Buckling Characteristics of High Manganese Non-magnetic Steel and Carbon Steel Hybrid Cruciform Columns †

- Investigation for Applying Dissimilar Materials to Steel Structures (Report III) -

You Chul KIM *, Hidetoshi TAHARA **, Eiji NAKAJI * and Kohsuke HORIKAWA******

Abstract

The validity of the results obtained by elastic-plastic large deformation analysis is confirmed by comparing load-displacement curves obtained in experiments using the central axis compression test. A series of analyses were performed in order to elucidate the buckling characteristics of dissimilar materials hybrid columns.

The local buckling mode of dissimilar materials hybrid columns (DMHC columns) is same as that of similar materials columns (SMC columns), but the overall buckling mode is different from that of SMC columns. The vertical displacement-load history of DMHC columns follows a history between those of SMC columns assembled from each material regardless of width-thickness ratio in the elastic range, but shows a peculiar behavior beyond the yield point. After reaching the maximum load, it follows a history between those of SMC columns again. Paying attention to the panels, although each panel of the DMHC column shows the same behavior as that of a panel of an SMC column in the elastic range, after yielding, each panel of the DMHC column shows a different progress of plasticity. It is found that the maximum load of a DMHC column might become smaller than that of an SMC column assembled from material in which the maximum load was smaller and its conditions are elucidated.

KEY WORDS: (Dissimilar Materials Columns)(Hybrid Cruciform Columns)(Buckling Strength) (Ultimate Strength) (Non-magnetic Steel)(FEM)

1. Introduction

Research and development have been pursued on magnetic levitation type vehicle systems as means of high-speed transportation in the 21st century. It is known that with the magnetic levitation type vehicle loaded with superconducting magnets, magnetic drag force occurs between the guide-way structure and the vehicle, and that this magnetic drag force increases the running resistance of the vehicle. As a preventive measure against the magnetic drag force, it is proposed to adopt non-magnetic steel for the guide-way structure. Since non-magnetic steel is more expensive compared with carbon steel, its utilization as a hybrid member with carbon steel is supposed to reduce the fabrication cost. However, there have been few studies of mechanical characteristics of dissimilar materials hybrids[1]. On the other hand, if the mechanical characteristics of dissimilar materials hybrid structures are elucidated, steels with different strengths to be used for repair and reinforcement of existing structures, etc. will be able to be comprised. So, the applicability of hybrid structures will be elucidated. In this respect, the mechanical properties and fatigue strength of high manganese non-magnetic steel (hereafter referred to as high Mn steel) and carbon steel dissimilar materials welded joints have been investigated [2, 3].

In this study, compressive tests subjected to the centrally applied load conducted on dissimilar materials hybrid cruciform columns (hereafter referred to as DMHC columns) of high Mn steel and carbon steel were simulated by elastic-plastic large deformation analysis. The validity of the results obtained by analysis is investigated by comparing the load-displacement curves obtained by experiments. The buckling characteristics of DMHC columns of high Mn steel/carbon steel are elucidated. The influences of material combinations of the panels on the buckling strength of DMHC columns are elucidated.

† Received on November 24, 1999

* Associate Professor
** Graduate Student
*** Mitsui Engineering & Shipbuilding Co, Ltd.
**** Professor

Transactions of JWRI is published by Joining and Welding Research Institute of Osaka University, Ibaraki, Osaka 567-0047, Japan.

Table 1 Mechanical properties obtained by tensile tests.

	SS400	SM490YA	0.25C-25Mn
Young's modulus E (GPa)	200	200	165
Yield stress σ_Y (MPa)	292	400	429
Tensile strength σ_U (MPa)	419	539	878
Poisson's ratio ν	0.3	0.3	0.3

Table 2 Width-thickness ratio and models.

