the temperature of ②, ③ and ⑤ rose to about 100 ~ 140°C. This is caused by the difference of distance from welded joints. But temperature didn't rise to 150°C even in the part within about 100mm from welded joints.

Peak temperature distributions were measured by thermo-paints of 191, 146, 101 and 52°C.

Figure 5 shows examples of peak temperature distributions in web plate. Thermo-paint of 191°C could not be measured in the cause of fume adhesion. As its part was about 30mm from welded joints, the part over 191°C is considered to be no more than 30mm in maximum. In the web plate, the part over 146°C is no more than about 70mm from the bearing stiffener plate. In the bearing stiffener plates, peak temperature at ② and ③ in Fig. 4, whose distance is 110mm from welded joints, was between 146 and 191°C. This difference between web plate and bearing stiffener plate is considered that welding heat was conducted far in the web plate, while in the bearing stiffener plates, whose width was narrow, the heat was reflected at the edge and accumulated in the plate.

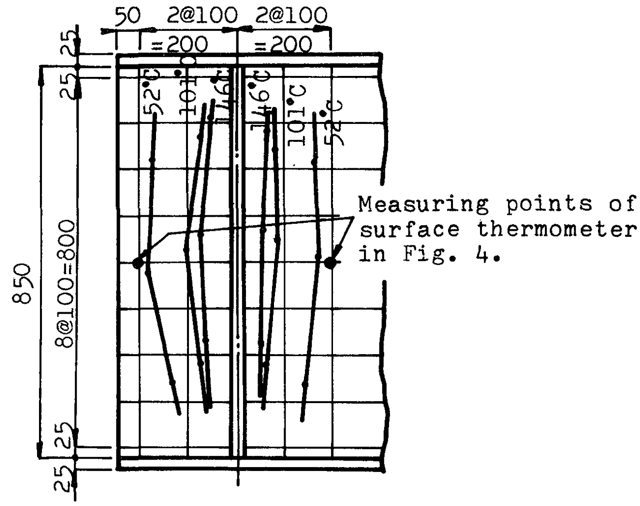


Fig. 5 Peak Temperature Distribution by Thermo-Paints.

3.2 Deformation by Repair Works

Figure 6 shows the out-of-plane deformations of the web plate. Dashed lines show initial deformations and solid lines show deformations after repair welding. Bold lines in cantilever panel of Case 4 show deformations after correction by heating.

The maximum displacements in each stage are shown in Table 5. There were some cases that the algebraical difference of the displacements before and after repair welding didn't become the maximum difference because these maximum displacement didn't occur at the same measuring points.

