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Safety Evaluation of Cruciform Columns Corrected by Heating†

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Abstract

In the Hanshin-Awaji earthquake (1995), many members of large steel structures were damaged. After the earthquake, the local buckling deformations of many members were rapidly corrected by heating and pressing. However, when correcting large deformation like buckling, the effects of heating correction on strength of members are unknown. So it is necessary to confirm the safety and reliability of members corrected by heating.

In this paper, a series of compressive tests of virgin specimens and ones corrected by heating was carried out. From the experimental results, the effects of heating correction on the strength of members were investigated, and safety evaluation of columns corrected by heating was performed. According to the results, buckling deformation modes of specimens corrected by heating were variously changed. The causes were residual imperfections and the increase of strength through work hardening. However, the ultimate strength of specimens corrected by heating was almost equal to that of virgin specimens.

KEY WORDS: (Heating Correction), (Buckling), (Buckling mode), (Ultimate strength), (Residual imperfection), (Work hardening)

1. Introduction

In the Hanshin-Awaji earthquake (1995), many members of large steel structures; box columns of bridges, plate girders and so on, were damaged. After the earthquake, for the traffic of the emergency (ambulances or fire engines) and transportation of aid goods, it was required that the damaged infrastructures were quickly repaired. So, local buckling deformations of many members, whose damage was mainly small, were rapidly corrected by heating and pressing[1)]. However, when correcting large deformation like buckling, the effects of heating correction on the strength of members are unknown. So it is necessary to confirm the safety and reliability of members corrected by heating.

In this paper, a series of compressive tests for cruciform columns is carried out to elucidate the effects of heating correction. The compressive tests of virgin specimens are carried out first. Through the tests, large deformation occurs by local buckling in each specimen. The columns damaged in compressive tests are then corrected by heating and pressing. Finally, they are compressed again. Based on the results of each compressive test, the effects of heating correction on the strength of cruciform columns are investigated.

2. Experiment

2.1 Mechanical properties of the materials

Tensile tests of carbon steel (SS400, SM490YA) and high manganese non-magnetic steel (KNM235) were carried out. **Figure 1** shows the relation between stress and strain. **Table 1** shows the mechanical properties of each material obtained from tensile tests. Yield stress of the high manganese non-magnetic steel (KNM235-M) [2), 3)] is 0.2% proof stress.

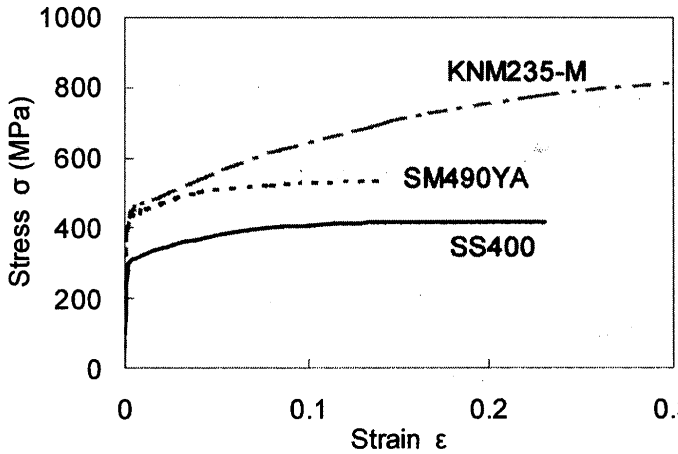

Fig.1 Stress-strain curves.

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Table 1. Mechanical properties obtained by tensile test.

	SS400	SM490YA	KNM235-M
Young's modulus E (GPa)	200	200	165
Yield stress σ_Y (MPa)	278	412	415
Tensile strength σ_u (MPa)	419	539	829
Elongation (%)	34	23	53

Table 2. Size of specimens and slenderness parameter.

Specimen	Materials	a (mm)	t (mm)	b (mm)	λ_p*
SS400	SS400	700	9	126	0.816
SM490-1	SM490YA	700	9	126	0.994
SM490-3	SM490YA	700	9	198	1.485
KNM235	KNM235-M	700	9	126	1.205

* $\lambda_p = \frac{1}{\pi}\sqrt{\frac{12\left(1-\nu^2\right)}{k}}\sqrt{\frac{\sigma_Y}{E}}\frac{b}{t}$: Slenderness parameter

where, ν = Poisson ratio = 0.3

k = buckling factor = 0.425

(By the boundary condition of projection panel [4])

