Identification of Factors Dominating Mechanical Behavior of Box Columns Corrected by Heating/Pressing†

HIROHATA Mikihito* **and KIM You-Chul****

Abstract

A series of experiments and numerical simulations were carried out to identify factors dominating mechanical behavior of box columns corrected by heating/pressing. Local buckling deformation was generated in the virgin columns by compressive loads and it was corrected by heating below the A_1 transformation temperature and pressing. After the correction, compressive loads were applied to the corrected columns again. Although the ultimate strengths of both the virgin and corrected columns were almost the same, the buckling mode of the corrected columns differed from that of the virgin columns. When considering the geometric residual imperfection resulting from incomplete correction by heating/pressing and the increase of yield stress due to large plastic deformation caused by local buckling and its correction process, the phenomena observed in the experiment could be simulated by elastic plastic large deformation analysis. Therefore, it was identified that the factors dominating the mechanical behavior of box columns corrected by heating/pressing were the residual imperfection and the increase of yield stress.

KEY WORDS: (Correction by Heating/Pressing) (Buckling) (Ultimate Strength) (Residual Imperfection) (Work Hardening)

1. Introduction

When steel members of infrastructures are damaged by fire, earthquake and so on, it is required that the damaged members are quickly repaired to ensure the passage of the emergency ambulances or fire engines and transportation of aid goods. Sometimes, local buckling deformation of damaged members, whose damages are slight, is rapidly corrected by heating/pressing on site[1]. Correction by heating/pressing is an effective method of temporary repair because it can be performed on site and it has no need of new members for repair. However, the effect of correction by heating/pressing on strength of members is not elucidated clearly when correcting large deformation like buckling. So it is necessary to confirm the safety and reliability of members corrected by heating/pressing.

A series of researches has been conducted in order to elucidate the effects of correction by heating/pressing on the mechanical behavior of steel structural mambers[2)-4)]. In this paper, a series of experiments for steel box columns are carried out and the effects of correction by heating/pressing on the mechanical behavior of box columns are investigated. Local buckling is generated in the virgin specimens by compressive loads and it is corrected by heating below the A_1 transformation temperature and pressing without dismantling the specimen. After the correction, compressive loads are applied to the corrected specimens. Furthermore, these experiments are simulated by the elastic plastic large deformation analysis for identifying the factors dominating the mechanical behavior of box columns corrected by heating/pressing.

2. Mechanical Behavior of Box Columns Corrected by Heating/Pressing

Here, in order to investigate the mechanical behavior of box columns corrected by heating/pressing, a series of experiments is carried out. At first, the specimens are locally buckled by compressive loads and then the local buckling part is corrected by heating/pressing. After that, the specimens are compressed again. By comparing these experimental results, the effect of correction by heating/pressing on the mechanical behavior of the box column is elucidated.

† Received on July 11, 2008
* Specially Appointed Assistant Professor
** Professor

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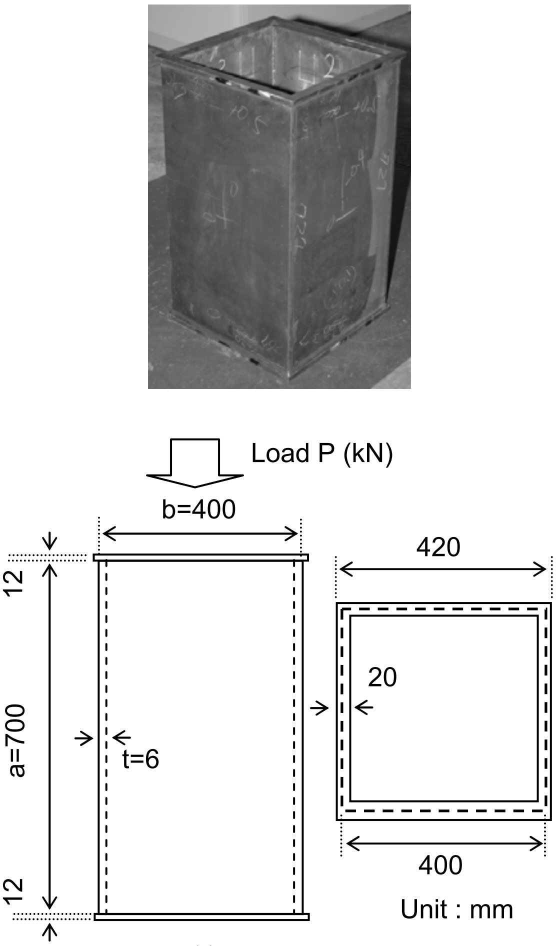
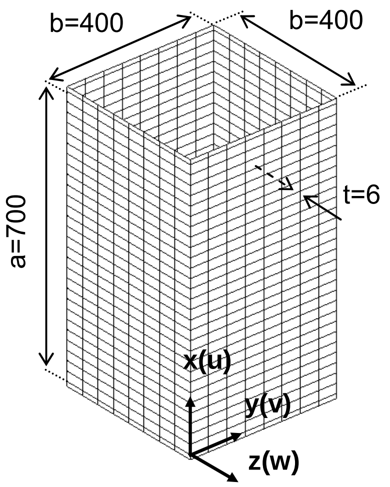
2.1 Specimen

The specimen is a box column with a square cross-section. To confirm the generality of the experimental results, two specimens (A and B) are used. **Fig. 1 (a)** shows the shape of specimen. The material is SM490Y and the thickness is 6 (mm), and its stress-strain curve obtained by a tensile test is shown in **Fig. 2**.



