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Fundamental Study on Welding to Bridge Members in Service Condition†

–Welding to Compression Members–

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Abstract

Many bridges, which have been constructed in the age of high growth of economy, sustain the damages by increase of heavy traffics. For example, increase of heavy cars leads the lack of cross sectional area of members. More cover plates are established in these members for strengthening.

Characteristics of repair and/or strengthening works are to be done under loading and vibration. There are few studies in relation to welding to members in service condition though the use of welding in repair and/or strengthening works has many advantages.

This paper describes some experimental and analytical studies on the effect of welding under loading on the deformation behaviors of plates.

KEY WORDS: (Deformation) (Repair Weld) (Strengthening Weld) (In-service Condition)

1. Introduction

The greatest concern of bridge engineers in the world is maintenance, repair and rehabilitation of bridges. This reason is a change of growth of economy from high to low. Bridges had been reconstructed easily by the insignificant reason in the age of high growth of economy. However, bridges became to be used for a long time as much as possible in the age of low growth of economy. Many bridges, which have been constructed in the age of high growth of economy, sustain the damages by increase of heavy traffics. Therefore, they need repair and/or strengthening. Deterioration occurs in concrete slab and fatigue crack initiates in steel members because of increase of traffic and/or heavy cars over design load. More stringers are established for the concrete slab or cover plates are set up in order to increase of cross sectional area of the member for repair and/or strengthening of these members. Increase of traffic also leads the lack of lanes. So, establishment of more main girders is needed for the widening of bridges.

Characteristics of repair and strengthening works are to be done under loading by dead and live load and under vibration by traffics if traffics are not controlled. In many cases, repair and/or strengthening works are performed in the condition of reduction of stress using staging and traffic control in order to avoid the above conditions.

The use of welding in repair and/or strengthening works has many advantages as compared with the use of bolt. There is not a loss of sectional area in repair and/or strengthening works using weld. Weld execution is very easy than bolt.

The study on repair and/or strengthening weld is apt to become a case study. Therefore, there are few fundamental studies. Tokuzawa et al.[1]) studied on mechanical properties under tension loading. Suzuki et al.[2]) studied on weld cracking under vibration. The study on deformation is not made till now. Weld length, heat input, magnitude of external load and others give the effect on deformation in the case of welding to members under loading.

In this paper, strengthening weld of cross direction against external load is supposed in the case of establishment of cover plates to compression members. And the effects of weld length and magnitude of external load on deformation are investigated experimentally.

2. Experimental Procedure

Material is the mild steel of 41 kg/mm^2 in the tensile strength (called SS41 in JIS G3101). Chemical com-

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position and mechanical properties are shown in **Table 1**. Test specimen configuration is shown in **Fig. 1**. Width and thickness of specimen are 150 mm and 6 mm, respectively. Distance between chucks is 300 mm. Specimen was welded as bead-on-plate using CO_2 arc welding. Weld condition was as follows; welding current 26A, welding voltage 200 V and welding speed 30 cm/min. Therefore, weld heat input was 10400 J/cm.

Table 2 shows experimental conditions. The ratio of weld length to specimen width (l/b) and magnitude of external load (σ^{∞}) were selected from many factors giving the effect on deformation in the case of welding to members under loading. C-0 specimen is equivalent to the condition of shop welding because external load does not apply. C-1 and 2 specimens are equivalent to the condition of field welding. C-1 and 2 specimens were simulated the condition of reduction of stress using staging and no reduction, respectively. Weld length is full width in these three specimens. Welding was performed continuously all over the width. C-3 ~ 5 specimens were simulated the condition that total weld length was divided some regions and welding was performed under the same loading as C-2 specimen.