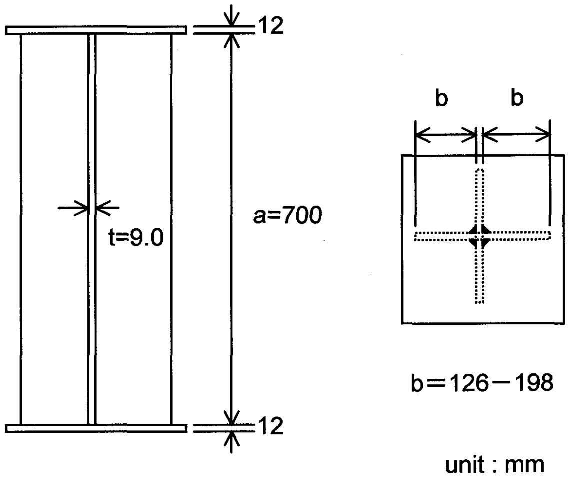


Fig.2 Column with cruciform cross-section.

2.2 Compressive tests of virgin columns

Compressive tests of cruciform columns composed by carbon steel (SS400 and SM490YA) and high manganese non-magnetic steel (KNM235-M) were carried out. **Figure 2** shows the appearance of the cruciform column and the sizes of columns are described in **Table 2**.

The buckling mode of the columns is local buckling of the panels and elastic-plastic buckling, that is to say large deformations of the panel occurs around yielding load through elastic buckling, and loads decrease suddenly after the ultimate situation. The buckling parts of the all columns are at the center of the panels. **Figure 3** shows the appearance of one specimen (SS400) after the compressive test. No cracks were observed in the welds after the tests.

2.3 Heating correction

Heating correction is performed at the local buckling parts of the columns. The process is as follows. The center of a panel around a free edge is heated by gas burner at first and then pressed through a jig by a pressing machine. Heating temperature is below the A_1 transformation temperature (550～650℃). **Figure 4** shows the procedure of heating correction.

Because heating correction is performed without subdividing the columns, one of them was corrected incompletely and cracks occurred near the weld metal. So, some imperfections were remained near the weld metal to prevent cracking. This imperfection is named 'residual imperfection' in this paper. **Figure 5** shows the appearance of this residual imperfection, and averages of residual imperfection in each panel of columns are shown in **Table 3**.

2.4 Compressive tests of columns corrected by heating

Compressive tests of columns after heating correction was carried out. In the case of all virgin columns, local buckling occurred at the center of each panel (refer to **Fig.3**), but the buckling part of columns corrected by heating is changed. **Figure 6** shows types of buckling mode for columns after heating correction, and the buckling modes after heating correction are classified into following three types.

(a) Mode-Ⅰ (SS400)
The part of local buckling is at the center of each panel as well as in virgin columns.

(b) Mode-Ⅱ (SM490-A and SM490-B)
The part of local buckling is at only the upper side of the projection panels.

(c) Mode-Ⅲ (KNM235)
The parts at which local buckling has started are at the upper side of the projection panels, but the deformation spreads in the overall part of panel gradually and the panel itself bends finally.

It is thought that the factor of the difference of the local buckling part in the columns corrected by heating is work hardening by plastic deformation. The detail of this phenomenon is described in next section.

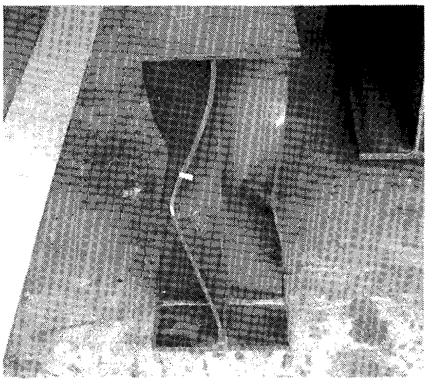


Fig.3 Buckling mode (virgin column).

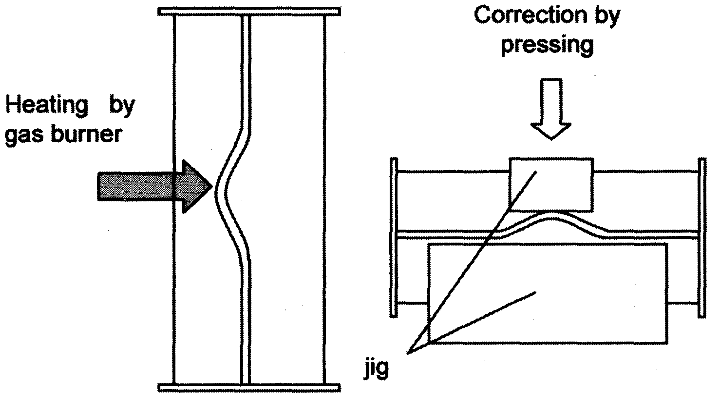


Fig.4 The procedure of heating correction.