(a) Test specimen.



(b) Model for analysis.

Fig. 1 Box column with square cross-section.

Thick steel plates (12mm) are attached on the top and bottom of the column in order that compressive loads act uniformly. The height of column is a=700 (mm) and the breadth of a panel is b=400 (mm). The size of specimen is decided by considering that the cross-section of the specimen is required to be enough widely open to allow the workability of correction by heating/pressing.

Slenderness parameter, which is calculated by Eq.(1), λ_P is 1.40.

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

Here, buckling factor k=4.0 which is decided by the simply supported condition[5].

It is confirmed that the initial deflection of the panels is below 1.5mm in the out-of-plane direction.

2.2 Compressive experiment for virgin box column

A compressive experiment was carried out on the virgin specimens.

Monotonic compressive loads act on the specimen and the loads are increased gradually. **Fig. 3 (a)** shows the buckling mode. The mode of local buckling is one cycle of a sine curve, symmetric with respect to the central point in the column's axial direction. The absolute value of out-of-plane deformation at the peak point of the buckling mode is about 20mm. No crack is observed in the welds after the experiment.

At the same time, in order to confirm the validity of FEM program used in this study[6], the compressive experiment is simulated by the elastic-plastic large deformation analysis. In the FEM program, bi-linear degenerated shell elements are used. **Fig. 1 (b)** shows the model for analysis. A multi-linear stress-strain curve is used in modeling the result of the tensile test. The initial deflection in the analysis is modeled by Eq. (2) and it is symmetrically applied into four panels.

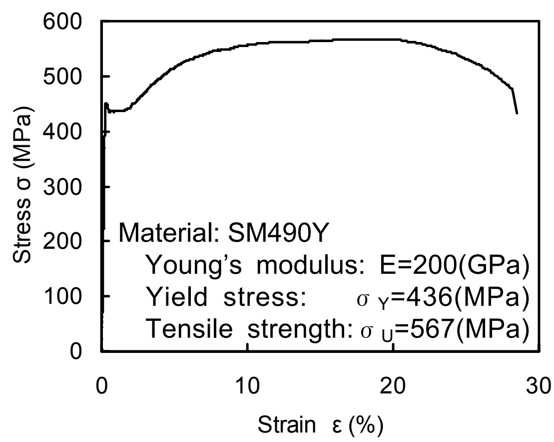


Fig. 2 Stress-strain curve.

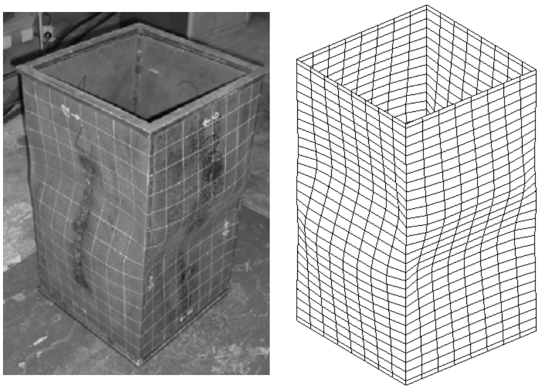


Fig. 3 Buckling mode (Virgin).

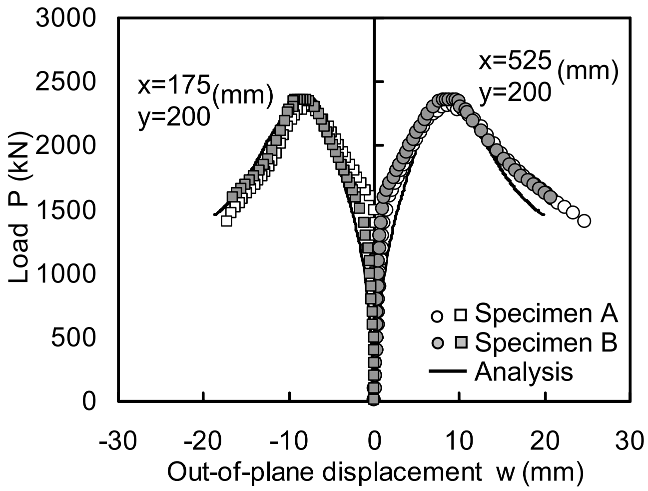


Fig. 4 Relation between load and out-of-plane displacement (Virgin).

$$w_0 = A_0 \sin\frac{2\pi x}{a}\sin\frac{\pi y}{b} \qquad (2)$$

Here, A_0 is 1.2 (mm), which is decided by actually measured values.

