Repair by Heating/Pressing of a Locally Buckled Steel Bridge Pier and Its Behavior under Cyclic Loads†

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Abstract

A series of experiments was conducted in order to elucidate behavior under cyclic loads of a steel bridge pier of which local buckling damage was repaired with correction by heating/pressing. The steel bridge pier specimens were locally buckled by loading simulating the situation of an earthquake. The locally buckled part was corrected by heating/pressing with or without water-cooling. Some deformations were left to avoid cracking in the welds, which were residual imperfections. After that, the same loading experiments were conducted. From the results, no deterioration was confirmed in the mechanical properties of the steel even with water-cooling only if the heating temperature was kept below the A_1 transformation temperature. Although ideally the local buckling deformation was repaired within an allowance of initial deflection in correction by heating/pressing, it was apparent that making the residual imperfection mode opposite to the local buckling mode was effective for ensuring the maximum load was the same level as that of the virgin pier.

KEY WORDS: (Repair), (Correction by heating/pressing), (Steel bridge pier), (Local buckling), (Residual imperfection)

1. Introduction

When steel structural members of infrastructures are damaged by an earthquake, a fire or other factors, they need to be repaired quickly to allow the passage of emergency vehicles (ambulances and fire engines) and the transportation of aid supplies.

Correction by heating/pressing for local buckling deformation, which is relatively mild damage, is widely used as temporary repair on site[1]. However, the effects of correction by heating/pressing on mechanical behavior of steel members are unknown. Therefore it is necessary to elucidate them in order to confirm the safety of structural members corrected by heating/pressing.

A series of researches for cruciform columns and box columns were conducted for investigating the effects of correction by heating/pressing on mechanical behavior of steel members under uniform compressive loads[2-5].

However, it is still unknown whether the results of those researches can be applied to large real structures such as bridge piers or girders under various types of loading.

This paper reports a series of experiments carried out on large specimens modeled on a steel bridge pier. At first, cyclic loading experiments for virgin specimens considering the loading condition of an earthquake were conducted in order to generate local buckling deformation in the specimens. Secondly, this deformation was repaired with correction by heating/pressing. And then, the same experiments were carried out on the repaired specimens. Comparing both experimental results, the behavior under cyclic loads of the steel bridge pier, in which the local buckling damage is repaired with correction by heating/pressing, is elucidated.

2. Cyclic Loading Experiment on Virgin Steel Bridge Pier

2.1 Specimens

Figure 1 shows the specimen modeled on a steel bridge pier.

Mechanical properties of material (SM490) and structural parameters are shown in **Table 1**.

Two specimens were labeled (A and B).

The slenderness parameter and the width-thickness ratio parameter are defined as Eq. (1), (2) respectively.

$$\lambda_C = \frac{1}{\pi}\sqrt{\frac{\sigma_Y}{E}}\frac{2h}{\sqrt{I/A}} \tag{1}$$

$$\lambda_P = \frac{1}{\pi}\sqrt{\frac{12(1-\nu^2)}{k}}\sqrt{\frac{\sigma_Y}{E}}\frac{b}{t} \tag{2}$$