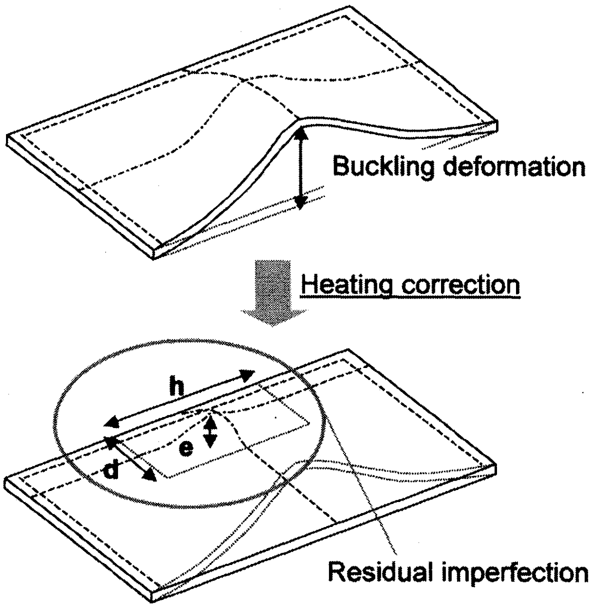


Fig.5 Residual imperfection.

Table 3 Residual imperfection (average of 4 panels).

Specimen	Residual imperfection (mm)		
	e	d	h
SS400	24.9	65.2	156.9
SM490-A	14.1	30.1	136.3
SM490-B	12.1	49.3	92.2
KNM235	1.3	67.0	134.4

Figure 7 shows the relations between load and vertical displacement obtained in each compressive test. That of SM490-A is omitted because it is similar to that of SM490-B. In this figure, dotted line shows load and vertical displacement for virgin columns, and the solid line for corrected columns.

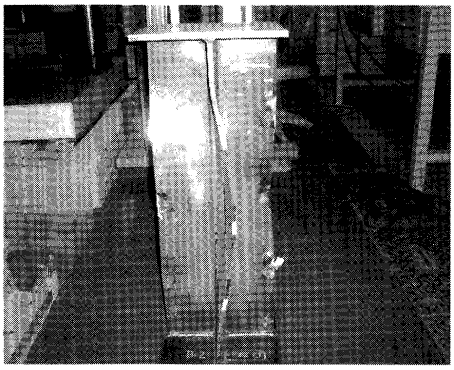
Comparing corrected columns with virgin ones, the ultimate load of all corrected columns are similar to those of the virgin columns, but in the case of columns corrected by heating, the stiffness decreases and the deformation up to the ultimate situation becomes larger. Post-buckling strengths of corrected columns decrease more slowly than those of the virgin columns.

3. Results and considerations

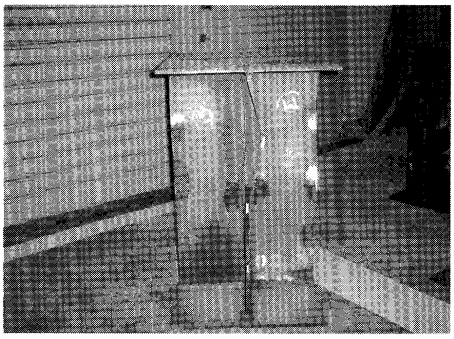
3.1 Buckling parts of cruciform columns corrected by heating

Buckling parts of all virgin columns are at the center of each panel, but those of the corrected columns are variously changed. It is considered that the cause is work hardening at the center of the projection panel following the correction of large plastic deformations. For examining the effect of this work hardening, Vickers hardness test was carried out.