It is impossible for the residual stress due to correction by heating/pressing to be considered precisely. Even if the residual stress is considered, the distribution and magnitude of residual stress due to correction by heating/pressing have no generality. Therefore, the residual stress is not considered in this examination.

Fig. 3 (b) shows the buckling mode obtained by the analysis. **Fig. 4** shows the relation between load and out-of-plane displacement obtained by the experiment and analysis. In the figure, the positive direction of displacement represents the direction toward the outside of the specimen. Because the behaviors of the out-of-plane displacement of four panels are almost the same, the result of only one panel is shown. The experimental results are successfully simulated by the analysis and the validity of the analytic program is confirmed.

2.3 Correction by heating/pressing

Correction by heating/pressing is performed at the local buckling parts of the specimens damaged by the compressive experiment. **Fig. 5** shows the procedure of the correction by heating/pressing.

The procedure of the correction by heating/pressing is as follows. At first, the local buckling parts are heated by a gas burner and then pressed through a thick steel plate by a pressing machine. Then a jig with the frame shape is used as a support for the reaction force, which is representative of an actual repair work on site such as the correction without dismantling the damaged members[1]. The heating temperature is kept below the A_1 transformation temperature (about 720 degrees centigrade) in order to prevent changing the mechanical properties of the steel[7]. Actually, the heating temperature is between 550 to 650 degrees centigrade. The heating temperature is controlled by using a surface temperature indicator.

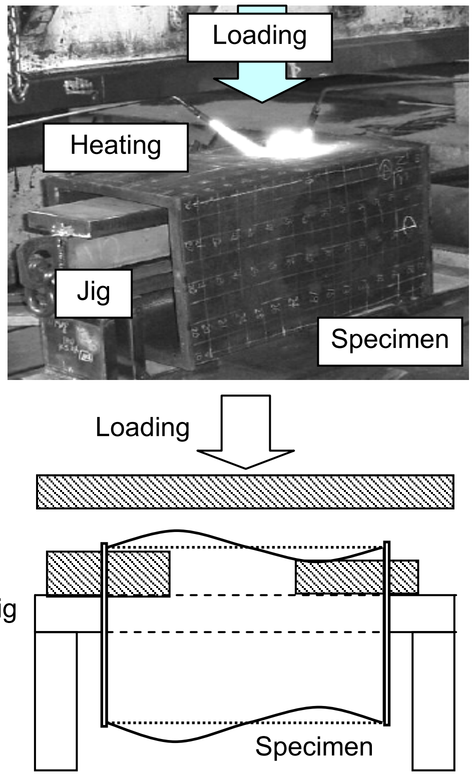


Fig. 5 Correction by heating/pressing.

It is intended that the out-of-plane deformation is corrected below the acceptable value decided in the Specifications for Highway Bridges[8]. The initial deflection toward the out-of-plane direction is decided below b/150; b is the breadth of a plate (b=400(mm)). In the case of this specimen, b/150=2.67 (mm). If the out-of-plane deformation is forced to be corrected perfectly, there is a possibility of the occurrence of cracking. Therefore, some geometric imperfection inevitably remains, and is named ‘‘residual imperfection’’.

Although the residual imperfection is a little larger than the initial deflection in the virgin situation (1.0-1.5mm) and the acceptable value (2.67mm), each specimen can be corrected without cracks in the welds.

2.4 Compressive experiment for box column corrected by heating/pressing

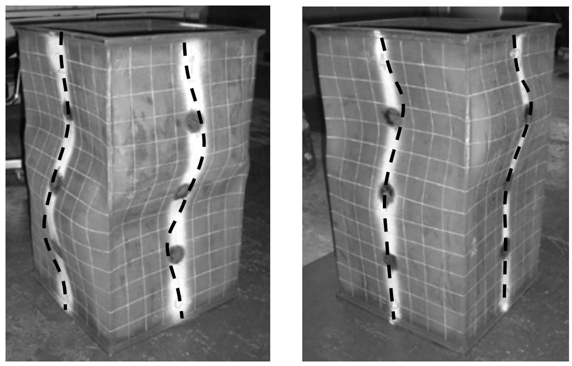
A compressive experiment on the box columns corrected by heating/pressing is carried out under the same condition as the virgin box columns. No crack occurs in the welds during and after loading. **Fig. 6** shows the buckling mode after the experiment.