Table 1 Chemical Composition and Mechanical Properties

C X100	Si X100	Mn X100	P X1000	S X1000	Y.S. kg/mm^2 (MPa)	T.S. kg/mm^2 (MPa)	El. %
18	5	63	16	23	34 (333)	45 (441)	29

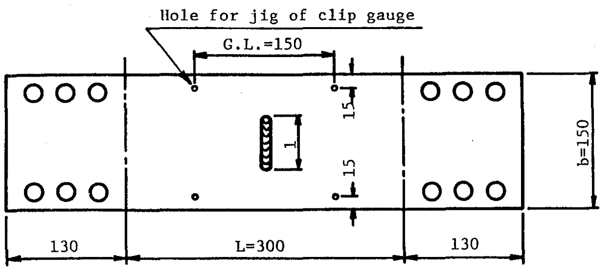

Fig. 1 Specimen Configuration

Table 2 Experimental Conditions

Specimen No.	Applied Stress σ^{∞}(kg/mm^2)	Normalized Weld Length l/b
C-0	0	1.0
C-1	-7	1.0
C-2	-14	1.0
C-3	-14	0.5
C-4	-14	0.25
C-5	-14	0.1

Test specimen was loaded till prescribed load. Holding this load, welding was performed. Test specimen was unloaded after it was cooled till room temperature. Deformation was measured from weld start to unloading using clip gauges. Jigs were attached the holes in Fig. 1 and clip gauges were set between them.

3. Experimental Results and Discussions

3.1 Effect of the magnitude of external load

Figure 2 shows the results of C-0 ~ 2 specimens. Start side and end side in this figure mean the output of clip gauges in starting and termination of welding. Horizontal axis is time after weld start and vertical axis is displacement.

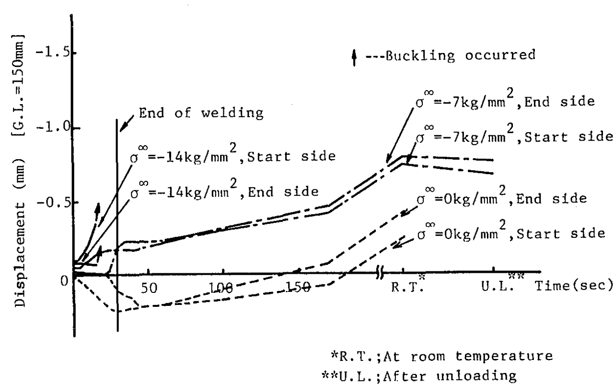

Fig. 2 Effect of the magnitude of external load

In C-0 specimen (dotted line), start side shows elongation deformation as soon as weld starts. Start side keeps this elongation deformation even at 170 seconds after weld start. The maximum of this elongation deformation is 0.25 mm at the end of welding (30 seconds after weld start). On the other hand, end side once shows a very little shrinkage deformation till 20 seconds after weld start and elongation deformation after that. This elongation deformation increases rapidly and becomes the maximum at 50 seconds after weld start. Its value is 0.2 mm. From 50 seconds, elongation deformation decreases gradually and shrinkage deformation appears again at 140 seconds. Both sides show shrinkage deformation at room temperature. Residual displacements are approximately –0.2 mm in start side and –0.4 mm in end side.

The reason why elongation and shrinkage deformation around weld start occur in start and end side respectively is following. Weld zone near starting of welding expands by welding heat. As a result of it, bending moment is produced in plane of specimen. Therefore this moment decreases and vanishes because weld zone increases according to weld run. The reason why elongation deformation occurs in both sides is that weld zone expands by welding heat. This elongation deformation decreases gradually as shrinkage begins from 30 seconds after weld start in start side and 50 seconds in end side. Shrinkage deformation remains finally.