Model	b/t	Panel 1&3	Panel 2&4
H 4	4	0.25C-25Mn	SS400
M 4	4	0.25C-25Mn	0.25C-25Mn
S 4	4	SS400	SS400
H14	14	0.25C-25Mn	SS400
M14	14	0.25C-25Mn	0.25C-25Mn
S14	14	SS400	SS400

2. Investigation of the Validity of the Computed Results by FEM

2.1 Experiment

2.1.1 Tensile test

Tensile tests are carried out high Mn steel (0.25% C-25% Mn steel) and carbon steels (SS400, SM490YA). **Table 1** shows the mechanical properties of the materials used in the tensile tests. **Table 2** shows the combination of materials and the names of the models.

2.1.2 Central axis compression test

The compressive tests subjected to the centrally applied load were performed for combinations of high Mn steel/SS400, high Mn steel/high Mn steel and SS400/SS400.

Figure 1 (refer to Model H14 in Table 2) shows the test pieces of the cruciform columns. The dimensions of the test piece are L=700 (mm) for column length, t=9 (mm) panel thickness and b=130.5 (mm) panel width, respectively. The strains in the compressive tests are measured with strain gauges, while the displacements are measured with displacement meters and theodolites, respectively.

2.2 Simulation of experiment by elastic-plastic large deformation analysis

The elastic-plastic large deformation analysis[4] is performed for the simulation of experiment. This program, which uses 4-node bilinear degeneration shell, has a freedom of nodes of degree 6. For investigating the progress of plasticity in the thickness direction of the panels, each element is divided into 10 layers in the thickness direction.

The initial imperfection is applied by superposing the sine waves indicated in the following formulas:

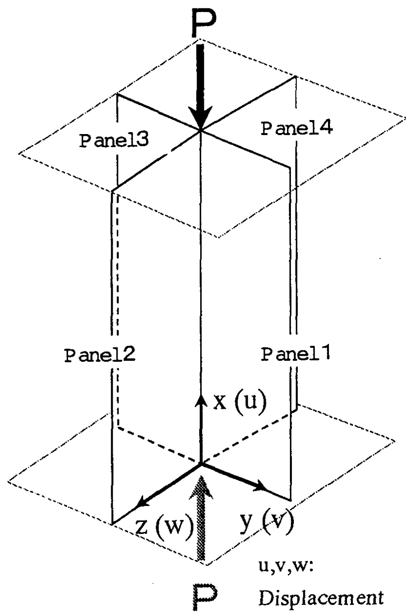


Fig.1 Configuration of model and coordinate systems.

y-direction:

$$v_0 = A_{0z}\sin\frac{\pi x}{l} + \sum A_{0mn}\sin\frac{m\pi x}{l}\sin\frac{n\pi z}{2b}$$

z-direction:

$$w_0 = A_{0z}\sin\frac{\pi x}{l} + \sum A_{0ij}\sin\frac{i\pi x}{l}\sin\frac{j\pi x}{2b}$$

In the above formulas, the first term indicates the bending distortion mode of the column, while the second term represents the local distortion mode of the panel.

No residual stress generated by welding is considered in large deformation analysis.

2.3 The investigation of the validity of the results

Figure 2 shows the horizontal displacement-load history. The result of large deformation analysis is about 10% smaller than the experimental result for the maximum load value, the general behaviors coincide well with each other.

Hereinafter, a series of analyses were carried out by large deformation analysis to elucidate buckling characteristics of the dissimilar materials hybrid cruciform columns.

3. Buckling Characteristics of High Mn Steel/Carbon Steel Hybrid Cruciform Columns

The large deformation analysis was carried out on the models of DMHC columns of high Mn steel and carbon steel with various width-thickness ratios to elucidate the buckling behavior of dissimilar materials hybrid columns.