Where, b is the breadth of plate. In a stiffened

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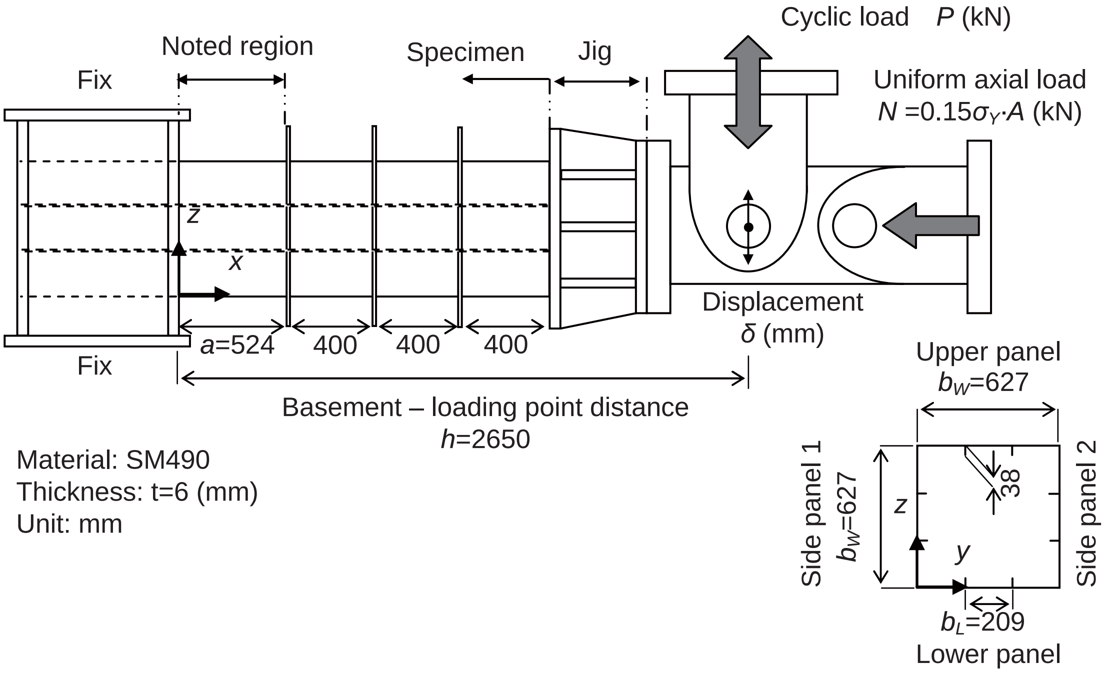


Fig. 1 Shape and dimension of specimen

Table 1 Mechanical properties of material and structural parameters of specimen.

Mechanical properties	Material		SM490
	Young's modulus	E (GPa)	200
	Yield stress (nominal)	σ_Y (MPa)	325
Sectional properties	Area of cross section	A (mm^2)	16728
	Moment of inertia	I (x10^{9}mm^4)	1.04
	Section modulus	Z (x10^{6}mm^3)	3.33
Slenderness parameter	A column	λ_C	0.27
	A stiffened plate	λ_{PF}	0.74
	A part between stiffeners	λ_{PR}	0.74
	A stiffener	λ_{PS}	0.41

plate (λ_{PF}), b=627(mm). In the part between stiffeners (λ_{PR}), b=209(mm).

In a stiffener (λ_{PS}), b=38(mm). Buckling factor; k depends on the support condition of panels[6]. In this specimen, k is 4.0 for λ_{PF} (a stiffened plate) and λ_{PR} (the part between stiffeners), and k is 0.425 for λ_{PS} (the stiffener).

Diaphragms (thickness: 16mm) were attached on the outside of the specimen taking consideration of the work efficiency of the correction.

The absolute value of initial deflections in the out-of-plane direction in the noted area of panels and stiffeners ($0 \leq x \leq 524$(mm)) was approximately 1mm.

2.2 Cyclic loading experiment on virgin specimen

The experiments considering the loading condition of an earthquake are carried out on virgin specimens.

Figure 2 shows the appearance of the experiment.

Under the uniform axial load corresponding to a dead load of an actual structure, the cyclic load by displacement control is applied to the specimen. This axial load is 15% of the nominal yield axial force (N=0.15σ_{YN}·A).

Figure 3 shows the loading pattern. The cyclic load increases by the integral multiple of the nominal yield displacement (δ_{YN}) at the loading point which is calculated by Eq. (3), (4).

$$\delta_{YN} = \frac{P_{YN} h^3}{3EI} \tag{3}$$

$$P_{YN} = \left(\sigma_{YN} - \frac{N}{A}\right)\frac{Z}{h} \tag{4}$$

In this specimen, δ_{YN} is 9.6mm.

The experiments are finished at the cycle in which the decrease of load is confirmed.

2.3 Results of experiment on virgin specimen

Figure 4 shows the relationship between the load (P) and the displacement at the loading point (δ) and its envelope curve. In these figures, symbol ○ represents the maximum load.

