Dominant Factors Deciding Compressive Behavior of Cruciform Column Projection Panel Corrected by Heating

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Abstract

In order to elucidate the reason why the compressive behavior of the specimen, which was steel cruciform column, corrected by heating differed from that in virgin situation, the elastic-plastic large deformation analysis was carried out. When considering only residual imperfection, which was left through heating correction inevitably, the experimental phenomenon could not be simulated by the analysis. Then considering not only residual imperfection but also the increase of yield stress made by work hardening, which was caused by large plastic deformation, the experimental phenomenon could be simulated totally. From the result of the analysis, it was elucidated that compressive behavior of the specimen corrected by heating was decided by both residual imperfection and the increase of yield stress made by work hardening.

Keywords: heating correction, 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 traffic 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 and pressing on site (Hanshin Expressway Management Technology Center, 1997). Heating correction is an effective method of temporary repair because it can be performed on site and it has no need of new members for repair. But the effect of heating correction on strength of members is not elucidated clearly when correcting large deformation like buckling. So it is necessary to confirm safety and reliability of members corrected by heating.

A series of compressive experiments for cruciform columns was carried out so as to elucidate the effect of heating correction on ultimate strength of a projection panel (KIM and HIROHATA, 2005). Figure 1 shows the appearance of the specimen. The shape of the specimen is decided because a cruciform column was stable for a compressive experiment and behavior of both a column and panels could be investigated. The compressive experiments for the virgin specimens were carried out at first. Through the experiments, large out-of-plane deformation was generated by local buckling in each projection panel. Then the projection panels damaged in the compressive experiment were corrected by heating and pressing. After that, they were compressed again. The effect of heating correction on ultimate strength of cruciform column projection panel was elucidated based on the results of each compressive experiment. According to the results, ultimate strength of the specimen corrected by heating was almost same as that of the virgin specimen. In the case of the corrected specimen, deformation at the ultimate situation became larger than that of the virgin specimen. The reason was residual imperfection, which was the deformation that remained in the specimen after heating correction. That is to say, if the deformation was forced to correct perfectly, there was a possibility of cracking at the welds. Therefore, in order to prevent cracking, residual imperfection was inevitably left.

On the other hand, the buckling mode of the corrected specimen considerably changed. In the virgin compressive experiment, projection panels were deformed at their midspan in all specimens. But in the compressive experiment after heating correction, the part at which large deformation occurred variously changed. The reason was not elucidated sufficiently.

In this paper, the compressive experiments are simulated by the elastic-plastic large deformation analysis in order to investigate the reason why buckling mode of the corrected specimen considerably changed comparing with that of the virgin specimen. Based on the results, the dominant factors governing the compressive behavior of cruciform column projection panels corrected by heating are identified.
2. Numerical Simulation of Compressive Experiments for Virgin Specimens

The compressive experiments for the virgin specimens are simulated by the elastic-plastic large deformation analysis based on FEM. In the FEM program, bi-linear degenerated shell elements are used (YAO et al., 1990). Table 1 shows the size of model for the analysis and the mechanical properties of the material used in the analysis.

Table 1. Mechanical properties and dimension of the specimens

<table>
<thead>
<tr>
<th>Model</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>SM490YA</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus $E$ (GPa)</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Yield stress $\sigma_Y$ (MPa)</td>
<td>412</td>
<td></td>
</tr>
<tr>
<td>Tensile strength $\sigma_U$ (MPa)</td>
<td>539</td>
<td></td>
</tr>
<tr>
<td>Poisson ratio $\nu$</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Length $a$ (mm)</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>Breadth $b$ (mm)</td>
<td>126 162</td>
<td></td>
</tr>
<tr>
<td>Thickness $t$ (mm)</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

Buckling mode of model 1 in the compressive experiment after heating correction differed from that in the virgin compressive experiment. On the other hand, buckling mode of model 2 in the compressive experiment after heating correction was the same as that in the virgin compressive experiment. By simulating the compressive experiment for each model, the factors governing the buckling mode of specimens under compressive loads that have been corrected by heating will be identified.

Initial deflection in the analysis is given by Eq. (1). In Eq. (1), the first term is the deflection of column’s axial direction, the second is the deflection of out-of-plane direction of projection panels. Residual stress is not considered in the analysis. $A_0$ is 0.5 and $A_{0,mn}$ is 0.1 (mm), which are decided as the actually measured values of initial deflection. As the number of the wave, $m$ is 1, and $n$ are 1 and 3.

$$w_0 = A_0 \sin \left( \frac{\pi x}{a} \right) \sum A_{0,mn} \sin \left( \frac{m\pi x}{a} \right) \sin \left( \frac{n\pi y}{2b} \right)$$

The results of the experiment and analysis are shown in Fig. 2 and 3. For each model, a relation between load and horizontal displacement at the free edge obtained by the analysis is good agreement with that obtained by the experiment. Both in the experiment and analysis, the part at which large out-of-plane deformation is generated by local buckling is the center of the projection panels. From the results, the compressive experiment can be simulated successfully by the analysis and the legitimacy of the analytic program by FEM is confirmed.

