Studies on Repair Welding in Japan†

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Abstract

Considerable numbers of bridges need repair and/or strengthening because those bridges have been constructed in the age of high growth of economy and have carried so much traffics but maintenance has not been made so completely owing to depressions after construction.

This is the common problem not only in Japan but also in the whole world.

One of the characteristic features of repair and/or strengthening welding is to be performed under static loading by own-weight of bridges as well as dynamic loading by traffics.

If welding can be performed under loading as mentioned above, there are many merits in repair and/or strengthening works.

In this paper, the background of the repair welding is introduced in Sec. 1, and the problems in repair welding to be discussed are listed up in Sec. 2, and several studies on repair welding are reviewed in Sec. 3 to 6.

KEY WORD: (Repair Welding)

1. Introduction

Many bridges had been needed and constructed in the age of high growth of economy due to the progress of motor traffics. Failures appear in the members of those bridges because the progress of motor traffics has been remarkable one such as the size of cars has become larger, the weight of cars has increased and traffic volume has also increased beyond expectation. Some bridges need widening and some need the reconstruction for deterioration.

Those bridges had been reconstructed easily in the age of high growth of economy even though they could stand the use of heavy traffics through repair and/or strengthening. However, the situation had changed in the age of low growth of economy. It is considered that even those bridges have to be reused by repair and/or strengthening so far from reconstruction after their expected life. The bridges not to match traffics of those days have been widened or strengthened. As maintenance has not been made so completely to the bridges constructed in the age of high growth of economy, they are rapidly deteriorated beyond expectation and need repair and/or strengthening.

This is the common problem not only in Japan but also in the whole world.

Under these backgrounds, IABSE (International Association for Bridge and Structual Engineering) held a colloquium, "Fatigue of Steel and Concrete Structures," in Lausanne[1] and a symposium, "Maintenance, Repair and Rehabilitation of Bridges," in Washington D.C.[2,3] both in 1982.

Failures were introduced at these meetings. Besides these, other failures are also reported in some publications. For example, reference 4) describes failures in America.

The following failures are reported recently in Japan, too.[5–9]

a. Fatigue failures in plate girder with non-uniform section

b. Fatigue failures in web gap

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c. Fatigue failures in steel pier
d. Fatigue failures at fillet weld between sole plate and lower flange
e. Fatigue failures at gusset plate connected with strut in arch bridge
f. Failure of bearing shoe by up lift
g. Delayed fracture of high strength bolts

Fatigue failures in plate girder with non-uniform section are shown in Figs. 1 and 2. Plate girder with non-uniform section is the structure that is cut off web near support to lower the web height from lower surface of beam on pier to upper surface of slab in overhead road. Fatigue cracks initiated at fillet weld in the corner and propagated to web. This cause was considered to be cyclic out-of-plane deformation, in one group. In the other group, out-of-plane deformation was not observed and considered to be only stress concentration or superposition of stress concentration, root gap and the shortage of effective throat depth with root gap. In the repair work, cracks had been gouged and welded, afterward splice plates with stiffeners were connected using H.T. bolts shown in Figs. 3 and 4. Depending on the causes, there were two cases in the type of connection. In one case, splice plates were connected to lower flange. In the other case, they were not connected.

If welding can be used in this work, it may bring many merits. However, there are many problems in welding under loading as listed up in Section 2. As several studies on them are done in Japan, they are reviewed in Section 3 to 6.

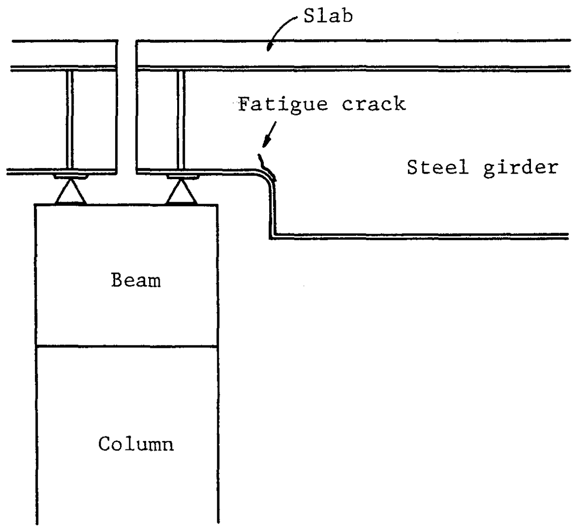


Fig. 1 Plate girder with non-uniform section and initiated fatigue crack – Case A –