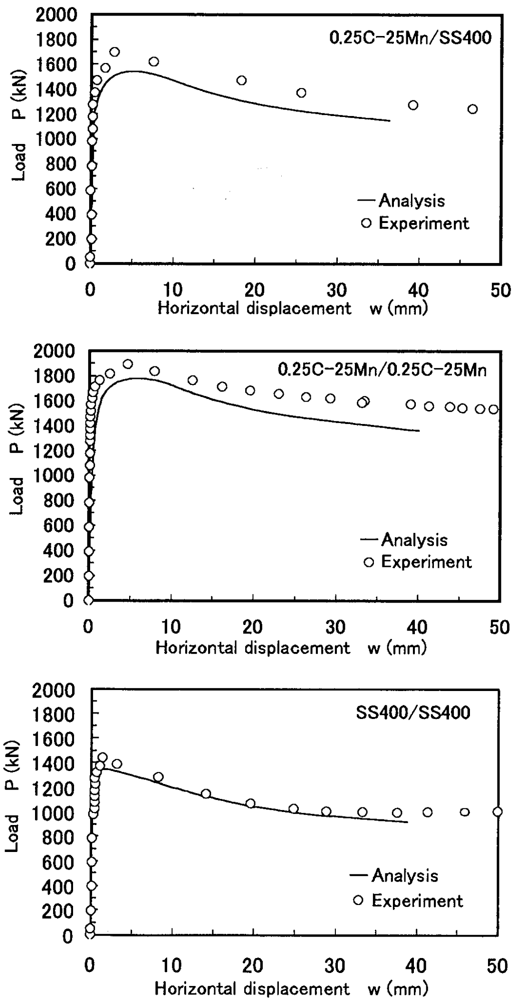
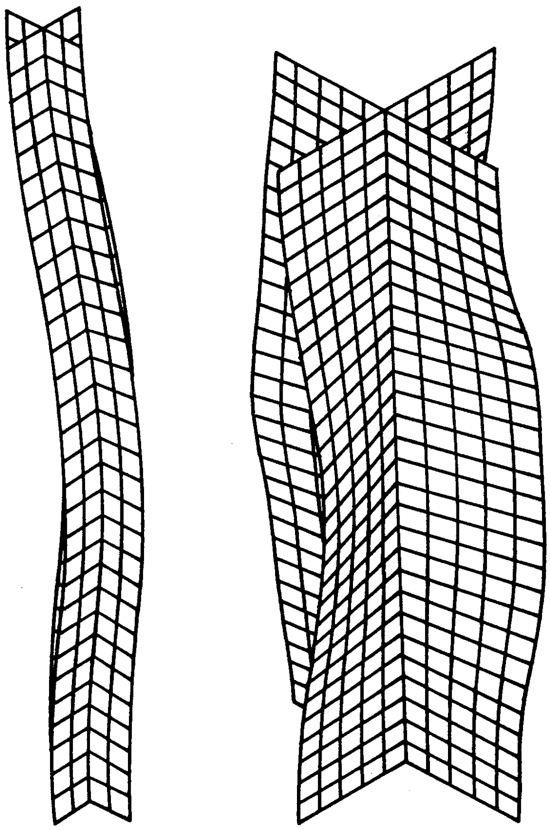


Fig.2 Comparison of the results obtained by experiment and elastic-plastic large deformation analysis.

3.1 Model of dissimilar materials cruciform columns

According to the compressive test results of similar material cruciform columns (hereafter referred to as SMC columns), it has been elucidated[1] that collapse occurs in the overall buckling mode of the columns at a width-thickness ratio of 4 (panel width is 36 mm) or under. On the other hand, collapse occurs in the local buckling mode of the panel at a width-thickness ratio of 10 (panel width is 90 mm) or over. Analyses were therefore performed on the models of DMHC columns of high Mn steel and carbon steel having the width-thickness ratio of 4 and 14. In addition, the deformation mode and the load history for overall buckling and local buckling are investigated in detail. Table 2 shows the width-thickness ratio of panels and combination of materials of the models.



(a) Overall buckling. (b) Local buckling.

Fig.3 Features of deformation mode.