In the case of specimen A, the buckling mode after the correction by heating/pressing is the same as that in the virgin situation, that is, one cycle of a sine curve. On the other hand, in the case of specimen B after the correction by heating/pressing, the buckling mode is different from that in the virgin situation. The buckling mode is not symmetric with respect to the central point in the axial direction. The absolute value of out-of-plane deformation at one peak point (x=525, y=200 (mm)) is about 30mm but that at another peak point (x=175, y=200 (mm)) is about 10mm.

Fig. 7 shows the relation between load and out-of-plane displacement. In the case of specimen A after the correction by heating/pressing, the behavior of out-of-plane displacement is almost the same as that in the virgin situation (Fig. 7 (a)). On the other hand, in the case of specimen B after the correction by heating/pressing, although the behavior up to the ultimate situation is almost the same as that in the virgin situation, the behavior after the ultimate situation differs from that in the virgin situation (Fig. 7 (b)). However, the ultimate strength after the correction by heating/pressing is not lower than that in the virgin situation.

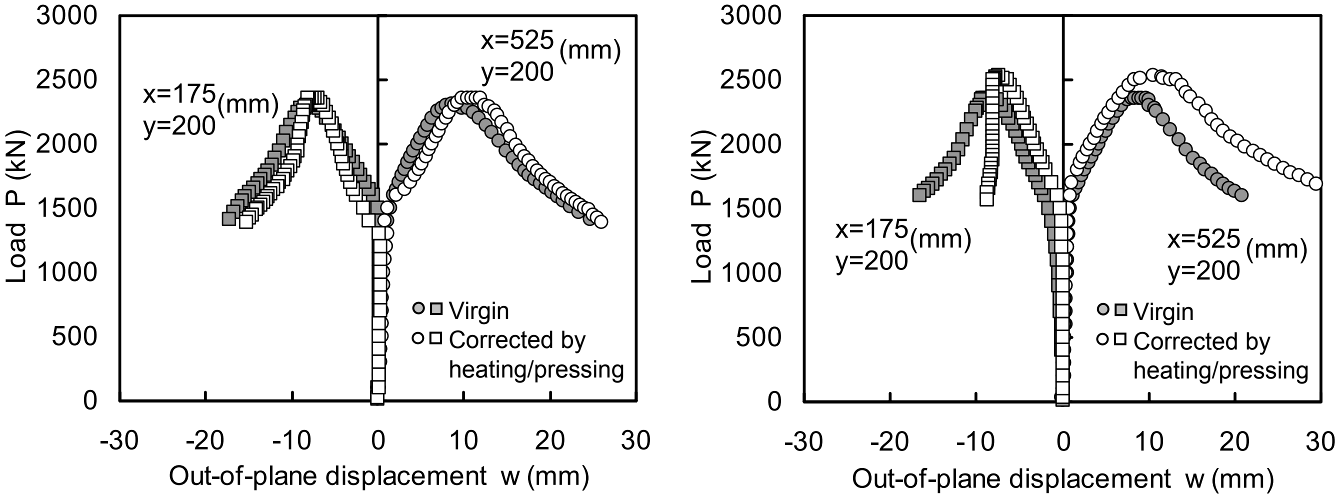
3. Identification of Factors Dominating Mechanical Behavior of Box Column Corrected by Heating/Pressing

Here, in order to identify the factors dominating the mechanical behavior of box columns corrected by heating/pressing, the compressive experiment is simulated by the elastic-plastic large deformation analysis.



(a) Specimen A. (b) Specimen B.

Fig. 6 Buckling mode (Corrected by heating/pressing).



(a) Specimen A. (b) Specimen B.

Fig. 7 Relation between load and out-of-plane displacement. (Virgin and corrected by heating/pressing).

3.1 Modeling of residual imperfection

In correcting the local buckling part of the box column, some geometric imperfection inevitably remained. The residual imperfection corresponds to an initial deflection of the columns corrected by heating/pressing. It is well known that the initial deflection largely affects the behavior of the members under compressive loads. Therefore, the residual imperfection is considered as an initial deflection in the analysis.