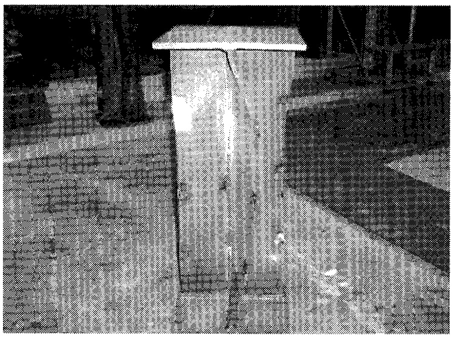
Figure 8 shows the measuring points of hardness and the results of the test. In **Fig.8** (b), maximum, minimum and average hardness in each measured range are shown. Hardness at the center of each panel, at which the buckling occurs in the virgin column, becomes higher. It is generally known that there is an interrelation between Vickers hardness and yield stress from the results of many experiments[5]. So it is estimated that strength distribution corresponding to the buckling deformation occurs in each panel. That is to say, it is considered that buckling occurs at the part, except the center of the panels, because the strength becomes higher (this case corresponds to SM490-A and SM490-B). But



Mode- I (SS400)

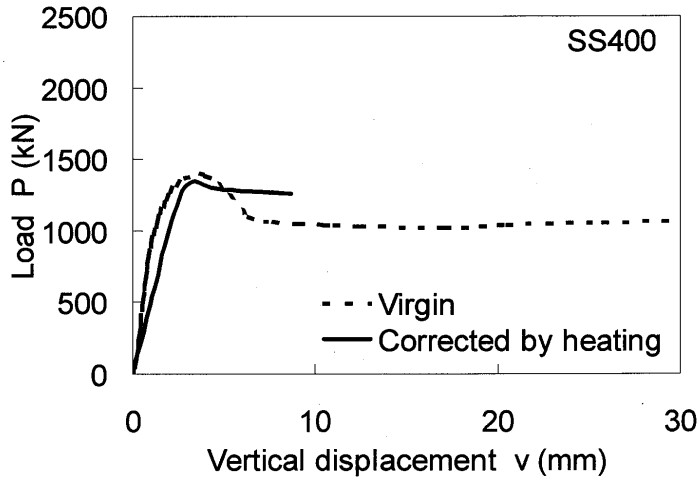


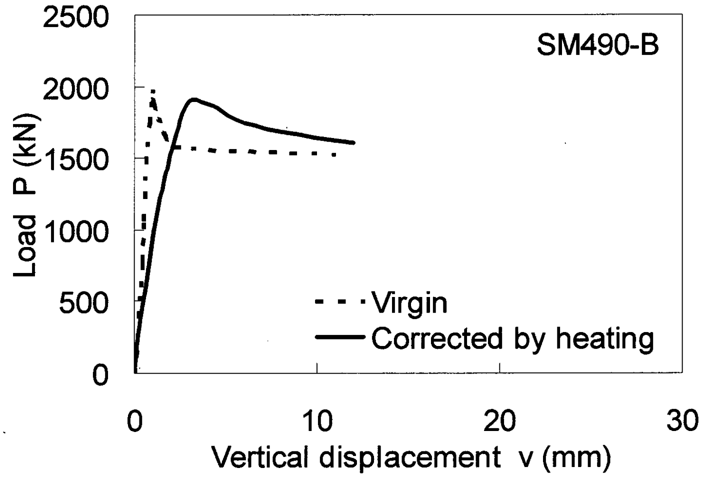
Mode- II (SM490-B)



Mode-III (KNM235)

Fig.6 Buckling mode (after heating correction).





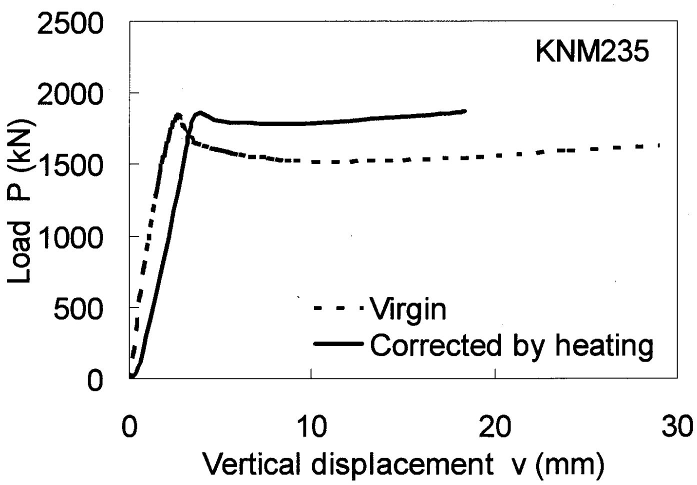
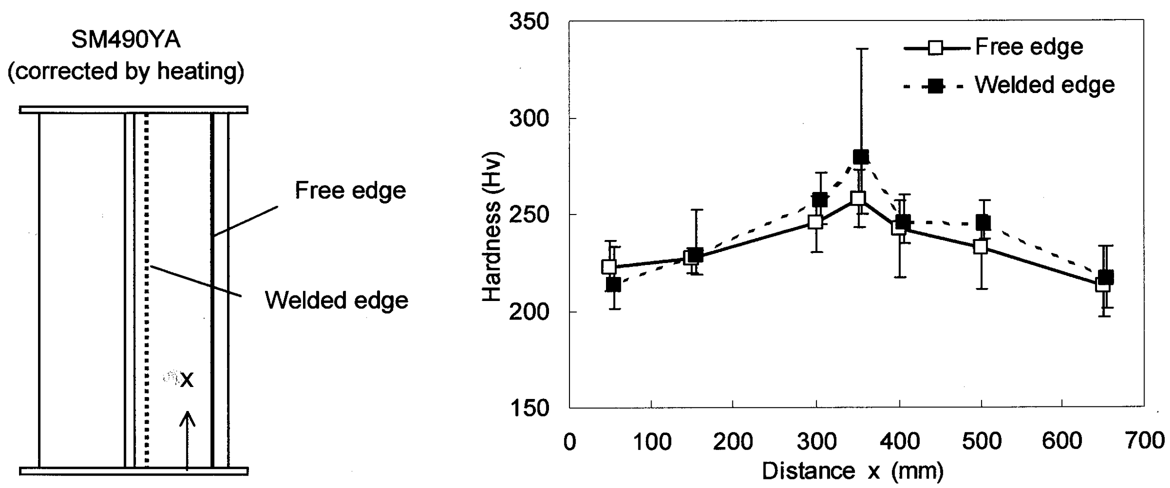