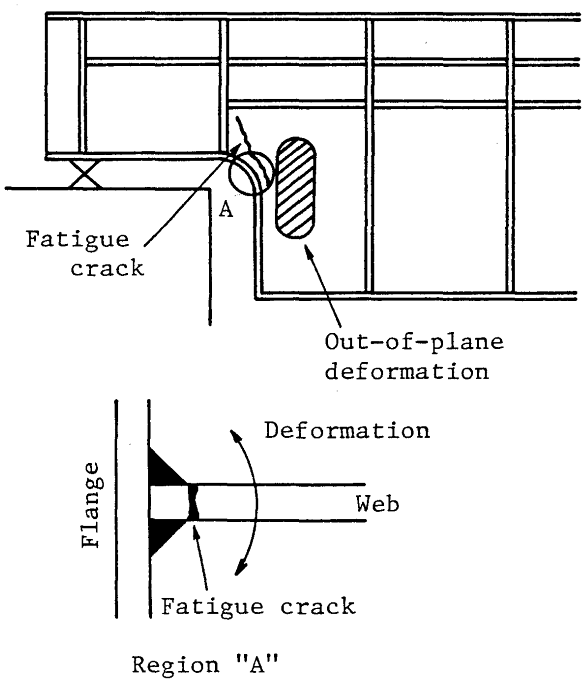


Fig. 2 Plate girder with non-uniform section and initiated fatigue crack – Case B –

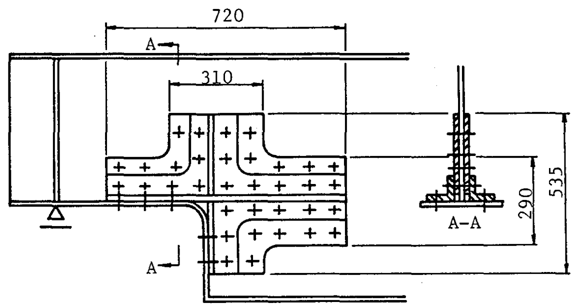


Fig. 3 Strengthening for case A

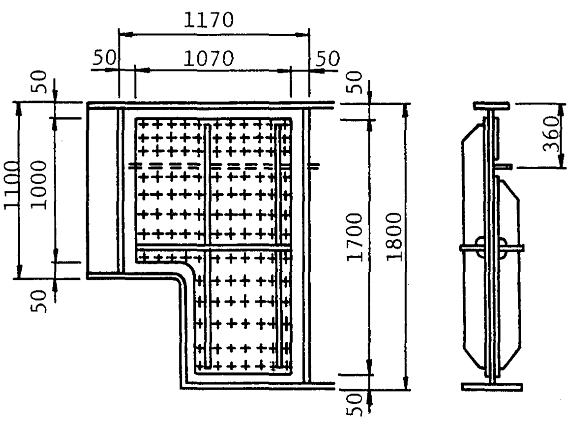


Fig. 4 Strengthening for case B

2. Approach to the Problems in Welding

Characteristic features of repair works on bridges in service condition are considered that the work is performed

1) under dead load and live load due to own weight and traffics,
2) under vibration occurred by traffics,
3) under worse workability depended on weather and work space.

These are completely different from problems in shop fabrication. So, there are unexperienced problems in repair welding. Item 3) may be solved by education and training of welder. Therefore, works are performed in many cases after applied stress are decreased using temporary supports and traffics are closed as to items 1) and 2). However, use of temporary supports needs additional cost. And working schedule is restricted because traffics are closed only at night or on holiday when traffics are not so heavy. Therefore, if welding can be applied in service condition, it is very beneficial in economical view points. But many problems, which should be solved, are there in repair welding.

