Mechanical Behavior under Compressive Loads of Cruciform Column Projection Panels Corrected by Heating†

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Abstract

In order to elucidate the mechanical behavior under compressive loads of a cruciform column projection panel corrected by heating, a compressive test was simulated by elastic-plastic large deformation analysis. When considering only residual imperfection, which was left through heating correction, inevitably the experimental phenomenon could not be simulated. Then considering not only residual imperfection but also the increase of yield stress caused by work hardening, which was caused by large plastic deformation, the experimental phenomenon could be simulated totally. From the results of analysis, it was revealed that both the residual imperfection and the increase of yield stress decide the mechanical behavior under compressive loads of a cruciform column projection panel corrected by heating.

KEY WORDS: (Heating correction), (Buckling), (Projection panel), (Residual imperfection), (Work hardening)

1. Introduction

When the steel members of large infrastructures are damaged by fire, earthquake and so on, it is essential that they are quickly repaired so as to ensure access by emergency service (ambulances or fire engines) and transportation of aid goods. Sometimes, local buckling deformations of many members, whose damages are mainly small, are rapidly corrected by heating and pressing on site[1]. 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. However, when correcting large deformations like buckling, the effect of heating correction on strength of members is not clearly elucidated. So it is necessary to confirm the safety and reliability of members corrected by heating.

A series of compressive tests for cruciform columns was carried out so as to elucidate the effects of heating correction on the ultimate strength of projection panels[2]. Figure 1 shows the appearance of the specimen. The compressive tests for virgin specimens were carried out at first. Through the tests, large deformation occurred by local buckling in each projection panel. Then the projection panels damaged in the compressive tests were corrected by heating and pressing. After that, they were compressed again, and results of each compressive test were compared. The following facts were revealed. Ultimate strengths of the specimens corrected by heating were almost the same as those in the virgin situation. In the cases of the corrected specimens, deformation at the

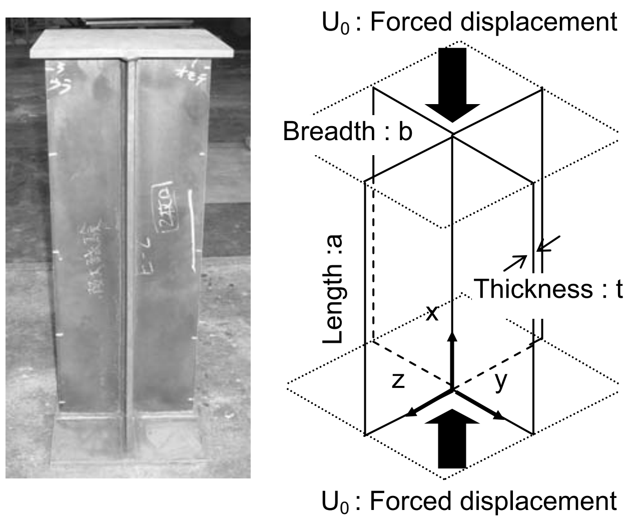

Figure 1. Model for analysis and coordinate system.

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ultimate situation became larger than that of virgin specimens. The reason was residual imperfection, which was the deformation remaining in the specimens after heating correction. If the deformation was forced to correct perfectly, there was a possibility of occurrence of cracking at the welds. Therefore, in order to prevent cracking, residual imperfection was inevitably left.

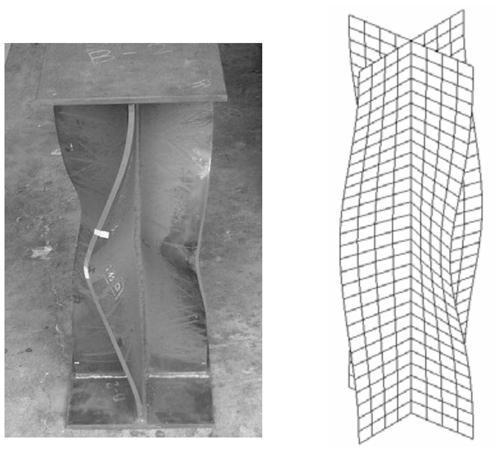
On the other hand, the deformation mode of the corrected specimens variously changed. In the virgin compressive test, the projection panels were deformed at the center in all specimens. But in the compressive test after heating correction, the part at which large deformation occurred largely changed. The reason was not entirely clear.

In this paper, the compressive tests are simulated by elastic-plastic large deformation analysis in order to investigate the reason why the deformation mode of the corrected specimens variously changed compared with that of the virgin specimens. Based on the results, the factors that decide the mechanical behavior under compressive loads of cruciform column projection panels corrected by heating can be clarified.