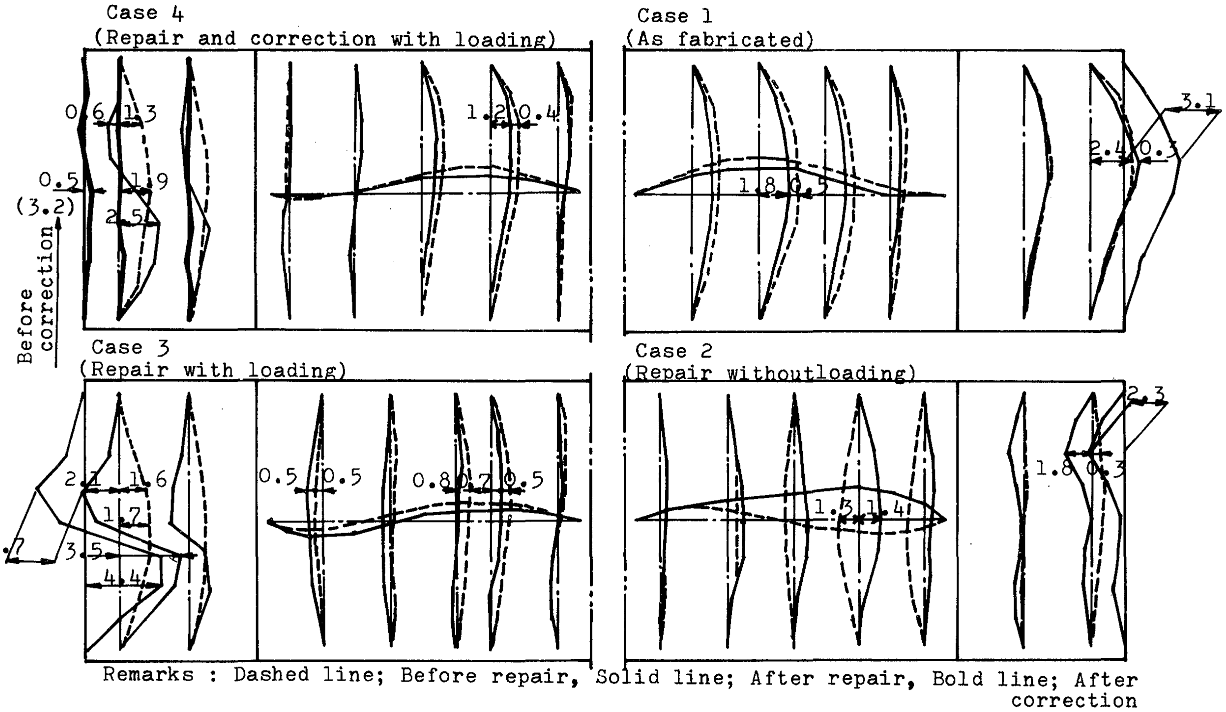


Fig. 6 Out-of-plane Deformations of the Web Plate

Table 5 Maximum Displacements before and after Repair Works and Ultimate Loads

		Case 1 As Fabricated	Case 2 Repair without Loading	Case 3 Repair with Loading	Case 4 Repair & Correction with Loading
Center Panel	Before Repair Welding (mm)	2.3	-1.3	1.2	1.4
	After Repair Welding (mm)	1.8	1.4	-1.0	1.2
	Difference (mm)	0.5	2.7	0.8*	0.4*
Cantilever Panel	Before Repair Welding (mm)	2.4	-0.4	1.7	1.9
	After Repair Welding (mm)	(3.1) 2.7	(2.3) 1.8	(4.4) 3.5	(3.2) 2.5
	Difference (mm)	0.3	2.2	3.7*	1.9*
	After Correction (mm)				(0.5) 0.4
	Difference (mm)				(2.7) 2.3
Ultimate Load (tons)		198	209	204	204
Ratio to Elastic Buckling Load		1.05	1.11	1.09	1.09
Ratio to Plastic Buckling Load		0.81	0.86	0.84	0.84
Ratio to Allowable Shear Stress Load		1.82	1.92	1.87	1.87

Remarks: 1) *; The difference doesn't become algebraical one of displacements before and after repair welding because maximum displacement didn't occur at the same point.
2) Value in parenthesis is displacement at the edge of the cantilever panel and value of out-of-parenthesis is displacement at 50mm from the edge.

In Case 1 using B panel of S-1 specimen (as fabricated), the values, which are shown in the row of "After repair welding," were measured after repair welding of Case 4 using A panel of S-1 specimen (repair and correction with loading). In Case 3 (repair with loading) and Case 2 (repair without loading), the repair of Case 3 was performed first, the repair of Case 2 was done secondly, afterward deformation was measured in both panels.

In these deformations, it was interesting that deformations before repair works were first mode in every cases but second mode was formed after repair works. Particularly comparing Cases 3 and 4 (repair with loading) with Case 2 (repair without loading), the deformations of Cases 3 and 4 showed second mode more evidently than that of Case 2.

This is considered to be both effects of loading and welding.

Figure 7 shows the out-of-plane deformation in the edge of specimen just after finish of welding of No. 1 welded joint. This experimental condition is Case 2 (repair without loading). The maximum displacement before repair was 0.6mm. The maximum displacement just after finish of welding of No. 1 welded joint was about 10mm and it occurred at the center of the web height.

This deformation was first mode and deflected to the welded joint. However, this was almost canceled by welding of No. 2 welded joint.

As for welding of Nos. 3 and 4 welded joint, they didn't largely influence on the deformation in the edge of specimen during works. The maximum displacement after cooling was 2.3mm (See Fig. 6). This is caused by the contraction in weld region with cooling.