In the case of specimen A, the maximum load was confirmed at the unloading point in the third cycle. The load decreased during the fourth cycle. On the other hand, in the case of specimen B, the maximum load was confirmed during the fourth cycle. The load decreased

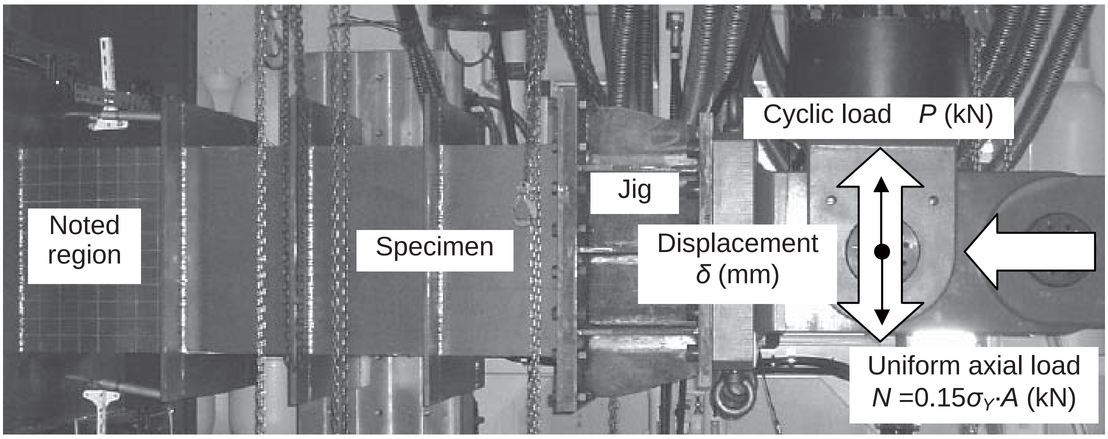


Fig. 2 Appearance of loading experiment

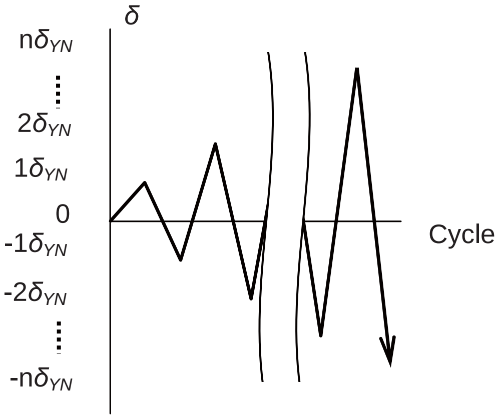


Fig. 3 Loading pattern

during the same cycle. No cracks could be observed in any welds during the experiments on the specimens A and B.

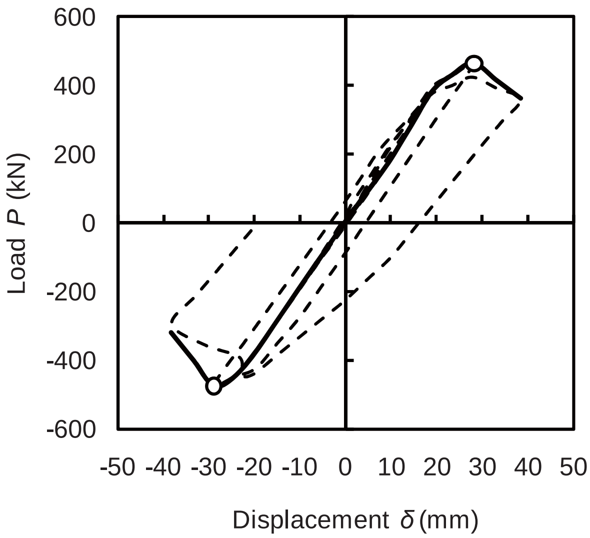
Figure 5 shows the mode of out-of-plane deformation at the section of x=196.5(mm), at which the magnitude of out-of-plane deformation was the maximum.

Due to the cyclic bending loads, the upper and lower panels crossing at right angles to the direction of loads deformed concavely to the cross section of the specimen. On the other hand, the side panels being parallel to the direction of loads deformed convexly to the cross section of the specimen. The large out-of-plane deformation occurred in the region of $100 \leq x \leq 300$(mm), (i.e. the distance from basement was from 100 to 300mm.) The maximum value of out-of-plane deformation was around 15mm. With regards to the out-of-plane deformation of stiffeners, that of the specimen A was 3-8mm, and that of the specimen B being 1-2mm.