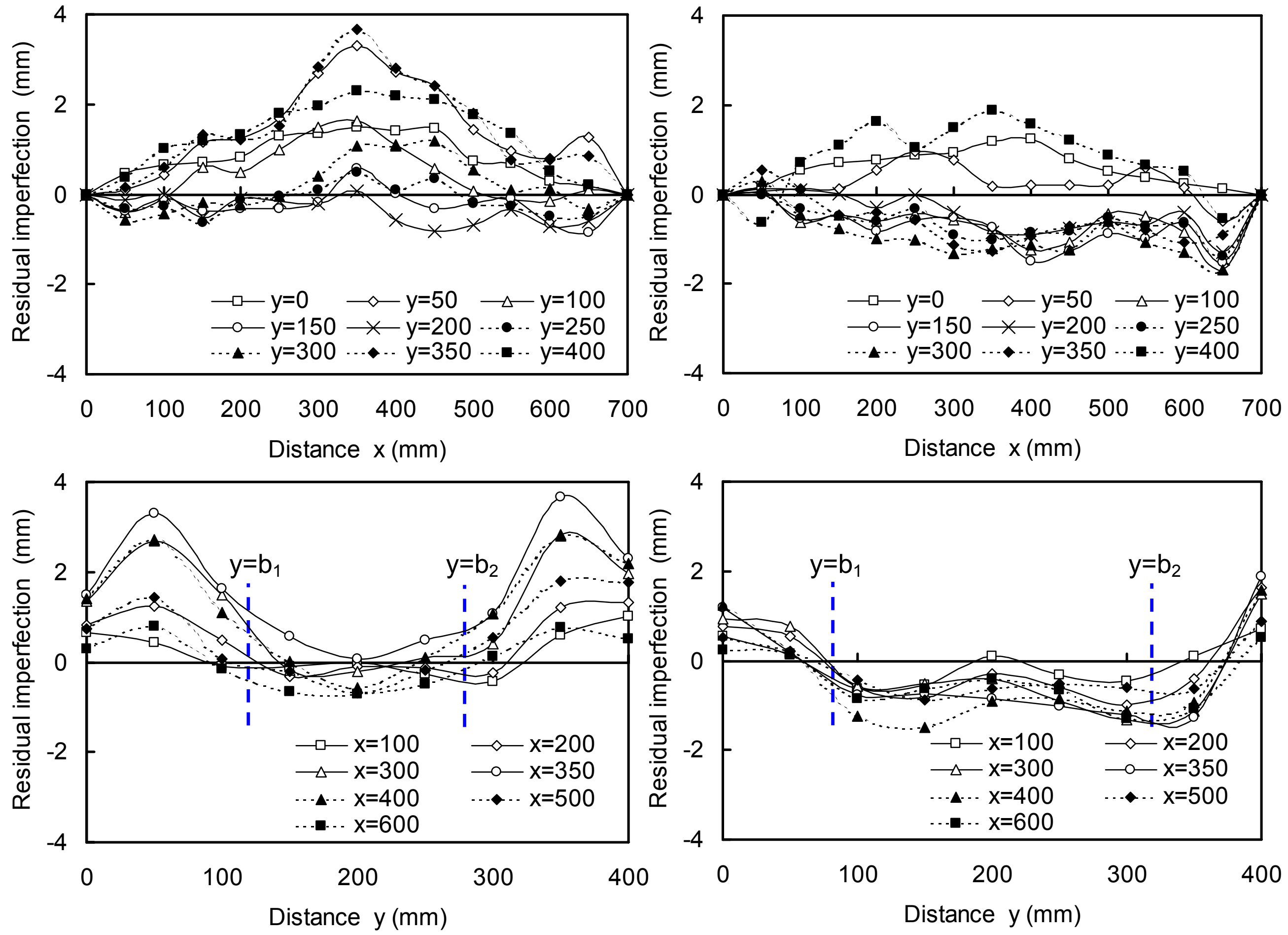
Fig. 8 shows the shape of the residual imperfection after the correction by heating/pressing. In each specimen, because the tendency of the shape of the residual imperfection in four panels is almost the same, the shape of the residual imperfection in only one panel is shown. In the figure, the positive direction of the deformation represents the direction toward the outside of the specimen.

In the axial (x) direction, the absolute value of the residual imperfection at the midspan of the column (x=350 (mm)) and at the corner part (y=0, 400 (mm)) is relatively large. In the breadthways (y) direction, the imperfection around the corner part ($0<y<b_1$, $b_2<y<400$) tends to jut toward the outside of the specimen. The absolute value of the imperfection is relatively large. On the other hand, the imperfection except the corner part ($b_1<y<b_2$) tends to dent toward the inside of the specimen. The absolute value of the imperfection is relatively small compared with that around the corner part. Because the out-of-plane deformation around the corner part is difficult to correct by heating/pressing, the relatively large imperfection probably remains around the corner part in order to prevent cracking.

Considering the tendency of the residual imperfection, the initial deflection of the box column corrected by heating/pressing is modeled by Eq. (3) - (5).

$$w_1 = A_0 \sin\frac{2\pi x}{a}\sin\frac{\pi y}{b} + A_1 \sin\frac{\pi x}{a}\cos\frac{\pi y}{2b_1} \quad (0<y<b_1) \qquad (3)$$

$$w_2 = A_0 \sin\frac{2\pi x}{a}\sin\frac{\pi y}{b} + A_2 \sin\frac{\pi x}{a}\sin\frac{\pi(y-b_1)}{b_2-b_1} \quad (b_1<y<b_2) \qquad (4)$$



(a) Specimen A. (b) Specimen B.