3.2 Results of analysis

3.2.1 Overall buckling

Figure 3(a) shows the deformation mode at the ultimate state of a DMHC column (Model H4).

Figure 4(a) shows the horizontal displacement at the central point of the column of each model in compressive condition. In SMC columns (Models M4, S4), the deformation progresses in the direction of weak axis (45° direction), as it is expected from the Euler's buckling theory. In DMHC columns, however, the deformation progresses in the direction of the SS400 panel (direction z) of larger Young's modulus compared with high Mn steel in the initial period, but the direction of deformation changes to the direction of about 45° as the DMHC column comes close to the ultimate state. After the ultimate state, the deformation progresses in the same direction as that of the SMC column. Thus, the buckling behavior of the DMHC column is remarkably different from that of the SMC column.

Figure 4(b) shows the vertical displacement-load history. The DMHC column follows a history between those of SMC columns of high Mn steel and of SS400 in the elastic range, and after yielding, reaches the ultimate compressive state with decreasing the tangential rigidity. After that, it again follows a history between those of SMC columns assembled from each material.

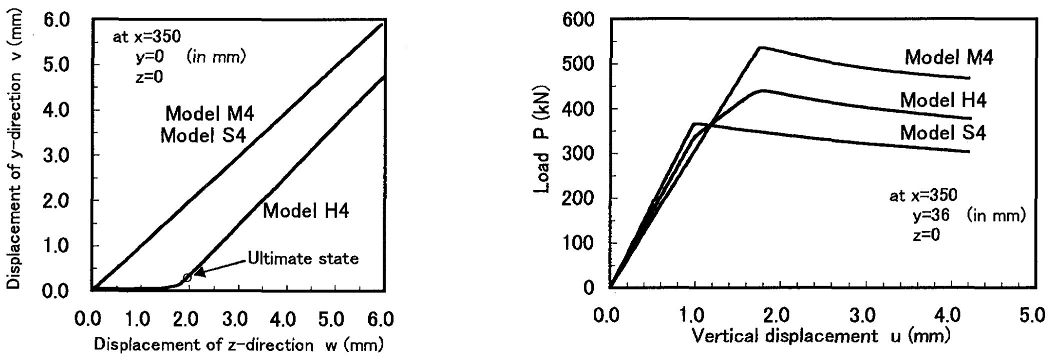
3.2.2 Local buckling

Figure 3(b) shows the deformation mode at the ultimate state of a DMHC column (Model H14).

Figure 5(a) shows the relationship between the vertical displacement and horizontal displacement at the central point of a free edge. From the figure, it can be noted that the local buckling mode of a DMHC column is equal to that for SMC columns of each material. The four panels of a DMHC column have exactly the same deformation behavior as panels of SMC columns in spite of their different materials.

Figure 6 shows the relationship between the load shared by the four panels comprising the DMHC column and the vertical displacement. The shared load is equal for the four panels in the case of the SMC column, but the load shared by each panel varies depending on the materials in the case of DMHC column.

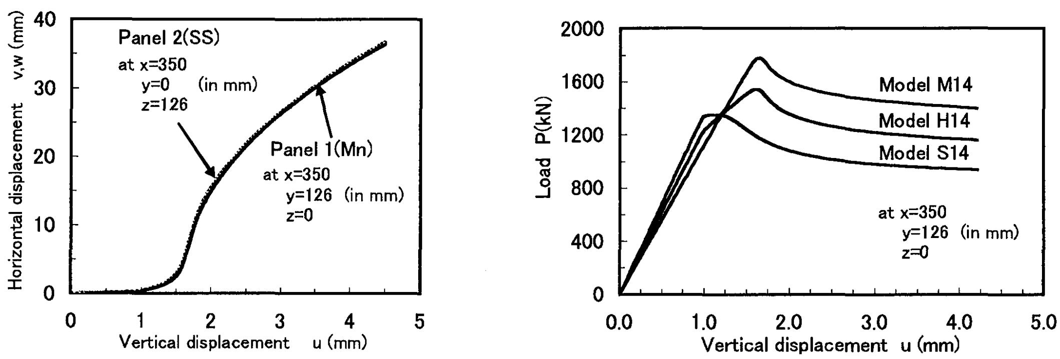
Figure 5(b) shows the vertical displacement-load



(a) Relation of horizontal displacement between w and v.