Repair welded joints or members should be examined on the following items.[11,12] It is needed that welding procedures and working condition are provided to make safety to these items.

I. Safety during works
  (1) Static tensile strength
  (2) Buckling strength
  (3) Excessive deformation
  . .
  . .

Yield point and Young's modulus decrease in steels according to increase of temperature and are equal to zero over 600°C. Therefore, safety during works should be verified by two strength analyses; one regards weld zone as lack of sectional area during welding, and the other considers decrease of yield point and Young's modulus in high temperature region by welding heat conduction after welding.

II. Properties of joints and members after works
 II. 1. Properties of joints
  (1) Deterioration of mechanical properties
  (2) Residual stress
  (3) Weld cracks
  . .
  . .
 II. 2. Properties of members
  (1) Static tensile strength
  (2) Buckling strength
  (3) Fatigue strength
  (4) Excessive deformation
  . .
  . .

As joints welded under loading are subject to stress by external force and thermal stress at the same time, mechanical properties, bead appearance, residual stress distribution and so on may be different from ones in members by shop fabrication. Deterioration of mechanical properties of these joints may cause reduction of strength of members. Therefore, it is needed to verify mechanical properties of joints welded under loading and strength of members having those welded joints.

3. Cracks of Joints Welded Under Vibration

Complicated vibration occurs due to traffics in bridges. Welding under this condition, bead appearance may become unfavourable and manipulation of electrode may not work well. As a result of these, there is a possibility of surface defects such as undercut, or internal defects such as blowhole. Moreover, hot crack may occur if vibration is applied during solidification.

Vibrations of bridges in service condition were measured and bead appearance and internal defects of joints welded under vibration were studied by I. Suzuki et al.[13] Three bridges were measured as shown in Fig. 5. Vibrating conditions in experiments were decided from results of measurements. Frequencies were 0.3 ~ 300 Hz and displacement ranges were Vs, 5 × Vs and 10 × Vs, where Vs was the measured maximum displacement range in each frequency. Vertical up and down welding were performed under in-plane or out-of-plane vibrations with above conditions. Results are shown in Figs. 6 to 8. It is obvious from these figures that many undercuts occur at 3 Hz in vertical up welding, that in-plane vibrations have influence on bead appearance more than out-of-plane vibration and that blowholes do not occur within 5 × Vs to harm the quality. Internal defects were blowholes, lack of joint penetration, lack of fusion and so on. Therefore, it is concluded that welding can be performed under vibration of bridges in service condition in case within 5 × Vs by paying considerable cares. Vertical down welding was better procedure under in-plane vibration than vertical up welding because it showed good results in bead appearance and blowholes even under 10 × Vs in-plane vibration.

Cracks of deposited metal using SS41 (t = 12 mm) which had been manufactured in 1963 and had been in service to 1981 as crane girder were examined by K. Horikawa et al.[11] U type restrained weld cracking test specimen (JIS Z 3157) was clamped to actuator of fatigue testing machine and was welded using four kinds of covered electrodes under vibration. Vibrating conditions, frequencies and displacement ranges, were selected from the data measured by I. Suzuki et al.[13] Direction of vibration was vertical in plane. It is concluded from the experimental results that vibration occurred in bridges in service condition does not influence on weld crack and microstructure.

Influence of vibration on hot crack was investigated using trans varestraint cracking test by Y. Tomita et al.[12] Crack length on surface and temperature distribution along weld line were measured at each applied strain. Results are shown in Fig. 9. It is said from this figure that hot cracks occur in case of applied strain over 0.9% and strain rate over $1.2 \times 10^{-3}\,^{\circ}C^{-1}$.