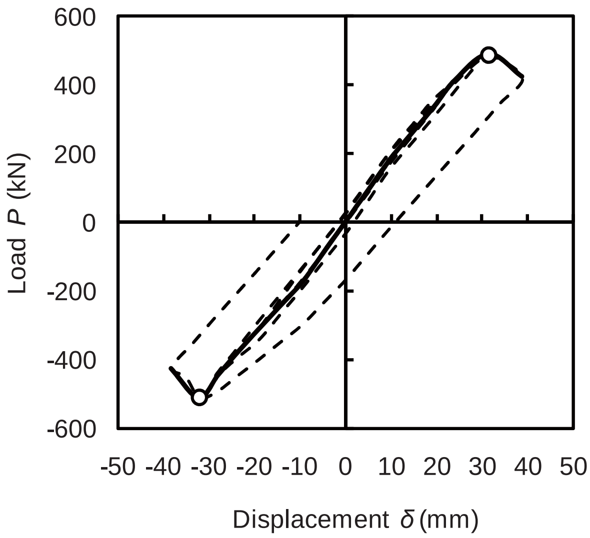
3. Repair with Correction by Heating/Pressing

The local buckling deformation parts generated in the experiments were corrected by heating with a gas burner and pressing with a jack.

The out-of-plane deformation generated by the loading experiments was corrected by heating with a gas



(a) Specimen A



(b) Specimen B

Fig. 4 Relationship between load and displacement of virgin specimens burner and pressing with a jack.

Figure 6 illustrates the appearance of correction by the heating/pressing method.

The correction by heating/pressing on site is commonly performed without dismantling the structures and reducing the dead load of the superstructures by setting the supports underneath[1]. In this research, the correction by heating/pressing was performed considering this condition on site.

The heating temperature was kept 550-650 degrees Celsius, which was below the A_1 transformation temperature (about 720 degrees Celsius within the general structural steel) in order to avoid changing the mechanical properties of the material.