(b) Load-displacement curves.

Fig.4 Overall buckling.



(a) Relation between vertical displacement, u and horizontal displacement, v and w.

(b) Load-displacement curves.

Fig.5 Local buckling.

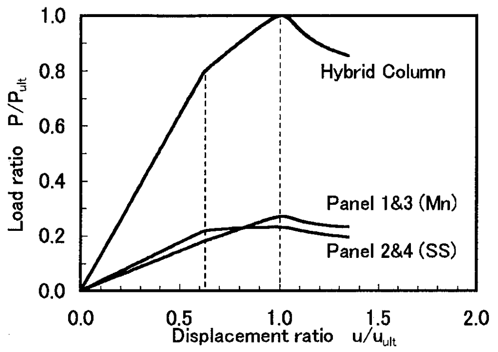


Fig.6 Load shared by each panel.

Table 3 Models in elastic-plastic large deformation analysis.

Model	Panel 1&3	Panel 2&4
SS /SM	SS400	SM490
Mn/SM	0.25C-25Mn	SM490
Mn/ SS	0.25C-25Mn	SS400
Mn/Mn	0.25C-25Mn	0.25C-25Mn
SS / SS	SS400	SS400
SM/SM	SM490	SM490

history. In the same way as in the case of the overall buckling model, a DMHC column follows a history between those of SMC columns of each material in the elastic range. After the initial yielding, the tangential rigidity decreases and a DMHC column reaches the ultimate compressive state, and then follows a history between those of SMC columns.

4. Buckling Strength and the Combination of Materials

The elastic-plastic large deformation analyses are carried out on models of DMHC columns assembled with a combination of three different kinds of materials. The influences of the mechanical properties on the buckling strength of the panels of the DMHC column are elucidated, while the differences in the plasticity progress of the panels are investigated.

4.1 Model

The elastic-plastic large deformation analysis is carried out on the DMHC cruciform column with a width-thickness ratio of 14 for the following three cases:

Case Ⅰ: Young's modulus is same but yield stress is different (SM/SS).

Case Ⅱ:Young's modulus is different but yield stress is same (Mn/SM).

Case Ⅲ:Young's modulus and yield stress are both different (Mn/SS).

Table 3 shows the combinations of the materials.

4.2 Results of large deformation analysis

Figure 7 shows the vertical displacement-load history of each model.

In all of the Cases I, II and III, the DMHC column follows a history between the history of SMC columns of each material in the elastic range. When the panels of lower yield stress become plastic, the tangential rigidity of the column decreases and reaches the ultimate state. After that, the DMHC column follows a history between the history of SMC columns again. Although the mechanical behavior of the columns are the same, in Case I and Case III, the maximum load of the DMHC column has an intermediate value between the maximum load of SMC columns of each material. In Case II, the maximum load becomes smaller than the maximum load of both columns constituted by each material.

Figure 8 shows the relationship between the load shared by each panel and the vertical displacement. From the results, it was found that there were cases when the maximum load of the DMHC column was still smaller than that of the SMC column assembled from the material for which maximum load was smaller.

The reason for this fact is considered below in relation to the panels comprising the column.