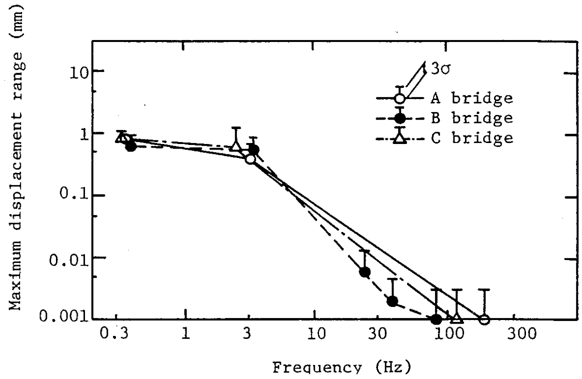


Fig. 5 Relation between frequency and maximum displacement range in in-plane vibration of bridges in service

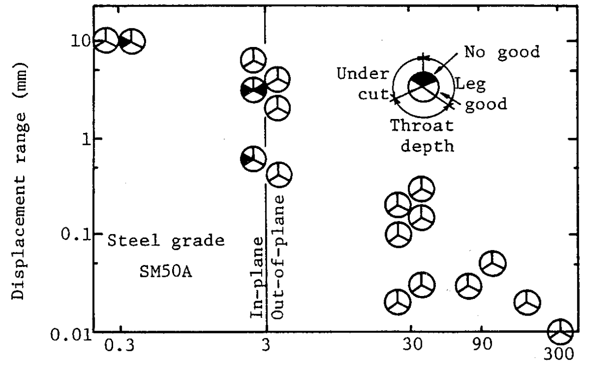


Fig. 6 Results of inspection on bead appearance by vertical up welding

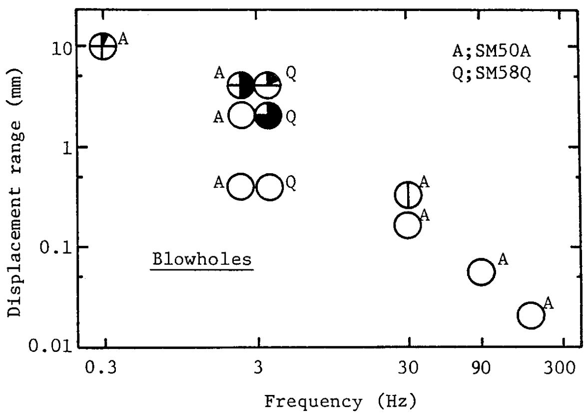


Fig. 7 Results of radiographic inspection on fillet weld by vertical up welding under out-of-plane vibration

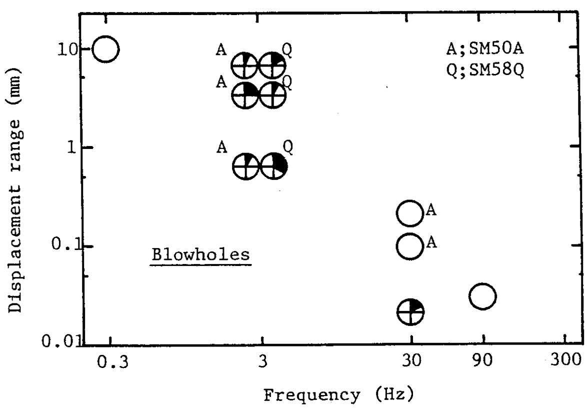


Fig. 8 Results of radiographic inspection on fillet weld by vertical up welding under in-plane vibration