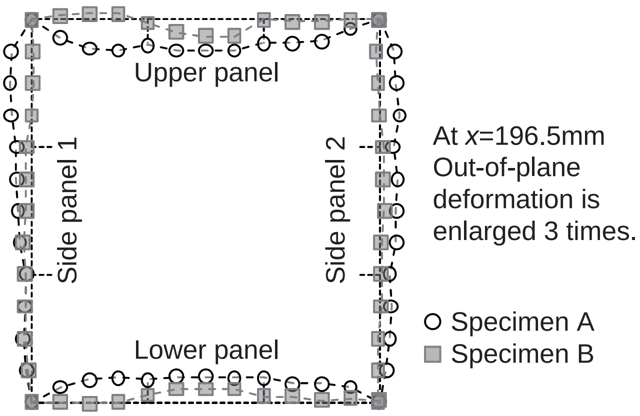


Fig. 5 Mode of out-of-plane deformation of virgin specimens

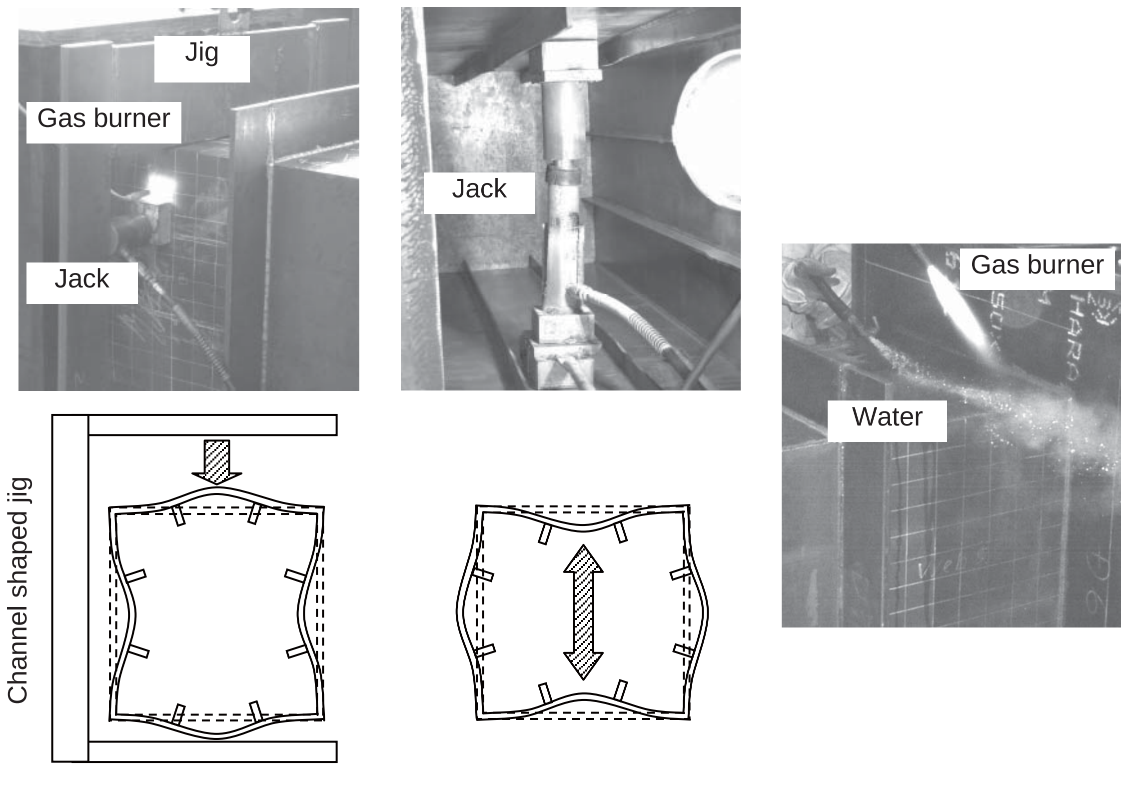
When pressing in the out-of-plane deformation convex to the cross section of the specimen, the channel-shaped jig was used to receive the reaction force. When pressing in the out-of-plane deformation concave to the cross section of the specimen, the facing panel received the reaction force (Fig. 6 (a) and (b)).

If the out-of-plane deformation was forcibly corrected, there was a risk of cracking in the welds. Therefore, some deformation was inevitably left. This is defined as the residual imperfection.

The residual imperfection is represented in **Fig. 7**.

The maximum value of the out-of-plane residual imperfection in the panels was about 7mm in the specimens A and B. This is about 5 times as large as the acceptance of the initial deflection (b_L/150=1.4mm)[6].

The mode of residual imperfection of specimen A was the same as that of the local buckling generated in the first loading experiment, meaning the upper and lower panels were concave while the side panels were convex to the cross section of the specimen. It was estimated that the maximum strength of specimen A in the experiment after correction largely decreased compared with that of virgin specimen A due to the mode of residual imperfection. Therefore, in the correction of specimen B, water-cooling was used in order to make the residual imperfection as small as possible (Fig. 6 (c)).



(a) Correction from outside (b) Correction from inside (c) Water-cooling

Fig. 6 Appearance of correction by heating/pressing

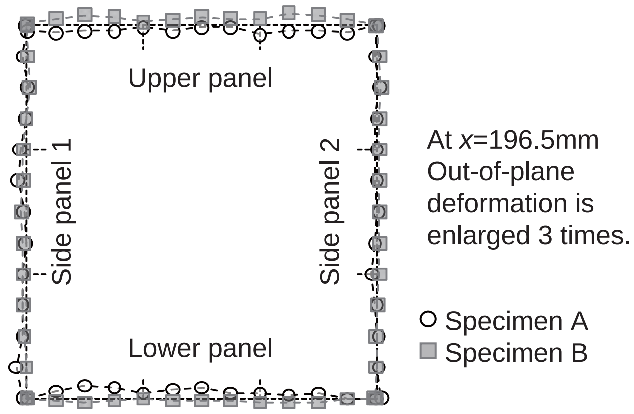


Fig. 7 Mode of Residual imperfection

Moreover, the upper and lower panels were pressed quite excessively to make the mode opposite to that of the local buckling. The concave out-of-plane deformation of upper and lower panels was made convex to the cross section of the specimen. It was expected that the mode opposite to that of the local buckling would resist the deformation due to loading in the experiments after correction.