In the case of repair with loading (Cases 3 and 4), the deformation during works was the same one as Case 2. During cooling after welding, the deformation mode changed from first mode to second mode.

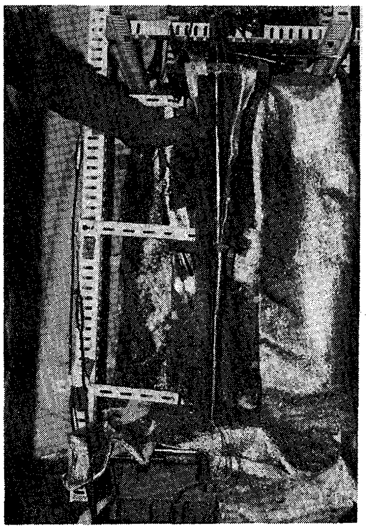


Fig. 7 Deformation just after Finish of Welding of No. 1 Weld Line. (Case 2, Specimen S-2)

By the way, the maximum deformations before repair welding were 1.2 ~ 2.3mm in inner panel, and 0.4 ~ 2.4 mm in cantilever panel. These are under the provision of the Standard Specifications for Highway Bridges of Japan Road Association: h/250=850/250=3.4mm, where h is the web height. And these are considered to be deformation which has been experienced in a factory.

The maximum deformation after repair welding in Case 3 was 3.5mm at 50mm from the edge of specimen. This is over the provision of the Standard Specifications (Figure 8 shows this deformation).

It is considered that the deformation caused by loading and welding concentrated on the edge of specimen where was a little restraint. Not a little deformation occurred after repair welding in Case 4 as well, but the flatness of the web plate could be gained by the correction under loading.

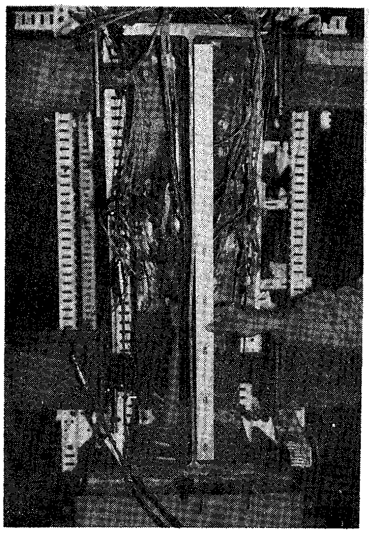


Fig. 8 Deformation after Repair Works with Loading. (Case 3, Specimen S-2, A panel)

Therefore, there is a case where the deformation over the provision of the Standard Specifications occurs by the repair welding under loading, but this deformation can be corrected under loading.

3.3 Ultimate Strength

Figure 9 shows P-δ curves. Solid lines show the out-of-plane displacement at the center of web and dashed lines show the vertical displacement at span center.

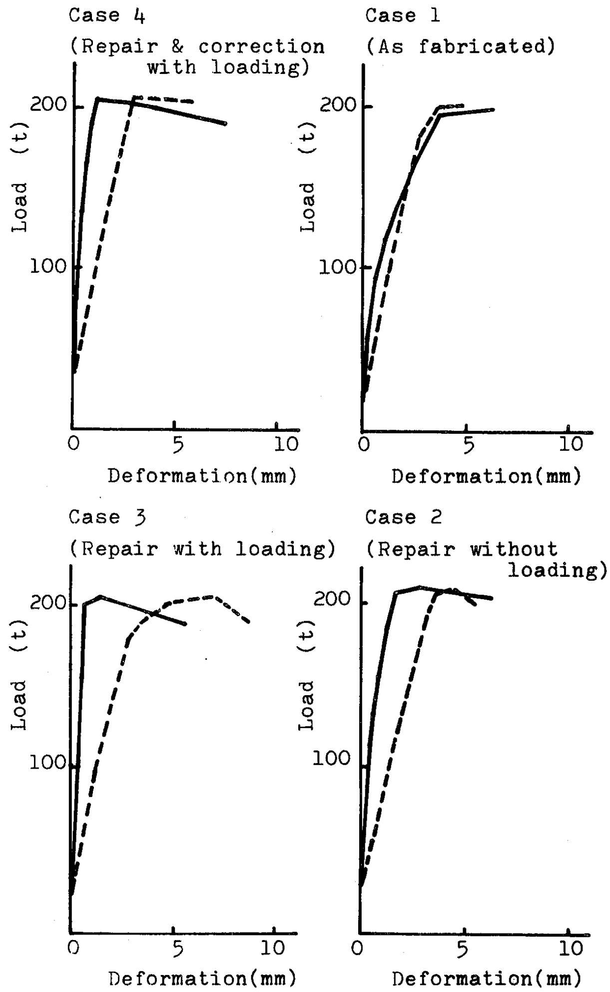
It is recognized from these figures that the ultimate strength of Cases 1 ~ 4 were 198 ~ 209tons (See Table 5). Here the ultimate strength is defined when the out-of-plane deformation increased rapidly.