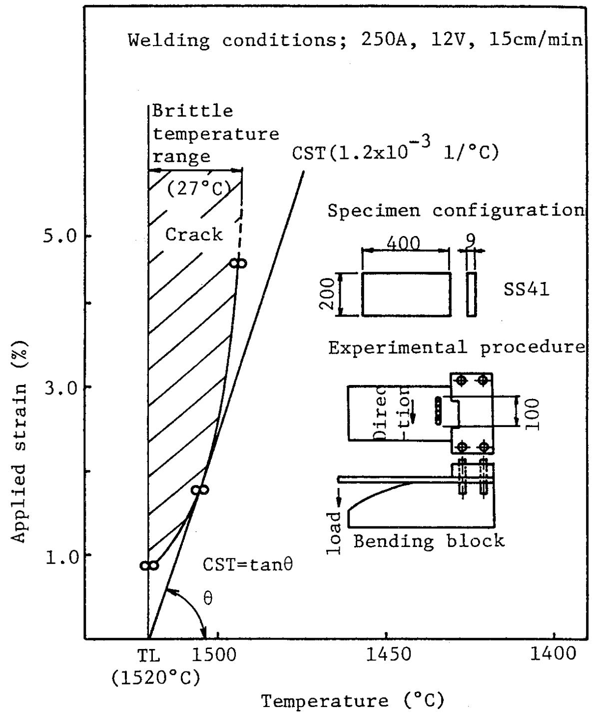


Fig. 9 Solidification brittleness temperature range

Weld cracking tests under pulsating stress were performed and fractography of crack, factors of influence on crack and conditions of welding procedure were examined by Y. Nakanishi et al.[14] It is reported from above results that welding under pulsating stress is possible when the restraint intensity of weld joints, stress range, groove length and stress frequency are within certain limits.

4. Mechanical Behaviors of Plates Welded Under Loading

4.1 Mechanical properties of joints

Table 1 is the summary of studies on mechanical properties and residual stress distributions of joints welded under loading. Mechanical properties are not deteriorated even though welding is performed under loading corresponding to allowable stress. Residual stress is reduced by the same amount as applied stress in case of welding under tensile loading, but it is not reduced in case of welding under compressive loading.

H. Suzuki et al.[16] considered on the residual stress of joints welded under loading using Fig. 10.

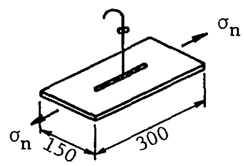
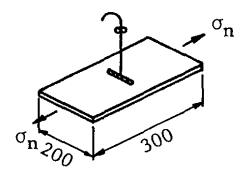
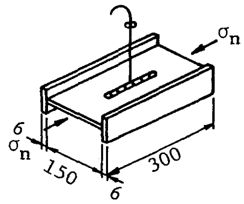
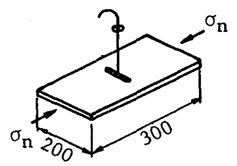
Thermal stress is expressed as

$$\sigma = -E\alpha\theta$$

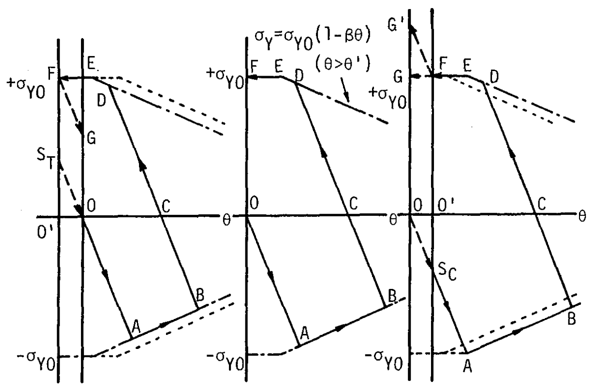
where E is Young's modulus, α is linear expansion coefficient and θ is temperature.

Without loading, compressive stress increases according to temperature. And yield stress decreases. Therefore, compressive stress reaches yield stress at point A and maintains yield stress along AB. With the beginning of