In C-1 specimen (dot-and-dashed line), start side shows a little elongation deformation till 5 seconds after weld start and shrinkage deformation after that. Though this shrinkage deformation increases gradually, it does not increase from 20 to 40 seconds. Shrinkage deformation increases again from 40 seconds and reaches the maximum at room temperature. It is approximately –0.75 mm. End side shows scarcely any deformation till 5 seconds after weld start. After that, it shows a little elongation deformation. This elongation deformation reaches the maximum at 20 seconds after weld start. However, this elongation deformation is not more than shrinkage deformation by compression load. Shrinkage deformation occurs after 20 seconds. This shrinkage deformation increases rapidly from 25 to 35 seconds and it is constant from 35 to 60 seconds. Shrinkage deformation increases gradually from 60 seconds and reaches the maximum at room temperature. Its value is nearly equal to start side one. Comparing residual deformation, C-1 specimen has 2 or 3 times as large as C-0 specimen. End side of C-1 specimen shows elongation deformation around weld start while one of C-0 specimen shows shrinkage deformation. In C-1 specimen, weld zone near starting of welding shows shrinkage deformation in the condition of compression loading as welding heat melts weld zone. This condition is equivalent that single edge-notched plate is loaded compression load, if weld zone is considered as notch. Therefore, reverse bending moment produces in C-1 specimen in comparison with C-0 specimen. The reason why deformation does not progress temporarily around end of welding in both sides is that expansion by welding heat is in balance with shrinkage by external load.

In C-2 specimen (solid line), start side shows a little elongation deformation till 3 seconds after weld start (Refer to Fig. 3) though the magnitude of external load is –14 kg/mm². This elongation deformation is the effect of welding heat. Shrinkage deformation progresses rapidly from 3 seconds and buckling occurs at 15 seconds after weld start. End side does not deform till 5 seconds after weld start. Elongation deformation increases gradually from 5 seconds because of the same reason as C-1 specimen and buckling occurs.

It is definitely shown by above results that the magnitude of external load has an effect on deformation behaviors. The reverse in-plane bending moment produces in loaded members in comparison with unloaded members. Loaded members have more residual deformation than unloaded members. Whether buckling occurs in member or not depends on the magnitude of external load.

3.2 Effect of weld length

The results of C-2 ~ 5 specimems are shown in **Fig. 3**.

As mentioned already, buckling occurred in C-2 specimen (solid line) when it was welded till half width. In this specimen, welding was tried continuously all over the width under the external load of –14 kg/mm².

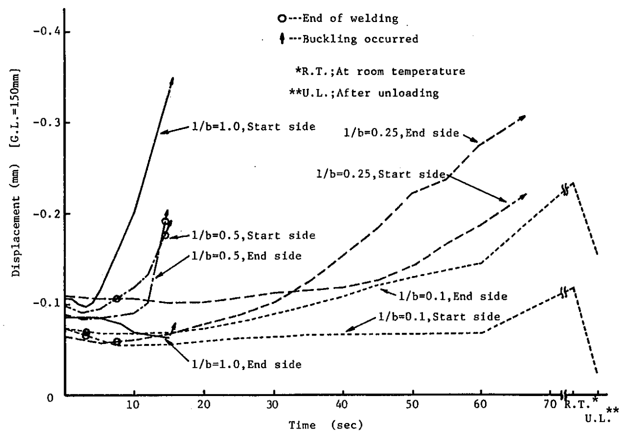

Fig. 3 Effect of weld length

The ratio of weld length to specimen width is 0.5 in C-3 specimen (dot-and-dashed line). In this specimen, start side shows elongation deformation from weld start to 3 seconds and shrinkage deformation after that. This shrinkage deformation increases rapidly and buckling occurs at the end of welding (15 seconds after weld start). On the other hand, end side shows elongation deformation from weld start to 3 seconds. This elongation deformation is a very little. Shrinkage deformation appears from 3 seconds and increases gradually. This increases rapidly from 12 seconds and buckling occurs. It is obvious from C-2 and 3 specimens that buckling occurs in the case of welding to the members with 0.5 in the ratio of weld length to width and the external load of –14 kg/mm² regardless of weld location.