3. Numerical Simulation of Compressive Experiments for Specimens Corrected by Heating

3.1. Modeling of residual imperfection

In the experiment, heating correction for the damaged projection panels is performed at the part which large out-
of-plane deformation is generated by local buckling (KIM and HIROHATA, 2005). Figure 4 shows the procedure of heating correction. The center of a panel around the free edge is heated by a gas burner at first and then pressed through a jig by a pressing machine. In order not to change the microstructure, heating temperature (550-650 degrees centigrade) is kept below A1 transformation temperature (about 720°C) (Japan Road Association, 2002). Because heating correction is performed without dismantling the specimens, there is a possibility of occurrence of cracks near the welds if the deformation is forced to correct completely. Therefore, some residual imperfection is left near the welds in order to prevent cracking. Figure 5 shows the appearance of residual imperfection, and average values of residual imperfection of 4 projection panels are shown in Table 2.

For the corrected specimen, residual imperfection corresponds to initial deflection for the virgin specimens. And the values of residual imperfection are much larger than the initial imperfection in the virgin situation. Therefore, it can obviously be understood that residual imperfection largely affects the compressive behavior of the specimens corrected by heating.

At first, the analysis investigates that the effect of residual imperfection on compressive behavior of the specimen after heating correction. So as to consider residual imperfection into the analysis, initial deflection of
The corrected specimen is modeled by Eq. (2). In Eq. (2), the first term is the deflection of column’s axial direction, the second is the deflection of out-of-plane direction of projection panels and the third is residual imperfection which exists locally \( x_1 \leq x \leq x_1 + h \) and \( 0 \leq y \leq d \).

\[
w_{res} = A_{0z} \sin \frac{\pi x}{a} + \sum A_{0mn} \sin \frac{m\pi x}{a} \sin \frac{m\pi y}{2b} + e \sin \frac{\pi (x - x_1)}{h} \sin \frac{\pi y}{d} \tag{2}
\]

Considering residual imperfection by Eq. (2), the compressive experiments for the corrected specimens are simulated. In the analysis, the values in Table 2 are given as residual imperfection. The value of \( A_{0z} \) is same as that in the virgin situation \( A_{0z} = 0.5 \) mm and \( A_{0mn} \) are shown in Table 2, which are decided as the actually measured values of the deflection after heating correction. The number of the wave (both \( m \) and \( n \)) is 1.

The obtained results of the analysis are shown in Fig. 6 and 7.

In the case of model 1 (Fig. 6), residual imperfection at the center of the panel is jutted out to the left in Fig. 6(a). Therefore, at first, the free edge \( (x = 350, z = 126 \) (mm)) moved to the left, that is, the same direction which residual imperfection is jutted out to. After that, in the experiment, the panel is deformed not at the center but at the upper side of the panel, which is moved to the right. At the same time, the free edge at the center turns to the right. On the other hand, in the analysis, large deformation is generated at the center of the panel at which residual imperfection exists. As a result, buckling mode obtained by the experiment cannot be simulated. With regards to ultimate strength, that obtained by the analysis is not in agreement with that obtained by the experiment. Ultimate strength in the analysis is lower than that in the experiment.

In the case of model 2 (Fig. 7), buckling mode obtained by the experiment can be simulated by the analysis. Both in the experiment and analysis, large out-of-plane deformation is generated at the center of the projection panel at which residual imperfection exists, and the direction to which the panel moved is the same as that to which residual imperfection protrudes. But a relation between load and horizontal displacement obtained by the
experiment cannot be simulated by the analysis. As well as model 1, ultimate strength obtained by the analysis is not in agreement with that obtained by the experiment. Ultimate strength in the analysis is lower comparing with that in the experiment.

From the results of the analysis, it can be known that the mechanical behavior of the specimens after heating correction under compressive loads cannot be explained enough by only residual imperfection.

3.2. Modeling the yield stress increase induced by work hardening

From above analysis, it is elucidated that buckling mode of the specimen corrected by heating is not decided by only residual imperfection.

In the case of model 1, local buckling does not occur at the center of the panels at which residual imperfection exists in the experiment. Both in model 1 and 2, ultimate strength obtained by the analysis is lower than that obtained by the experiment. These results indicate that the center of the panel after the correction should be hard to deform and the strength of the material should be increased.

When considering such a factor, it is probably work hardening by large plastic deformation. That is to say, large plastic deformation is generated at the center of the panels, which is caused by the virgin compressive experiment and its heating correction. Therefore yield stress may become larger by work hardening in that region. It is possible that this increase of yield stress affects buckling mode of the corrected specimens.