2. Simulation of a compressive test for a virgin specimen

A compressive test for a virgin specimen is simulated by elastic-plastic large deformation analysis. In the analytic program, bi-linear degenerated shell elements are used[3]. Table 1 shows sizes of an analytic model and mechanical properties of the material used in analysis. Initial deflection in analysis is given by Eq.(1). In Eq.(1), the first term is a deflection of a column's axis, the second is a deflection in the out-of-plane direction of a projection panel. Residual stress is not considered in the analysis. A_{0Z} is 0.5 and A_{0mn} is 0.1(mm), which are selected as actually measured values of initial deflection. The number of waves,m is 1,and n are 1 and 3.

$$w_0 = A_{0z}\sin\frac{\pi x}{a} + \sum A_{0mn}\sin\frac{m\pi x}{a}\sin\frac{n\pi y}{2b} \qquad (1)$$



(a) Experiment (b) Analysis

Figure 2. Shape of virgin specimen.

Results of the experiment and analysis are shown in Figure 2 and 3, the former are deformation modes of the specimen obtained by the experiment and analysis, and the latter is the relation between load and out-of-plane displacement. Both in the experiment and analysis, the point at which large out-of-plane deformation occurred was at the center of the projection panels. From the results, it can be said that the experimental results could be simulated successfully by analysis. That is, the adequacy for the result of analysis was confirmed.

3. Simulation of a compressive test for the specimen corrected by heating

3.1 Modeling of residual imperfection

In the experiment, heating correction for the damaged projection panels was performed at the part which large out-of-plane deformation by local buckling occurred[2]. The center of a panel around a free edge was 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 was kept below A_1 transformation temperature (550-650 ℃)[4]. Because

Table 1. Mechanical properties and dimension of specimens.

Material	SM490YA
Young's modulus E (GPa)	200
Yield stress σ_Y (MPa)	371
Tensile strength σ_U (MPa)	535
Poisson's ratio ν	0.3
Length a (mm)	700
Breadth b (mm)	126
Thickness t (mm)	9

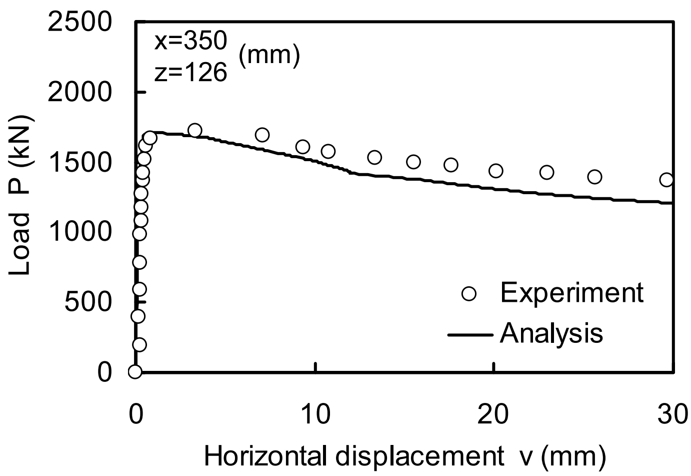


Figure 3. Load – horizontal displacement diagram.

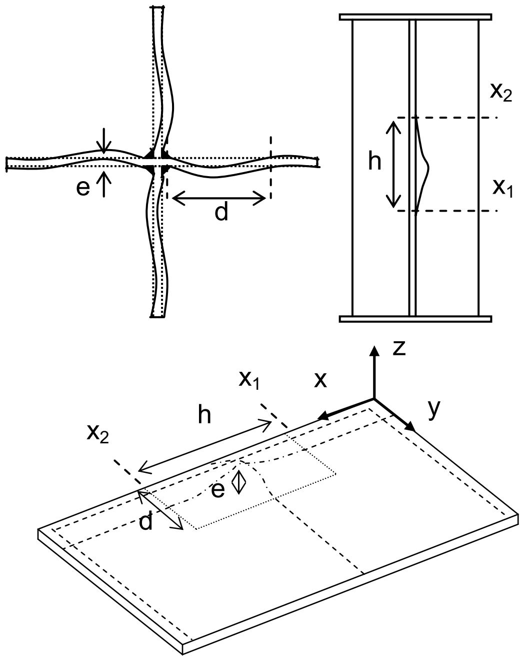


Figure 4. Residual imperfection

heating correction was performed without subdividing the specimens, one of them was corrected incompletely and cracks occurred near the weld metal. Therefore, some imperfection was left near the weld metal in order to prevent cracking. This was named residual imperfection. Figure 4 shows the appearance of the residual imperfection, and average values of the residual imperfection of 4 projection panels in the objective specimen are shown in Table 2.