Table 1 Summary of mechanical properties and residual stress distribution

	Under tensile stress		Under compressive stress	
Direction	Parallel	Transverse	Parallel	Transverse
Specimens	SS41 (t=6mm) 	SM41B (t=6mm) 	SM41B (t=6mm) * 	SM41B (t=6mm) ** 
Welding Conditions	390A, 44V, 50cm/min, 20 600J/cm	315A, 33V, 50cm/min, 12 500J/cm	315A, 33V, 50cm/min, 12 500J/cm	315A, 33V, 50cm/min, 12 500J/cm
Experimental conditions	1.Welding without loading 2.Welding without loading, then loading of σ_n=14kg/mm^2 3.Welding under σ_n=14kg/mm^2 4.Welding without loading, then welding under σ_n=14kg/mm^2 5.Welding under σ_n=24kg/mm^2	1.Welding without loading 2.Welding under σ_n=14kg/mm^2	1.Welding without loading 2.Welding without loading, then loading of σ_n=-14kg/mm^2 3.Welding under σ_n=-14kg/mm^2 4.Welding without loading, then welding under σ_n=-14kg/mm^2	1.Welding without loading 2.Welding under σ_n=-14kg/mm^2
Mechanical properties	No deterioration	No deterioration	No deterioration	No deterioration
Residual stress	Reduction corresponding to applied stress	Reduction corresponding to applied stress	No reduction	No reduction
FEM analyses	Yielded region enlarged by transient stress	Under consideration	Yielded region enlarged by transient stress	Under consideration
References	15)	16)	12,16,19)	16)

*) Stress release treatment after welding of flanges to prevent from buckling
**) Strengthening by angle bars with clamps to prevent from buckling



(a)With ten. load (b)Without load (c)With comp. load

Fig. 10 Stress histories

cooling, compressive stress decreases (B to C) and tensile stress occurs at a certain temperature (point C). This tensile stress increases with cooling and reaches tensile yield stress (point D). Tensile stress maintains yield stress after here (D to F). The residual stress on weld bead becomes tensile yield stress at room temperature (point F).

Tensile pre-loading can be shown as line OS_T in Fig. 10(a). The stress history to room temperature is the same as the case without loading (S_T to F). When pre-load is unloaded, residual stress on weld bead decreases as the same as applied tensile stress (F to G).

Under compressive loading, stress history goes from O to S_C and then the stress history to room temperature is the same as the others (S_C to F). Tensile residual stress might increase in elastic body by unloading (F to G'). However, tensile residual stress over yield stress disappears because of yielding in elasto-plastic body and tensile residual stress maintains yield stress (F to G).

It is also known from results of FEM analyses[15,19] that yielded region enlarges by transient stress redistribution. Therefore, there is a possibility of increase of deformation under tensile loading and buckling by decrease of rigidity under compressive loading.

Residual stress distribution by welding under static loading was studied experimentally by Y. Nakamura et al.[18] and reported that the stress didn't occur in repair welded zone for static load during welding.

4.2 Deformation of plates

As for the deformation of plates welded under loading, assumed fatigue cracks were filled up by welding and cover plates were welded to tensile or compressive member.[11,17,20] In these studies, welding was performed in transverse direction against load to plates under tensile or compressive loading. Parameters were external load and the ratio of weld length (l) to plate width (b). The conclusions are summarized in Table 2.

5. Plate Girders Welded under Loading

Some studies were performed using girders like existing bridges and procedures were adopted according to the practical ones.

The followings are considered in works heating the structures in practical repair and/or strengthening works.

(1) Cracks are removed by gouging.
(2) It is filled up by welding.
(3) New reinforcing members are welded if necessary.
(4) Deformation caused by welding is corrected by heating with gas flame if necessary.
(5) In reshape works, gas cutting is also used.

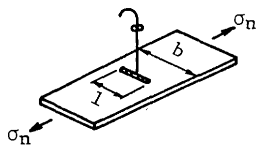
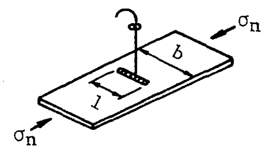
Preheating is also considered besides these heating works. However, it may be no problem because of low temperature.

Repair works according to above (1), (2) and (4) to four fillet weld lines between bearing stiffeners and web were performed under loading corresponding to allowable shearing stress in web, and behaviors during works as well as ultimate strength of specimens after works were examined by K. Horikawa et al.[21]

Specimens (Fig. 11) were stable during works or buckling didn't occur. Table 3 shows out-of-plane deformations in web and ultimate strength after works. Experimental results are summarized as follows.