Fig. 8 Residual imperfection.

$$w_3 = A_0 \sin\frac{2\pi x}{a}\sin\frac{\pi y}{b} + A_3 \sin\frac{\pi x}{a}\sin\frac{\pi(y-b_2)}{2(b-b_2)}$$

$(b_2<y<400)$ (5)

Here, in the case of specimen A, A_0=1.2, A_1=A_3=3.5, A_2=-0.5, b_1=120, b_2=280 (mm). In the case of specimen B, A_0=1.2, A_1=A_3=2.0, A_2=-1.5, b_1=80, b_2=320 (mm). These values are decided as the average of four panels.

3.2 Modeling of increase of yield stress induced by work hardening

In the members corrected by heating/pressing, plastic deformation has been generated by local buckling and its correction process. According to the degree of work hardening due to the plastic deformation, it is probable that the yield stress of the material is increased compared with that in the virgin situation. Therefore, a stress-strain curve modeling the increase of yield stress is used in the analysis.

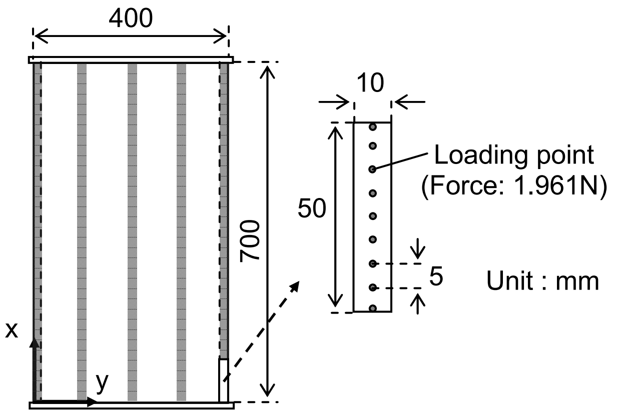
In order to investigate the degree of work hardening, a Vickers hardness test was carried out on a box column: specimen C, which is a preliminary specimen and has been locally buckled and then corrected by heating/pressing as well as specimens A and B. **Fig. 9** shows the measuring positions of hardness and the result of hardness test. The average values in each specimen are shown in the figure.

In the axial (x) direction, the hardness in the middle part whose length is about 200mm (250<x<450) is higher compared with that around the top and bottom of the column. In the breadthways (y) direction, the hardness becomes gradually higher from the corner part (y=0, 400) to the center.

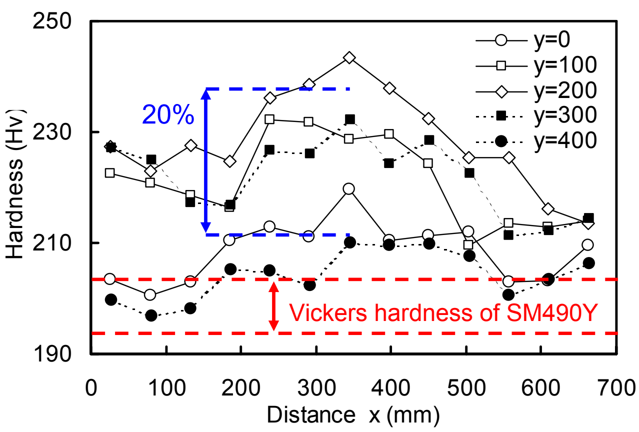
The yield stress in the panel probably becomes higher by work hardening as well as the hardness because there is an interrelation between them[9]. It is supposed that a stress-strain curve of the panel corrected by heating/pressing traces the bold line in **Fig. 10 (a)**, and the panel has a trapezoidal distribution of yield stress based on the results of the hardness test (**Fig. 10 (b)**).

3.3 Result of analysis and consideration

The compressive experiment on the box columns corrected by heating/pressing is simulated by considering two factors; the residual imperfection and the increase of yield stress. **Fig. 11** shows the relation between load and out-of-plane displacement. **Fig. 12** shows the

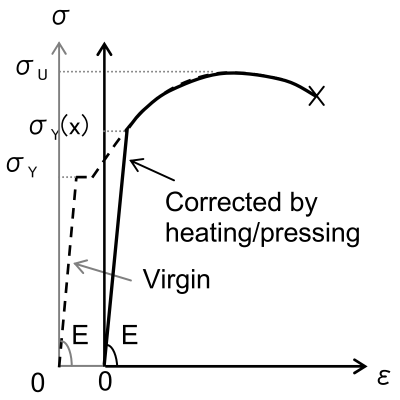


(a) Measuring points of hardness.