For the corrected specimen, this residual imperfection corresponds to initial deflection. And the values of the residual imperfection are much larger than the initial imperfection in the virgin situation. Therefore, it can easily be said that the residual imperfection should largely affect the mechanical behavior under compressive loads of the specimens corrected by heating.

At first, the effects of the residual imperfection on the mechanical behavior under compressive loads of the specimen after heating correction are investigated by analysis. So as to consider the residual imperfection in the analysis, initial deflection of the corrected specimen is modeled by Eq.(2). In Eq.(2), the first term is a deflection of a column's axis, the second is a deflection in the out-of-plane direction of a projection panel, and the third is the residual imperfection which exists locally.

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

Here, the third term is given in $x_1 \leqq x \leqq x_2$, $0 \leqq y \leqq d$.

The values in Table 2 are given as the residual imperfection. A_{0Z} is -0.5 and A_{0mn} is -1.0(mm), which are selected as actually measured values of initial deflection after heating correction. The number of

Table 2. Sizes of residual imperfection.

Initial deflection of axis A_{0Z} (mm)	1.0
Out-of-plane deformation of free edge A_{0mn} (mm)	-1.5
Residual imperfection	
e (mm)	14.1
d (mm)	65.3
h (mm)	136.3

waves, both m and n are 1.

Considering the residual imperfection by Eq.(2), the compressive test for the corrected specimen was simulated. The results of analysis are shown in Figure 5 and 6. The former show deformation modes of the specimen and the latter show the relation between load and horizontal displacement.

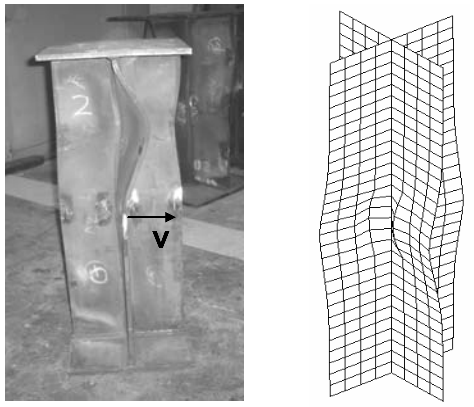
The residual imperfection at the center of the panel was jutted out to the left side in Figure 5. Therefore, at first, the free edge (x=350, z=126(mm)) moved to the left side, that is, the same direction toward which the residual imperfection was jutted out (Figure 6). After that, in the experiment, the panels were deformed, not at the center but at the upper side of the panels, and that point moved to the right side (Figure 5 (a): Experiment). At the same time, the free edge at the center turned over to the right side. On the other hand, in analysis, as a natural result, a large deformation occurred at the center of the panel at which the residual imperfection existed (Figure 5 (b): Analysis). A deformation mode under compressive loads of the specimen obtained by the experiment could not be simulated by analysis.

By the way, the ultimate strength obtained by analysis was not in agreement with that obtained in the experiment. The ultimate strength in analysis was lower than that in the experiment.

From these results, it can be said that the change of the deformation mode under compressive loads of the specimen after heating correction could not be explained by residual imperfection alone.

3.2 Modeling of increase of yield stress by work hardening

From the above results, it was concluded that the deformation mode under compressive loads of the specimen corrected by heating was not decided by residual imperfection alone. When considering another factor, it is probably work hardening due to large plastic deformation. That is to say, large plastic deformation, involved in the virgin compressive test and its correction, occurred at the center of the panels. Therefore yield stress should become higher by work hardening in that region. It is possible that this increase of yield stress



(a) Experiment (b) Analysis

Figure 5. Shape of the specimen corrected by heating.