1) Out-of-plane deformations by repair works were only a little in inner panel, 1.0 ~ 1.8 mm, and not a little in cantilever panel, 2.3 ~ 4.4 mm.

Table 2 Summary of deformation

	Under tensile stress	Under compressive stress
Direction	Transverse	Transverse
Specimens	SS41  Pl. 6x200x500 Pl. 6x150x500	SS41  Pl. 6x150x500
Welding conditions	1)200A, 26V, 30cm/min, 10 400J/cm 2)170A, 25V, 15cm/min, 17 000J/cm	1)200A, 26V, 30cm/min 10 400J/cm
Experimental conditions	1)l/b=0.05~1.0 σ_n=0,14kg/mm^2 2)l/b=1.0 σ_n=0,7,14,21kg/mm^2	1)l/b=0.1~1.0 σ_n=-14kg/mm^2 2)l/b=1.0 σ_n=0,-7,-14kg/mm^2
Conclusions	1)Can be welded, if l/b≦0.5 2)Can be welded, if σ_n≦7kg/mm^2 3)Greater effect of welding heat input than welding speed	1)Can be welded, if l/b≦0.1 2)Can be welded, if σ_n≧-7kg/mm^2
References	11,20)	17)

2) Deformation occurred by repair works in cantilever panel could be reduced by means of heating and cooling with jacks under loading.
3) There was a case where the out-of-plane deformation in web in cantilever panel was over the provision ($h/250 = 3.4$ mm, where h is web height) of the Standard Specifications for Highway Bridges of Japan Road Association as a result of repair works under loading. However, the difference of only 5% was found in ultimate strength among these cases, so it was not considered to be the meaningful diffrence. These ultimate strength corresponded to 182 ~ 192% to the load on the basis of allowable shearing stress.

The experiments on the reshape of a plate girder from uniform section to non-uniform section were performed under loading according to above-mentioned (3) and (5), and safety during welding as well as deformation after works were studied and the attentions in practice were examined by K. Horikawa et al.[22]

The results (Fig. 12) are summarized as follows.
1) In case of gas cutting after welding of stiffeners, deflection at the span center increased only 1.0 mm at most even when gas cutting was done at the location of $\sigma = 1000$ kg/cm^2 in lower flange and $\tau = 500$ kg/cm^2 in web.
2) In case of welding of lower flange after gas cutting, gas cutting could be done up to stiffener, cut length = 440 mm. However, deformation increased excessively and applied load decreased when gas cutting was done beyond stiffener, cut length = 720 mm. As dead load does not decrease in existing bridges, this state is considered to be fracture.

From these results, practical procedures in existing bridges were considered and recommended as Fig. 13.