So as to confirm the increase of yield stress by work hardening, a tensile test is a proper way. But it is difficult that cutting out many specimens for tensile tests from cruciform column projection panels. Then considering an interrelation between hardness of Vickers and yield stress (NAKAZAWA, 1987), instead of tensile tests, Vickers hardness test for the corrected specimen is conducted. Figure 8(a) shows the measured points of hardness and results of the hardness test are shown in Fig. 8(b). In Fig. 8(b), maximum, minimum and average values of hardness in each measured range (50 mm) are described. From the results, it is well known that at the center of the panel, that is, the part at which large out-of-plane deformation is generated in the virgin compressive experiment is hardened both at the free edge and the welded edge.
Therefore, as well as hardness, yield stress at the center of the panel may become larger by large plastic deformation. In order to consider the increase of yield stress into the analysis, it is supposed that a stress-strain curve of the panel corrected by heating traces the bold line in Fig. 9(a), and the projection panel has a parabolic distribution of yield stress based on the results of the hardness test (shown in Fig. 9(b)). Actually, the peak point of the distribution of yield stress should not be just the center of the panel. So as to consider the difference of the peak point, the peak point is located at $x = 332.5$ (mm) where the element next to the center point exists.

Using above stress-strain curve and residual imperfection by Eq. (2), the analysis is conducted again.

The results of the analysis are shown in Fig. 10 and 11. In the case of model 1 (Fig. 10), when considering only residual imperfection, buckling mode of the specimen cannot be simulated (refer to Fig. 6(a)), but by considering the increase of yield stress also, the buckling mode and relation between load and horizontal displacement are simulated successfully. By considering the increase of yield stress, ultimate strength obtained by the analysis is same as that in the experiment.

In the case of model 2 (Fig. 11), buckling mode of the specimen can be simulated as effectively as before when the increase of yield stress was not considered (refer to Fig. 7(a)). Moreover, ultimate strength obtained by the analysis is same as that in the experiment.

From these results, it is elucidated that the mechanical behavior under compressive loads of cruciform column projection panels corrected by heating is decided by both residual imperfection and increase of yield stress by work hardening.

The reason of the change of buckling mode is as follows. Residual imperfection exists at the center of the projection panel. At the same time yield stress becomes larger around this region. Therefore out-of-plane deformation is not generated at the center necessarily. It is generated in the other part such as the upper side of the panels in the case that residual imperfection is relatively small as in model 1. On the other hand, even if yield stress becomes larger at the center of the projection panels, in the case...
that residual imperfection is relatively large as in model
2, large out-of-plane deformation is generated at the center
of the projection panels at which residual imperfection
exists.

When noting ultimate strength, in the case considering
only residual imperfection, ultimate strength obtained by
the analysis is lower comparing with that obtained by the
experiment. But by considering the increase of yield stress
also, ultimate strength is simulated accurately by the
analysis. That is, the increase of yield stress is a factor
deciding ultimate strength of the panels corrected by
heating.

In any case, it is elucidated that the dominant factors
deciding mechanical behavior of cruciform column projection
panels corrected by heating under compressive loads are
both residual imperfection and the increase of yield stress
by work hardening.

4. Conclusions

In order to elucidate the reason why compressive
behavior of cruciform column projection panel corrected
by heating differed from that of the virgin one, compressive
experiments for virgin specimen and that corrected by
heating are simulated by elastic-plastic large deformation
analysis.

The obtained main results are as follows:
(1) Compressive experiment for virgin cruciform column
specimens was simulated by the elastic-plastic large
deformation analysis and the legitimacy of the analytic
program by FEM was confirmed.
(2) In heating correction for specimens after the
compressive experiment, some deformation was inevitably
left in order to prevent cracking, which was residual
imperfection. When compressive experiment for the
specimen after heating correction was simulated, the
experiment was not simulated successfully by only
considering residual imperfection.
(3) From the result of Vickers hardness test for the
specimen after heating correction, work hardening, which
was caused by buckling deformation and its heating
correction, was confirmed. Presuming another factor
except residual imperfection, it was proposed for analysis
a stress-strain curve considering increase of yield stress
by work hardening.
(4) Considering not only residual imperfection but also
increase of yield stress by work hardening, the experimental
results of buckling mode and a relation between load and
horizontal displacement were successfully simulated by
the analysis.
(5) It was elucidated that the dominant factors deciding
mechanical behavior of cruciform column projection
panels corrected by heating under compressive loads
were both residual imperfection and the increase of yield
stress.

References

Hanshin Expressway Management Technology Center
(1997), Overcome the large earthquake - the observations
of recovery construction from the earthquake, Hanshin
of Cruciform Column Corrected by Heating”, International
Journal of Steel Structures, KSSC, Vol. 5, No. 2, pp. 167-
171
Japan Road Association (2002), Specifications for Highway
Bridge Part II: Steel Bridge, Maruzen Publish Division
(in Japanese).
Collapse of Plates under Cyclic Loading”, Journal of
Marine Science and Technology, The Society of Naval