The specimens A and B could be corrected by heating/pressing without cracking in the welds.

4. Cyclic Loading Experiment on Repaired Steel Bridge Pier

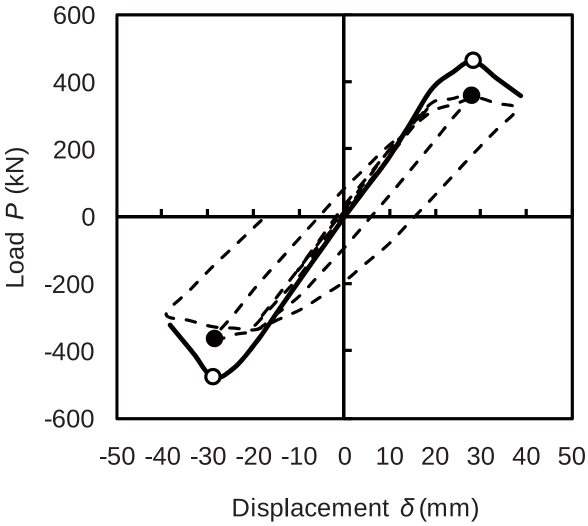
4.1 Result of experiment on repaired specimen

After the correction by heating/pressing, the same loading experiments as in the virgin situation were conducted on both corrected specimens.

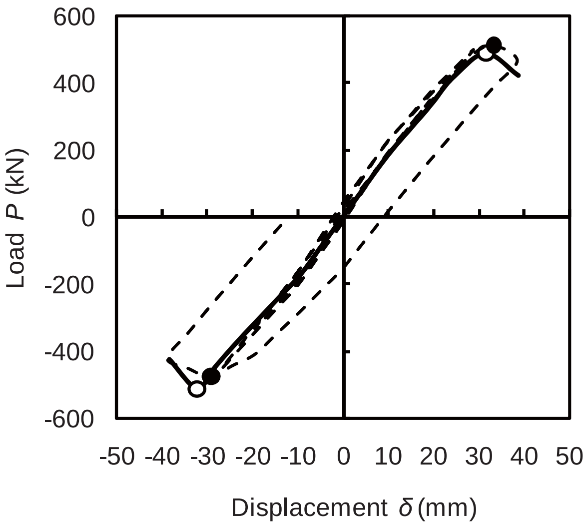
Figure 8 shows the relationship between the cyclic load (P) and the displacement at loading point (δ).

The bold lines in the figures show the envelope curves of the relationship between the load and the displacement of the virgin specimens. In these figures, symbol ● represents the maximum load of the repaired specimens A and B respectively.

In the case of repaired specimen A, the maximum load was confirmed at the unloading point in the third cycle. The load decreased during the fourth cycle which was the same as in the case of virgin specimen A. The maximum load of repaired specimen A was 20% lower than that of virgin specimen A. In the case of repaired specimen B, the maximum load was confirmed during the fourth cycle. The load decreased during the same cycle which was similar to that of virgin specimen B. The maximum load and the displacement at that time were almost the same as those of virgin specimen B. No cracks could be observed in the welds after the experiments in the repaired specimens A and B. The results indicated that the mechanical properties of the material did not deteriorate by heating/cooling only if the heating temperature was kept below the A_1 transformation temperature.