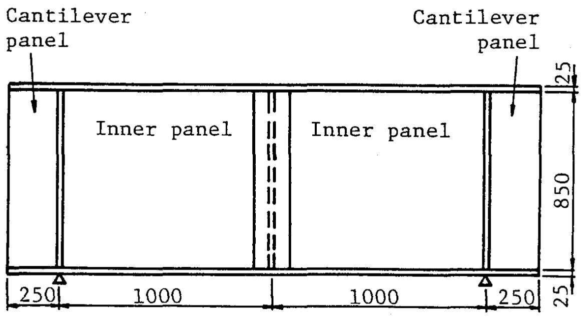


Fig. 11 Specimen configuration

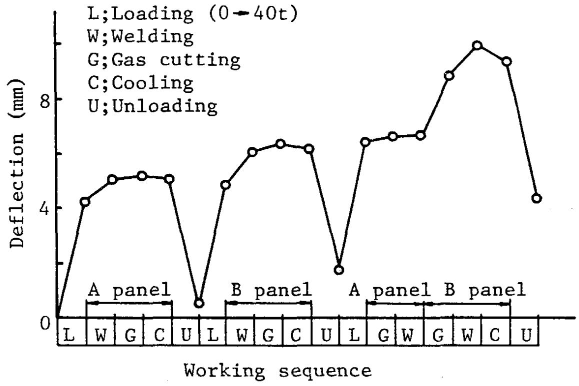


Fig. 12 Deflection at center of span

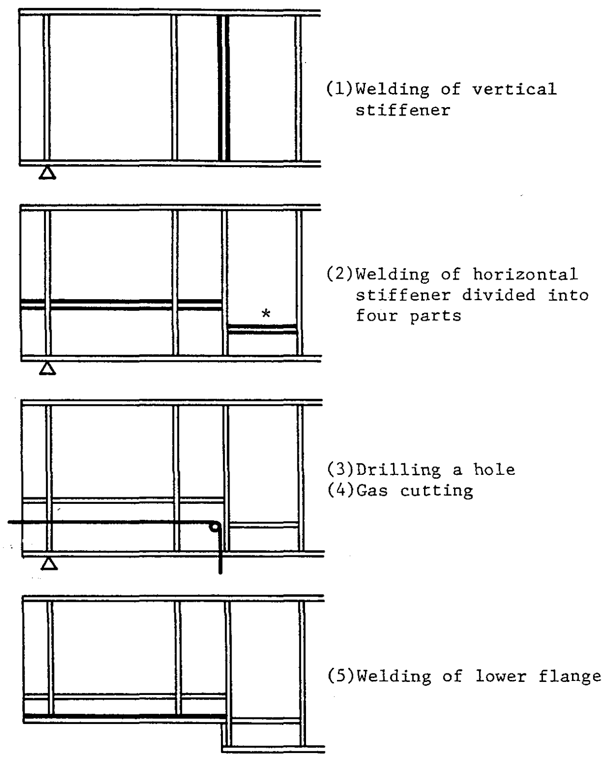


Fig. 13 Recommended procedures for bridge in service

Table 3 Out-of-plane deformations in web and ultimate loads

	Case 1	Case 2	Case 3	Case 4
Deformation in inner panel (mm)	1.8	1.4	1.0	1.2
Deformation in cantilever panel (mm)	3.1	2.3	4.4	3.2
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 shearing stress load	1.82	1.92	1.87	1.87

(1) At first, welding of vertical stiffeners
(2) Secondly, welding of horizontal stiffeners
It is desirable that the stiffeners marked by * in Fig. 13 is welded on the same line as lower flange of (5) and welded to next vertical stiffener.
(3) Then drilling a hole
(4) And gas cutting
(5) Finally, welding of lower flange

Influence of repair welding of fillet welds jointed web to upper flange on shear buckling in web as well as local buckling in flange was investigated by H. Suzuki et al.[23]

6. Pipe Columns Welded under Loading

As for the study on repair and/or strengthening welding to members under axial loading, pipes welded under axial compressive loading were studied.[24] In this study, gusset plates or ring stiffeners were welded to pipe columns, and mechanical behaviors of pipes during welding as well as ultimate strength after welding were examined.

The followings were shown from this study.

1) In pipe with diameter of 216.3ϕ, gusset plate with length of 200 mm or ring stiffener with length of 230 mm were able to be welded even under compressive loading of $\sigma_n = 240$ MPa, yield stress of STK 41 in JIS G 3444.
2) In case of welding on gusset plate with length of 150 mm to pipe with diameter of 48.6ϕ, pipe was stable under compressive loading of $\sigma_n \leqslant 100$ MPa. As for ring stiffener with 50 mm, pipe was stable under $\sigma_n \leqslant 80$ MPa.
3) In ultimate strength after welding, there was no significant difference between pipes with 216.3ϕ welded attachments and ones welded nothing. On the other hand, there was a difference in pipes with 48.6ϕ. This difference was considered as a result of deformation caused by welding under loading.

7. Concluding remarks

This paper described the background of, the problems in and reviews of several studies on repair welding in Japan. Study on repair welding is just started. So, lots of problems remains to be proved. However, if characteristic features of welding under loading are understood, and welding procedures and working conditions are provided to make safety during welding, welding can be done to structures in service condition. As increase of repair works is predicted in future, studies on repair welding are expected to be performed much more to obtain a safe and economical procedure.

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