These ultimate strength, 198 ~ 209tons, corresponds to 105 ~ 111% to the elastic buckling load (P=188tons) that is calculated using the nominal thickness of members. Similarly these strength corresponds to 81 ~ 86% to the plastic buckling load (P=243tons) and 182 ~ 192% to the allowable shearing stress load.

The slope of P-δ curve in Case 1 changes at P=109tons. As repair works were performed under this load, this specimen has had the load history till 109tons, but does not over 109tons. It is considered that the reason why this change can't be found in Case 2 ~ 4 is the effect of the heat of the repair welding.

It is recognized from Table 5 that there are no relation between the difference of initial deformations before loading test in inner and cantilever panel and the ultimate strength.

From above results, the decrease of the ultimate strength could not be recognized in these specimens repaired using welding under loading. Therefore, it can be said that deformations occurred by repair works have little effect on the ultimate strength.



Solid line is the out-of-plane displacement at the center of web.
Dashed line is the vertical displacement at span center.

Fig. 9 P-δ Curves

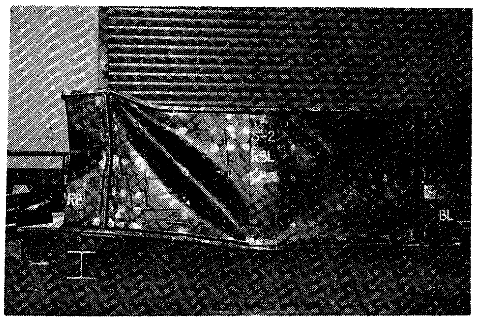


Fig. 10 S-2 Specimen after Loading Test

Figure 10 shows S-2 specimen after the loading test.

4. Conclusions

In this study, the repair works were performed under loading equivalent to allowable shearing stress to the joint between the bearing stiffener plates and web plate of specimen with similar proportion to the existing bridges, and the behaviors were studies. Moreover, the deformation in the cantilver panel occurred by repair welding was corrected by heating under loading, and this effect was examined. Finally, loading tests of specimens repaired by welding were done, and the ultimate strength was verified.

These results are summarized as follows.

(1) The part affected by heat of repair welding was the full width of stiffener plate, and in the web plate about 70mm from bearing stiffener, but its peak temperature was no more than 150°C.

(2) Deformation by repair welding occurred a little in inner panel, but not a little in cantilever panel.

(3) The maximum displacement during works was about 10mm in cantilever panel, and welding on inner panel didn't largely influence on the deformation in cantilever panel during works. It was obvious that the maximum deformation of 10mm was canceled by symmetrical welding to the web plate. The larger deformation occurred during cooling than working (i.e. the high temperature condition).

(4) The magnitude of out-of-plane deformation in web plate was independent of existence of loading during works, but the deformation mode changed from first mode to second mode.

(5) Deformation in cantilever panel occurred by repair welding could be reduced by means of heating and cooling with jacks under loading.

(6) There was a case where the out-of-plane deformation in web plate in cantilever panel was over the provision of the Standard Specifications for Highway Bridges as a result of repair welding under loading. However, the difference of only 5% was found in ultimate strength being under the control of the shear buckling, so it was not considered to be the meaningful difference. These ultimate strength corresponded to 105 ~ 111% to the elastic buckling load, 81 ~ 86% to the plastic buckling load, and 182 ~ 192% to the allowable shearing stress load.

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