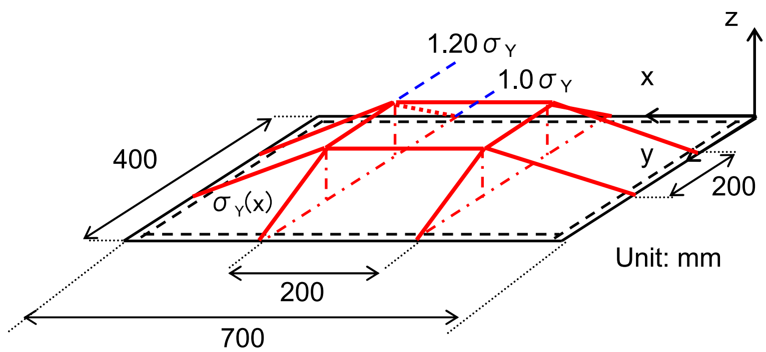


(b) Distribution of hardness.

Fig. 9 Result of Vickers hardness test.

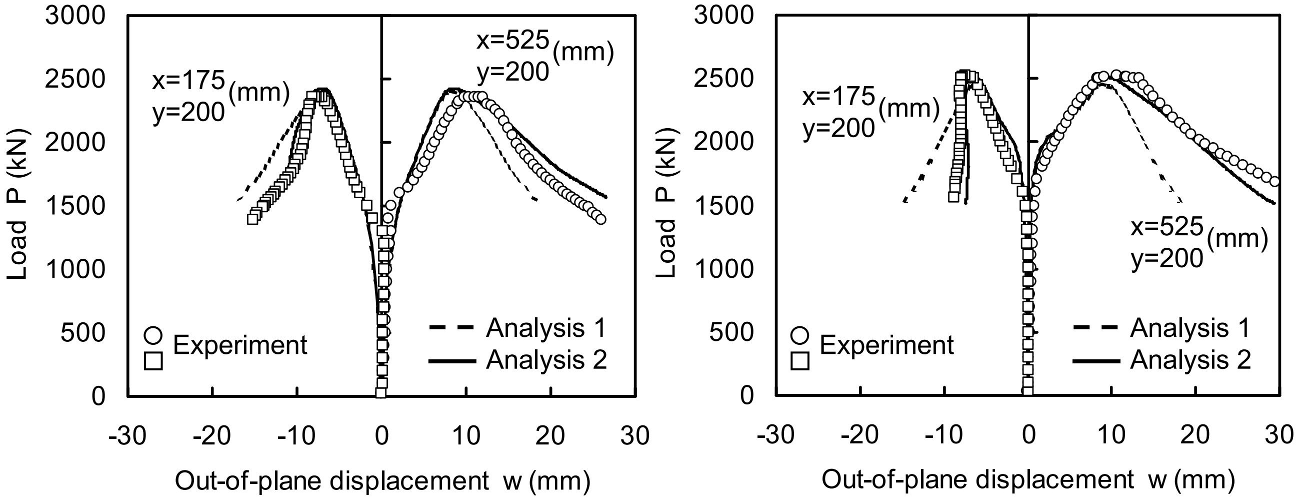


(a) Stress-strain curve.



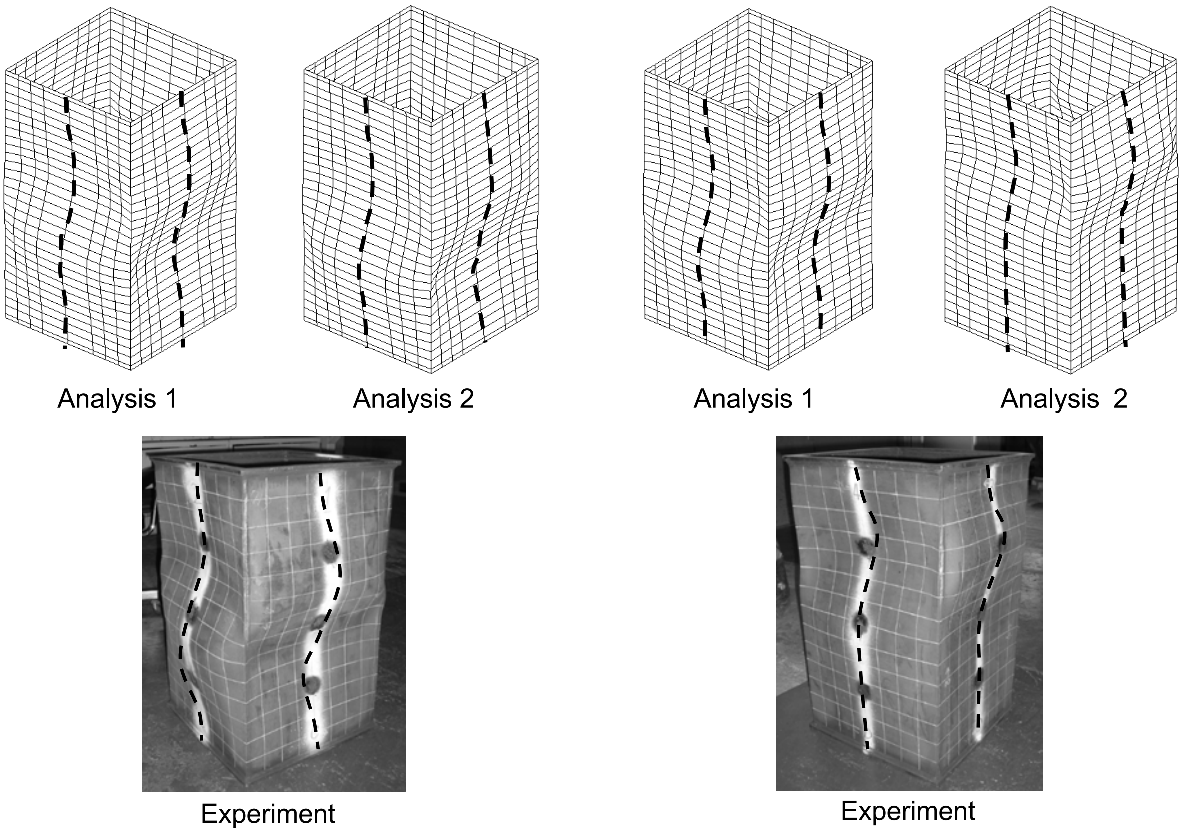
(b) Distribution of yield stress.