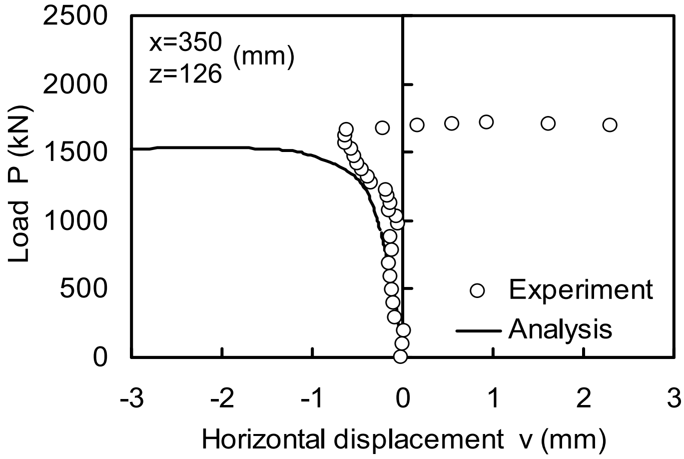
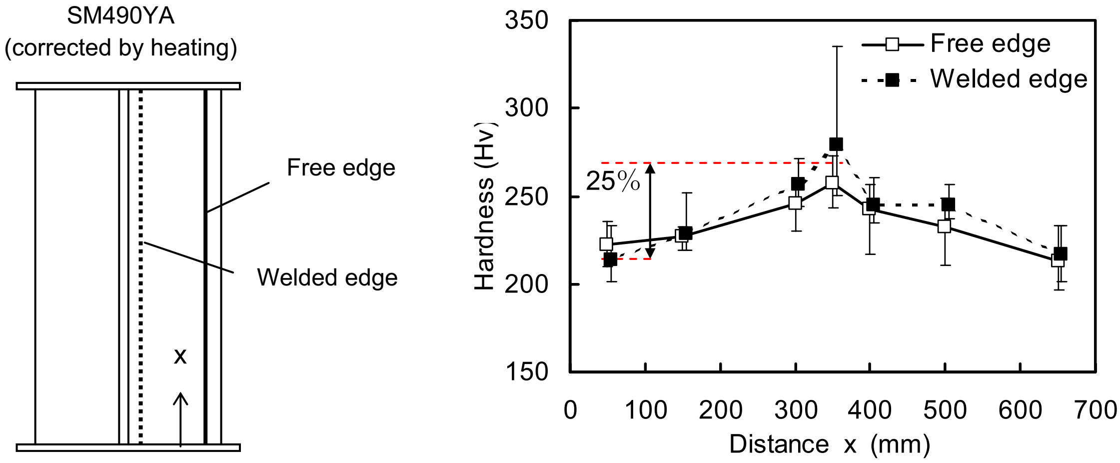
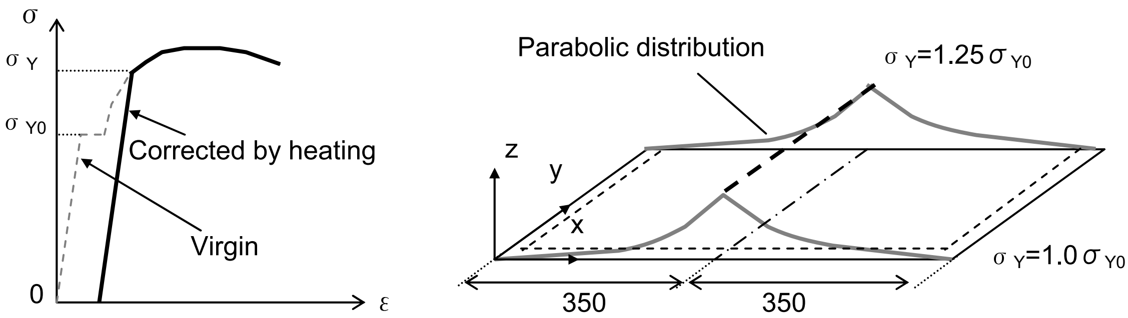


Figure 6. Load – horizontal displacement diagram.



(a) Measuring points of hardness. (b) Distribution of hardness.

Figure 7. Result of Vickers hardness test.



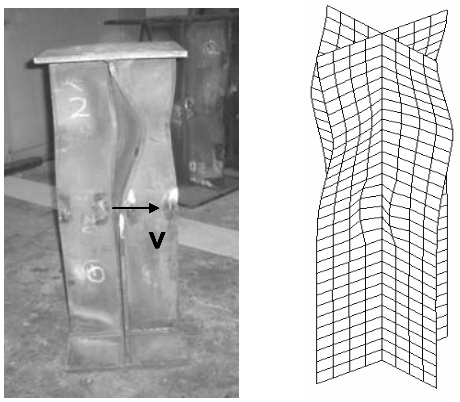
(a) Model of stress – strain curve. (b) Distribution of yield stress.

Figure 8. Strength distribution model.

affects the deformation behavior of the corrected specimen.

To confirm the occurrence of work hardening and the increase of yield stress through plastic deformation, a tensile test is a convenient method. But, it was difficult to cut out many specimens for tensile tests from cruciform column projection panels. Then, noting an interrelation between Vickers hardness and yield stress [6], instead of tensile tests, Vickers hardness tests for the corrected specimen were conducted.