Let's consider the behaviors of these specimens analytically. For the sake of simplicity, the specimens are assumed the column with eccentricity. From above assumption, secant formula can be used for this problem. Secant formula is

$$\sigma = \frac{P}{A}\left(1 + \frac{e}{k'} \sec \frac{1}{2r} \sqrt{\frac{P}{A \cdot E}}\right) \qquad (1)$$

where, P: external load, A: area of cross section, e: eccentricity, k′: core radius, r: radius of gyration of area and E: Young's modulus.

For members with rectangular section, secant formula becomes as

$$\sigma = \frac{P}{b \cdot t}\left(1 + \frac{6e}{t} \sec \frac{1}{t}\sqrt{\frac{3 \times P}{b \cdot t \cdot E}}\right) \qquad (2)$$

where, b is the plate width and t is the plate thickness.

Substituting the values of C-3 specimen into eq. (2), eccentricity before welding becomes

$$e = 0.283 \text{ mm} \qquad (3).$$

At this time, the stress which was measured by strain gauge at the center of specimen was used.
Subsequently, eq. (2) is tranformed as

$$\sec\left(\frac{1}{t}\sqrt{\frac{3 \times P}{b \cdot t \cdot E}}\right) = \left(\frac{b \cdot t \cdot \sigma}{P} - 1\right) \times \frac{t}{6e} \qquad (4).$$

As left member of eq. (4) has to be not less than unit,

$$\left(\frac{b \times t \times \sigma}{P} - 1\right) \times \frac{t}{6e} \geqq 1 \qquad (5)$$

is obtained.

Assuming that buckling occurs at $\sigma = \sigma_Y$, eq. (5) becomes

$$b \geqq \left(\frac{6e}{t} + 1\right) \times \frac{P}{t} \times \frac{1}{\sigma_Y} \qquad (6)$$

where, σ_Y is yield stress.
Substituting the values of specimen and eq. (3) into eq. (6), plate width is obtained as

$$b \geqq 80.2 \text{ mm}.$$

Namely, plate width needs to be not less than 80 mm in order that buckling does not occur in specimens with 6 mm thickness under loading of -14 kg/mm^2. Weld zone has not stiffeness because weld zone is the condition of melt or high temperature. Therefore, effective specimen width was 75 mm approximately when buckling occurred in C-2 and 3 specimens. As effective width became under the minimum width, buckling occurred.

In C-4 specimen (dashed line) with 0.25 in the ratio of weld length to specimen width, start side shows scarcely deformation till around 40 seconds after weld start. After that, shrinkage deformation increases and buckling occurs at 65 seconds. End side also shows the similar behavior to start side. End side shows scarcely deformation till around 15 seconds. Shrinkage deformation increases after that and buckling occurs. In C-2 and C-3 specimens, weld zone should be considered as lack of cross section rather than decrease of stiffeness and/or yield stress by welding heat because buckling occurred during and just after welding. On the other hand, the reason of buckling at 57.5 seconds after end of welding in C-4 specimen should be that stiffeness and yield stress reduced by transfer of welding heat to the other part of weld zone. Hence the additional experiment was performed in the same conditions as C-4 specimen for the purpose of verification of reappearance and finding thermal distribution at buckling. Buckling occurred at 40 seconds in the additional specimen while buckling occurred at 65 seconds after weld start in C-4 specimen. This difference is the effect of initial imperfection. The bending stress by out-of-plane moment after loading is ± 2.4 kg/mm^2 in C-4 specimen and ± 3.2 kg/mm^2 in the additional specimen.

Figure 4 shows the thermal distribution on center line at buckling in the additional specimen. Temperature was measured at the back of specimen using thermo-couples.