Fig. 10 Model of a stress-strain curve based on the result of hardness test.



(a) Specimen A. (b) Specimen B.

Fig. 11 Relation between load and out-of-plane displacement.



(a) Specimen A. (b) Specimen B.

Fig. 12 Buckling mode.

buckling mode. In the figures, analysis 1 represents the case in which only the residual imperfection is considered. The stress-strain curve of the virgin situation is used in the analysis. On the other hand, analysis 2 represents the case in which both the residual imperfection and the increase of yield stress are considered.

At first, the relation between load and out-of-plane displacement (Fig. 11) is noted. Both in specimens A and B, the results of analysis 1 and 2 up to the ultimate situation are the same. And they successfully simulate the result of the experiment. This result indicates the validity of the residual imperfection modeled by Eq. (3) - (5). Noting the behavior after the ultimate situation, although the result of analysis 1 disagrees with the experimental result, that of analysis 2 agrees with the experimental result.

Next, the buckling mode (Fig. 12) is noted. In the case of specimen A, the buckling modes of analysis 1 and 2 are symmetric with respect to the central point in the axial direction, which agrees with the experimental result. On the other hand, in the case of specimen B, although the buckling mode of analysis 1 is symmetric with respect to the central point in the axial direction, which disagrees with the experimental result, that of analysis 2 successfully simulates the experimental result.

From these results, it is confirmed that the mechanical behavior of box columns corrected by heating/pressing is dominated by both the residual imperfection and the increase of yield stress. The result of analysis 1 shows that the residual imperfection is a factor dominating the behavior up to the ultimate situation of the members corrected by heating/pressing. The result of analysis 2 shows that the behavior after the ultimate situation is largely affected by the increase of yield stress. According to the shape of the residual imperfection and the degree of the increase of yield stress, the buckling mode variously changes. However, the increase of yield stress due to work hardening does not decrease the ultimate strength of the members corrected by heating/pressing and the buckling mode is decided after the ultimate situation. Therefore the change of the buckling mode is not important when diagnosing the soundness of the members corrected by heating/pressing. The most important issue is how to control the residual imperfection dominating the behavior up to the ultimate situation.

By the way, in both specimens A and B, although the residual stress is not considered, the experimental result can be successfully simulated by the analysis with considering the residual imperfection and the increase of yield stress. This result suggests that the residual stress is not a factor dominating the mechanical behavior of the corrected specimens.

4. Conclusions

A series of experiments on box columns was carried out in order to elucidate the mechanical behavior under compressive loads of box columns corrected by heating/pressing. From the results of the experiments, the following conclusions were obtained;

(1) Ultimate strength under compressive loads of the box columns corrected by heating/pressing was almost the same as that in the virgin situation.

(2) The buckling mode of the box columns corrected by heating/pressing changed compared with that in the virgin situation.

The compressive experiment on the box columns corrected by heating/pressing was simulated by the elastic-plastic large deformation analysis in order to identify the factors dominating the mechanical behavior under compressive loads of box columns corrected by heating/pressing. From the results of the analysis, the following conclusions were obtained;

(3) The factors dominating the mechanical behavior under compressive loads of the members corrected by heating/pressing were both the residual imperfection and the increase of yield stress due to work hardening.

(4) The residual imperfection dominated the behavior up to the ultimate situation under compressive loads of the members corrected by heating/pressing. The increase of yield stress dominated the behavior after the ultimate situation. Therefore, the increase of yield stress is not important when diagnosing the soundness of the members corrected by heating/pressing. It was elucidated that the most important issue was how to control the residual imperfection dominating the behavior up to the ultimate situation.

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