5. Considerations

In Case I (SM/SS), each panel of a DMHC column follows the same history as that of the panels of SMC columns (SM/SM and SS/SS) in the elastic range (Fig.9). The load increases even after yielding in the SS panels (SM/SS(SS)) of a DMHC column. This is probably because the SM panels (SM/SS(SM)) of a DMHC column of higher buckling strength restrict the rotational displacement of the SS panels. On the contrary, the tangential rigidity of the SM panels decreases after the SS panels yield, and SM panels reach the maximum load at the vertical displacement in which the panels of the SMC column have the maximum load, while the SS panels also reach the maximum load. The maximum load of the SS panels comprising the DMHC column become approximately 7(%) larger compared with the SS panels comprising an SMC column, but the maximum load of the SM panels of the DMHC column is approximately 6(%) smaller compared with that of the SM panels in the SMC column. It is considered that this is why the maximum load of a DMHC column is positioned between the maximum loads of SMC columns assembled from each material. Basically the same behavior is indicated also in Case III (Mn/SS).

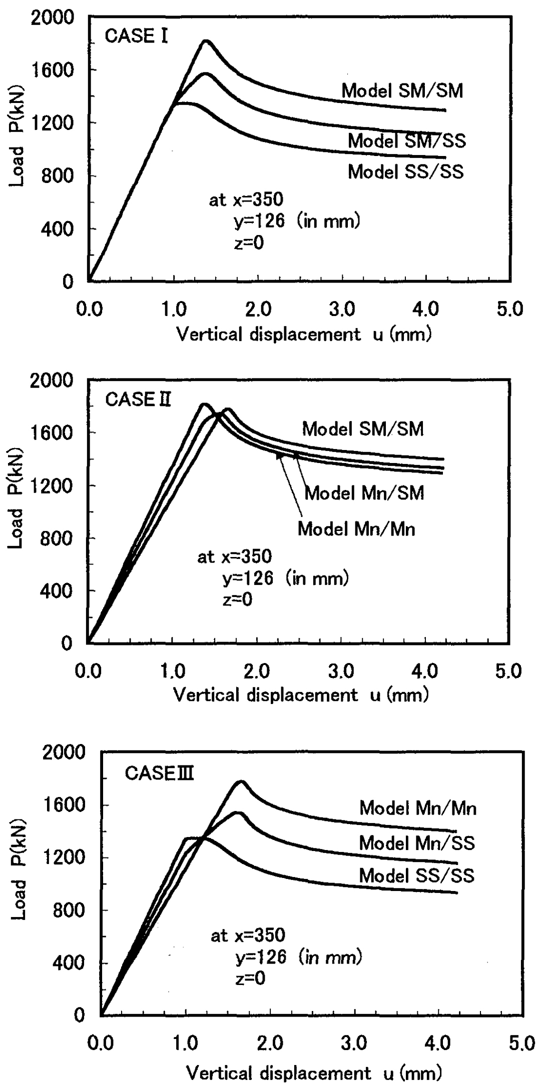


Fig.7 Load-displacement curves.