Fig.7 Relation between load and vertical displacement.

in the case of SS400, because residual imperfections are large (e=24.9mm), the effect of the residual imperfection becomes greater than that of work hardening, and the buckling occurs at the center of each panel as well as the virgin columns. It is considered that KNM235 has a different buckling mode from other columns because its work hardening tendency is large and residual imperfection is small.

In any cases, both the degree of residual imperfection and work hardening decide the buckling part of the corrected columns. And, post-buckling strength rises because yield stress becomes higher by work hardening.



(a) Measuring points of hardness.

(b) Distribution of hardness.

Fig.8 Result of Vickers hardness test.

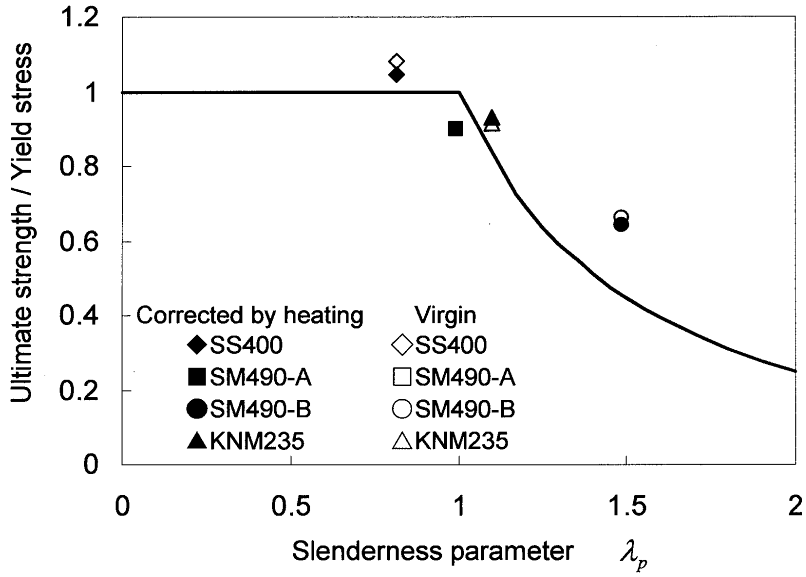


Fig.9 Ultimate strength. (Virgin & corrected by heating)

3.2 Ultimate strength of the columns corrected by heating

Figure 9 shows ultimate strengths of the virgin and corrected columns. In the figure, open symbols represent ultimate strength of the virgin columns, and the solids represent that of the corrected ones. Comparing these, the ultimate strength of the corrected columns by heating is not inferior to that of the virgin columns.

4. Conclusions

Compressive tests were carried out to the virgin columns and the ones corrected by heating. The main results obtained were as follows:

(1) Ultimate strength of the corrected columns is not inferior to that of the virgin columns.
(2) Because of residual imperfection, stiffness of the corrected columns becomes lower.
(3) Both the degree of residual imperfection and work hardening decide the buckling part of the corrected columns.
(4) In the case of the corrected columns, post-buckling strengths become higher by work hardening.
(5) Cracks occur in neither welds of the virgin nor the corrected columns.

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