(a) Specimen A



(b) Specimen B

Fig. 8 Relationship between load and displacement of repaired specimens

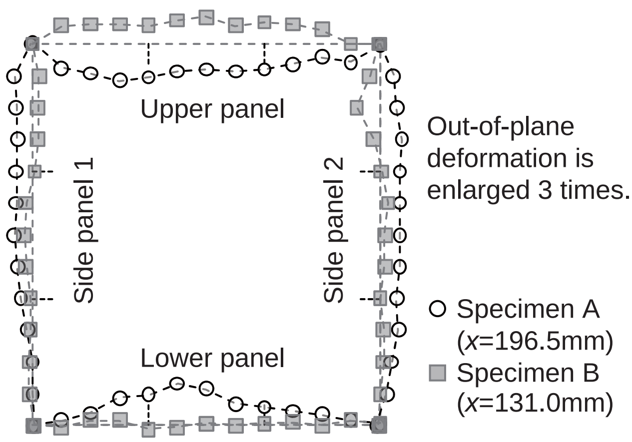


Fig. 9 Mode of out-of-plane deformation of repaired specimens

Similar to that of virgin specimens, the large out-of-plane deformation occurred within the same region of $100 \le x \le 300$(mm) (distance from the basement being from 100 to 300mm) in the repaired specimens. In the case of repaired specimen A, the magnitude of out-of-plane deformation was the maximum at the section of x=196.5mm. Conversely in the repaired specimen B, the magnitude of out-of-plane deformation was the maximum at the section of x=131.0(mm).

Figure 9 shows the mode of out-of-plane deformation of repaired specimens A and B (specimen A; x=196.5(mm), specimen B; x=131.0(mm)).

In the case of repaired specimen A, the upper and lower panels were concave and the side panels were convex to the cross section of the specimen which was the same as the case of virgin specimen A. Alternatively, the mode of out-of-plane deformation of repaired specimen B differed from that of virgin specimen B. Furthermore the upper panel of virgin specimen B was concave, which was in direct contrast to that of repaired specimen B, namely, the upper panel of repaired specimen B was convex to the cross section of the specimen. However, the modes of out-of-plane deformation of the lower and side panels were relatively the same as those of virgin specimen B.

4.2 Effect of correction by heating/pressing on behavior of repaired steel bridge pier

From the results of above experiments, it was elucidated that the mechanical properties of the material did not deteriorate only if the heating temperature was kept below the A_1 transformation temperature in the repair with correction by heating/cooling. In the actual repair work, it is most important that the heating temperature is controlled below the A_1 transformation temperature.

Furthermore, it could be said that the mode of residual imperfection largely affected the behavior of the repaired specimens. In the actual repair work, it is ideal if the residual imperfection is controlled within the acceptance of initial deflection. However, when it is difficult, the results indicate that making the mode of residual imperfection opposite to the mode of local buckling is effective for ensuring the maximum load of the repaired pier is the same level as that of virgin situation.

5. Conclusions

In order to elucidate the behavior under cyclic loads of the steel bridge pier, of which the local buckling damage was repaired with correction by heating/pressing, a series of experiments was carried out.

Obtained main results are shown as follows.

(1) The virgin specimens were locally buckled by the cyclic loads considering the loading conditions of an earthquake. The panels crossing at right angles to the loading direction deformed concavely to the cross section of the specimen. The panels being parallel to the loading direction deformed convexly to the cross section of the specimen. No cracks could be observed in the welds after the experiments.

(2) The out-of-plane deformation generated by the cyclic loads was corrected by heating/pressing below the A_1 transformation temperature (about 720 degrees Celsius). It was impossible that the out-of-plane deformation was perfectly corrected and some deformations were inevitably left (the residual imperfection). The magnitude of the residual imperfection was around 5 times as large as the acceptance of initial deflection.

(3) The same experiments on the specimens after correction by heating/pressing were carried out again. In the case that the mode of residual imperfection was the same as that of out-of-plane deformation, the maximum load of the repaired specimen was 20% lower than that of the virgin specimen.

(4) In the case that the mode of residual imperfection was made to be opposite to that of out-of-plane deformation, the maximum load of the repaired specimen was the same as that of the virgin specimen.

(5) No cracks could be observed in the welds of the repaired specimens after the loading experiments.

(6) The results indicated that the mechanical properties of the material did not deteriorate only if the heating temperature was kept below the A_1 transformation temperature.

(7) It is naturally demanded that the residual imperfection is controlled within the acceptance of initial deflection. However, when it is difficult, there is a possibility that correcting the out-of-plane deformation opposite to the mode of local buckling of the panel is effective for ensuring the maximum load of the repaired pier is the same level as that of the virgin pier.

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