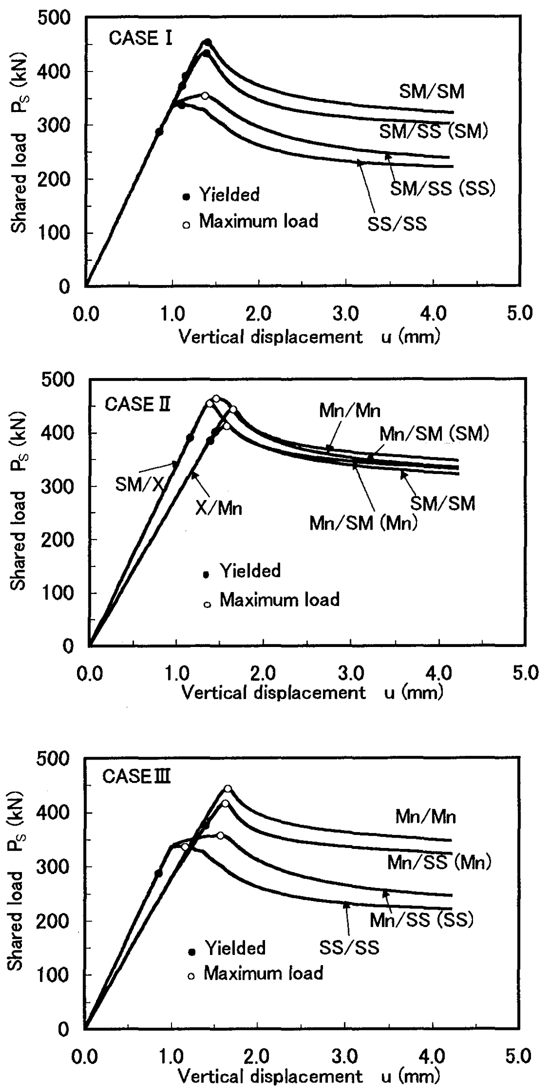


Fig.8 Load shared by each panel and displacement curves.

In Case II (Mn/SM), as in Case I, each panel of a DMHC column follows the same history as that of the panels of SMC columns assembled from each material in the elastic range. After yielding, the SM panels, in which yield stress is almost equal but where Young's modulus is high, come closer to the ultimate state earlier than the Mn panels. This is because the SM panels experience buckling displacement earlier than the Mn panels. For that reason, the maximum load of the SM panels in the DMHC column become only slightly larger compared with those of the SM panels in the SMC column. Conversely, the maximum load value of the Mn panels in the DMHC column decreases remarkably compared with the Mn panels comprising the SMC column. This is because, after the buckling of the SM panels in the DMHC column, the Mn panels, in which yield stress is almost equal but where Young's modulus is small, must resist the external forces by themselves. It is probably for this reason that the maximum load of a DMHC column becomes smaller than that of an SMC column assembled from materials of smaller maximum load.

Table 4 shows the influences of the combination of materials on the buckling strength of the panels comprising a DMHC column. The way to evaluate the buckling strength of the panel constituting a DMHC column is explained for combinations given in the first columns of Table 4. The case where Young's modulus of material A is smaller than Young's modulus of material B and where the buckling strength of the panels of an SMC column assembled from material A is smaller than the buckling strength of the panels of an SMC column assembled from material B, is considered.

Table 4 Buckling strength of panel in hybrid columns.

E	σ_{cr}	δ_{cr}	σ^{H}_{cr}
$E_A < E_B$	$\sigma_{cr\,A} < \sigma_{cr\,B}$	$\delta_{cr\,A} < \delta_{cr\,B}$	$\sigma^{H}_{cr\,A} > \sigma_{cr\,A}$ ↑
		$> \delta_{cr\,B}$	$< \sigma_{cr\,A}$ ↓ $^{\circ}$
$< E_B$	$> \sigma_{cr\,B}$	—	$< \sigma_{cr\,A}$ ↓
$> E_B$	$< \sigma_{cr\,B}$	—	$> \sigma_{cr\,A}$ ↑
$> E_B$	$> \sigma_{cr\,B}$	$< \delta_{cr\,B}$	$> \sigma_{cr\,A}$ ↑ $^{\circ}$
		$> \delta_{cr\,B}$	$> \sigma_{cr\,A}$ ↓

E_X : Young's modulus of X material
$\sigma^{H}_{cr\,X}$: Buckling strength of X-panel in hybrid column