Figure 7 (a) shows the measuring point for hardness and a result of the hardness test is shown in Figure 7 (b). In Figure 7 (b), maximum, minimum and average values of hardness in each measured range (10mm) are described. From the result, it is well known that at the center of the panels, that is, the part at which large out-of-plane deformation occurred in the virgin compressive test, were hardened both at the free edge and



(a) Experiment (b) Analysis

Figure 9. Shape of the specimen corrected by heating.

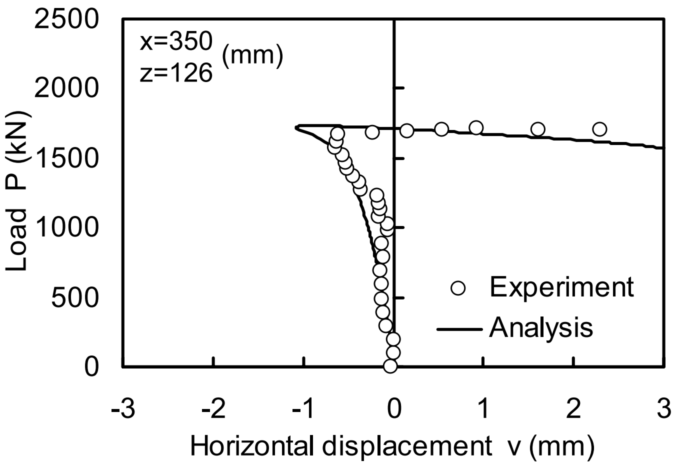


Figure 10. Load – horizontal displacement diagram.

the welded edge. Therefore, as well as hardness, yield stress at the center of the panels should become higher due to large plastic deformation.

In order to consider the increase of yield stress in the analysis, it is assumed that the stress-strain curve of the panels corrected by heating traces the solid line in Figure 8 (a), and the projection panels have a parabolic distribution of yield stress based on the result of the hardness test (shown in Figure 8 (b)).

Using this stress-strain curve and the residual imperfection from Eq.(2), analysis was conducted again.

The results of analysis are shown in Figure 9 and 10. When considering only residual imperfection, the deformation mode under compressive loads of the specimen could not be simulated (refer to Figure 5), but by considering the increase of yield stress also, the deformation mode under compressive loads of the specimen and relation between load and horizontal displacement were simulated successfully (Figure 9 and 10).

From these results, it was concluded that the deformation mode under compressive loads of cruciform column projection panels corrected by heating was decided by both the residual imperfection and the increase of yield stress through large plastic deformation.

The reason of the change of the deformation mode is as follows. The residual imperfection exists at the center of the projection panel. At the same time yield stress becomes higher around this region. Therefore out-of-plane deformation does not occur at the center necessarily, and it occurs in the other part such as the upper side of the panels. When the residual imperfection is relatively large, out-of-plane deformation should occur at the center of the panels. But when it is relatively small, out-of-plane deformation should occur not at the center but at the other part in the panel such as the objective specimen. It is probable that the deformation mode under compressive loads of the specimen corrected by heating is decided by both the degree of the residual imperfection and the increase of yield stress.

By the way, when noting the ultimate strength, in the case of considering only the residual imperfection, the ultimate strength obtained by analysis was lower comparing with that obtained by the experiment (refer to Figure 6). But by considering the increase of yield stress also, the ultimate strength is simulated accurately by analysis (refer to Figure 10). That is, the increase of yield stress is also a factor deciding the ultimate strength of the panels corrected by heating.

In any case, it was concluded that the factors governing the mechanical behavior under compressive loads of a cruciform column projection panel corrected by heating were both the residual imperfection and the increase of yield stress by large plastic deformation.

4. Conclusions

In order to elucidate mechanical behavior under compressive loads of a cruciform column projection panel corrected by heating, compressive tests in a virgin situation and after heating correction were simulated by elastic-plastic large deformation analysis.

The obtained main results are as follows:

(1) By simulating a compressive test for a virgin specimen, the adequacy of the analytic program was confirmed.

(2) Considering only the residual imperfection, a compressive test for the specimen after heating correction was not simulated successfully.

(3) Considering not only the residual imperfection but also the increase of yield stress, the experimental results such as deformation mode and relation between load and horizontal displacement were successfully simulated by analysis.

(4) It was concluded that the factors governing the mechanical behavior under compressive loads of a cruciform column projection panel corrected by heating were both the residual imperfection and the increase of yield stress by large plastic deformation.

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