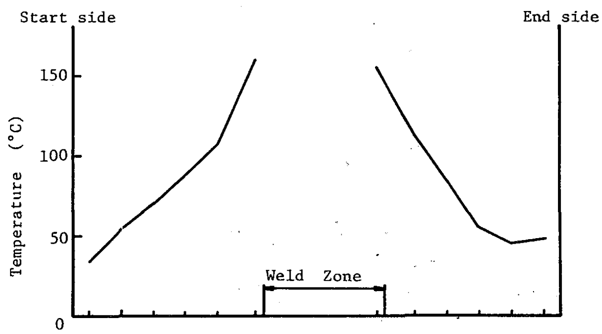

Fig. 4 Thermal distribution on center line at buckling

Temperature at buckling is 150°C at starting and termination of welding and approximately 40°C at both sides of specimen. There is not a significant difference between distributions of start side and end side.

Let's take the same analytical consideration as one in C-2 and 3 specimens. Eccentricity before welding becomes

$$e = 0.232 \text{ mm},$$

using eq. (2).

Assuming that buckling occurs at $\sigma = \sigma_Y$, the minimum specimen width can be obtained by eq. (6). However, yield stress reduces in the other part of weld zone because of heat. Therefore, let us suppose from the results of additional experiment for the first approximation that the average temperature in the other part of weld zone is 100°C. Yield stress at 100°C is shown to reduce to 75% of yield stress at room temperature from tensile test in high temperature.[5] Hence

$$\sigma_{Y,100°C} = \sigma_Y \times 0.75 \qquad (7)$$

is used as σ_Y in eq. (6).
Substituting the values of specimen and eq. (7) into eq. (6), plate width is obtained as

$$b \geqq 101 \text{ mm}.$$

Plate width is 112.5 mm when weld zone is considered as lack of cross section. These values show the relatively good agreement though welding deformations are not taken into account. The maximum weld length being able to weld continuously be obtained using secant formula for the first approximation, considering weld zone as lack of cross section and reduction of yield stress.

The ratio of weld length to specimen width is 0.1 in C-5 specimen (dotted line). In this specimen, start side shows gradual elongation deformation after weld start and scarcely deformation from 10 seconds to 60 seconds after weld start. End side shows scarcely deformation from weld start to 20 seconds and shows gradual shrinkage deformation after that. Both deformations reach the maximum at room temperature. Their values are –0.12 mm in start side and –0.23 mm in end side. Buckling does not occur in this specimen.

Finding the eccentricity before welding using eq. (2),

$$e = 0.132 \text{ mm}$$

is obtained.

Subsequently, transforming eq. (6), it becomes

$$\sigma_Y \geqq \left(\frac{6e}{t} + 1\right) \times \frac{P}{t} \times \frac{1}{b} \qquad (8).$$

Substituting the values of specimen into eq. (8), the minimum yield stress is found as

$$\sigma_Y \geqq 17.7 \text{ kg/mm}^2.$$

Namely, buckling occurs when yield stress in the other part of weld zone reaches 17.7 kg/mm^2. 17.7 kg/mm^2 is equivalent to 52% of yield stress at room temperature. Tensile test in high temperature shows that yield stress at 300°C reduces to approximately 50% of one at room temperature. Buckling did not occur in C-5 specimen because the average temperature at the other part of weld zone did not reach 300°C.

4. Conclusions

In this paper, the effect of strengthening weld to the members under compression loading on deformation was investigated experimentally. In addition to the experiments, analytical considerations were performed for some specimens. These results are considered to be applied to the establishment of cover plates, brackets and others on compression members in service condition. The main results are as follows.

(1) The member has buckling when the strengthening weld is performed continuously over quarter width to the member with the external load of –14 kg/mm^2. For the purpose of prevent the buckling, weld length needs to be divided into ten equal parts, otherwise stress needs to be reduced using staging.
(2) The member can be welded continuously over full width if stress is reduced under external load of –7 kg/mm^2 using staging.
(3) Initial imperfection should be paid attention in the case of welding to members in service condition because the effect of initial imperfection on deformation is very large.
(4) The maximum continuous weld length was estimated using secant formula. In this analysis, weld zone was considered as lack of cross section and reduction of yield stress by welding heat was considered.

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