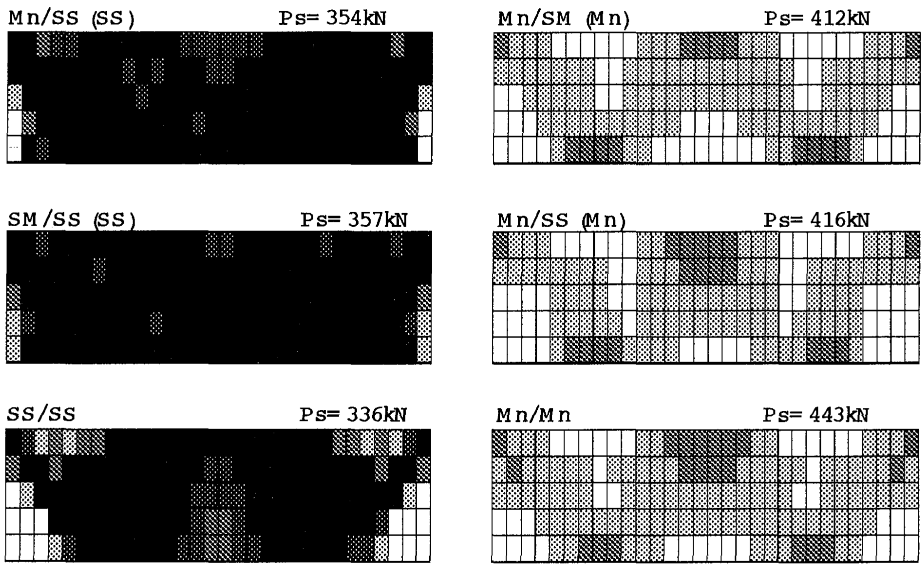


Fig.9 Progress of plasticity.

The buckling strength of the panel is determined depending on the buckling displacement δ_{cr} of material A and material B and whether the buckling strength σ^{H}_{crA} of material A panels in the DMHC column is larger than the buckling strength σ_{crA} of material A panels in the SMC column. The direction of the arrow mark in the table represents the increase (↑) and decrease (↓) of the buckling strength of the panels of a DMHC column. Moreover, the mark $^{\circ}$ indicates the combination of materials in which the buckling load of a DMHC column becomes smaller than that of the SMC column, as in Case II.

Figure 9 shows the plasticity progress of the panels in the ultimate state of compression. The portion in white color represents the elastic range and indicates that, the darker the color, the more the plasticity is progressed. As is apparent from this figure, the Mn panels become plastic to an equal extent, regardless of whether they are the panels of an SMC column or the panels of a DMHC column. On the other hand, the SS panels show greater much plasticity when composed with SM or Mn panels, though their buckling load slightly increases, showing a remarkable difference from the situation of plasticity of the SS panels comprising an SMC column.

6. Conclusion

Elastic-plastic large deformation analysis can be carried out to elucidate the buckling characteristics of DMHC columns under compressive load. From the analysis results, the buckling behavior and the influence of combination of materials of DMHC columns on the buckling strength are investigated.

The results obtained from this study are as follows:

(1) According to the simulation of experiments using elastic-plastic large deformation analysis, the analysis results well reflected the test results, throughout the whole load-displacement history.

(2) The local buckling mode of a DMHC column is same as that of an SMC column, but the overall buckling mode is different from that of the SMC column.

(3) The vertical displacement-load history of a DMHC column follows a history between those of SMC columns assembled from each material, regardless of width-thickness ratio in the elastic range, but shows a peculiar behavior as a hybrid column beyond the yield point. After reaching the maximum load, however, it follows a history between those of SMC columns again. Paying attention to the panels comprising the column in which the local buckling occurs, while each panel of a DMHC column shows the same behavior as that of the panels of an SMC column in the elastic range, after the yielding, each panel of a DMHC column shows peculiar plasticity behavior.

On the other hand, it was found that there are cases when the buckling strength of the column decreases depending on the combination of panel materials constituting the column. That is,

(4) In a DMHC column assembled from material A and material B, both the Young's modulus of material A and the buckling strength of an SMC column assembled from material A are smaller (larger) compared with the Young's modulus of material B and the buckling strength of an SMC column assembled from material B. Moreover, in the case where the buckling displacement of an SMC column assembled from material A is larger (smaller) than the buckling displacement of an SMC column assembled from material B, the buckling strength of the DMHC column decreases compared with an SMC column assembled from material A of lower buckling strength. Special attention is required to this point because it becomes meaningless to fabricate hybrid columns with such combinations of materials.

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