Ultimate Strength of Outstanding Plates in Cruciform Columns Assembled from Dissimilar Steels †

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Abstract

The ultimate strength for outstanding high Mn steel panels in the dissimilar steels hybrid cruciform columns (DMHC columns) assembled from high Mn steel and carbon steel was obtained. In elastic buckling, the ultimate strength of the Mn panel combined with dissimilar steels was nearly equal to that of a Mn panel combined with similar steels. However, in elastic-plastic buckling, both of the ultimate strengths were different. Whichever similar steels or dissimilar steels might be assembled, the stress-displacement behavior of each outstanding panel was the same as that of the steel itself. When the existing structures are repaired or reinforced, the use of steels whose strength is larger than that of the present steels makes the ultimate strength of the existing structures larger.

KEY WORDS: (Load carrying capacity) (Dissimilar steels) (Ultimate strength) (Outstanding plate) (Non-magnetic steel) (Elastic-plastic large deformation analysis) (FEM)

1. Introduction

Although a large number of studies have been carried out on buckling problems for columns or plates, most have been confined to structures assembled with similar steels. There are few studies on buckling problems for the structures assembled by dissimilar steels. It is important to elucidate the buckling characteristics of hybrid structures assembled by dissimilar steels based on new concepts.

Under these situations, a series of researches on the hybrid structures assembled with high manganese non-magnetic steel (0.25C-25Mn steel) and carbon steel (SS400, SM490Y) have been carried out, for the construction of magnetic levitation type vehicle systems[1]. Weldability and mechanical properties have been investigated primarily for the dissimilar steels welded joints of high manganese non-magnetic steel (hereafter referred to as Mn steel) and carbon steel [2]. Consequently, fatigue tests have been conducted to examine the applicability of these joints for structural members [2].

Furthermore, the compressive tests[3] subjected to the centrally applied load conducted on dissimilar steels hybrid cruciform columns (hereafter referred to as DMHC columns) composed of Mn steel and carbon steel are simulated by elastic-plastic large deformation analysis [4]. The accuracy of the simulation results is confirmed and the buckling characteristics of the DMHC columns composed of Mn steel and carbon steel [5] are investigated. The influences of the material combinations of the panels on the buckling strength of the DMHC columns are elucidated [5].

In this study, the buckling characteristics of the Mn steel outstanding plates of the DMHC column assembled from Mn steel and carbon steel and the Mn steel cruciform column (hereafter referred to as SMC columns) are examined. First, the ultimate strength curves for the Mn outstanding plates of the DMHC columns and SMC columns are obtained through the elastic-plastic large deformation analysis by FEM under the conditions of being simply supported at both end and in axial compression. Discussing the results, the influences of steel combinations and the difference of buckling form (elastic or elastic-plastic buckling) on the ultimate strength of the outstanding plates are elucidated.

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2. Model for Analysis and Conditions

2.1 Model for analysis

Figure 1 shows the model for analysis. **Table 1**, **Table 2** and **Table 3** show the dimensions of the model, combination of steels and the mechanical properties, respectively. **Figure 2** shows the stress-strain curves of the steels obtained from tensile tests. In the elastic-plastic large deformation analysis by FEM, the stress-strain curve is used an approximation with the multi-liner.

The initial deflection w_0 is applied by superposing the sine waves indicated in the following formula. The maximum deflection is 1/10 of the plate thickness. No residual stress generated by welding is considered in the analyses.

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

where,

a : length of the panel (mm)
b : width of the panel (mm)
m : order of the deformation mode in longitudinal direction (= 1, 3)
n : order of the deformation mode in transverse direction (= 1)
A_{mn} : maximum value for mn order mode (mm)

2.2 Conditions

The elastic-plastic large deformation analyses are carried out for the DMHC columns assembled from Mn steel and carbon steel (SS400, SM490Y) and the SMC column assembled with Mn steel under the conditions of axial compression and being simply supported at both ends. This program, which uses a 4-node bilinear degeneration shell, has a freedom of nodes of degree 6 [4]. The panels are divided into 5 meshes in the width direction (y and z direction) and 30 meshes in the longitudinal direction (x direction), respectively. For investigating the progress of plasticity in the thickness direction of the panels, the thickness direction is divided into 10 layers.

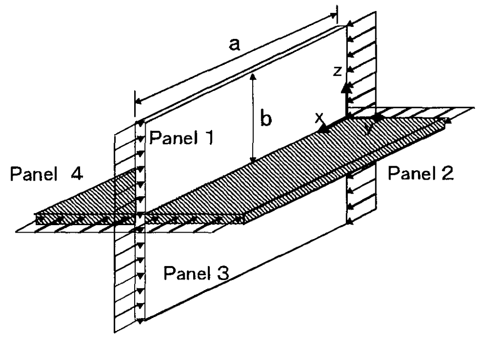


Fig.1 Model and coordinate systems.

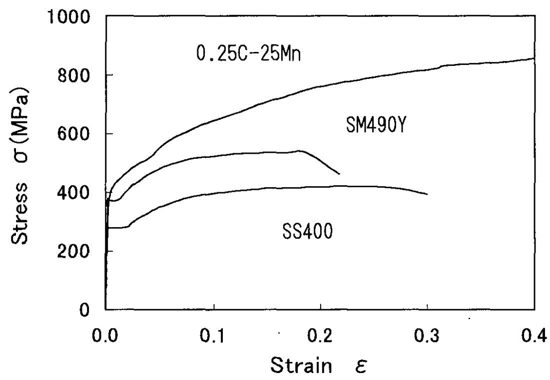


Fig.2 Stress-strain curves.

Table 1 Dimensions of model.

Panel length a (mm)	500
Panel width b (mm)	100
Thickness t (mm)	5,6,7,9,12,16
a/b	5
b/t	6.3, 8.3, 11.1, 14.4, 16.7, 20.0

Table 2 Combination of steels.

	Panel 1 & 3	Panel 2 & 4
SM/SS	SM490Y	SS400
Mn/SM	0.25C-25Mn	SM490Y
Mn/SS	0.25C-25Mn	SS400
Mn/Mn	0.25C-25Mn	0.25C-25Mn
SM/SM	SM490Y	SM490Y
SS/SS	SS400	SS400

Table 3 Mechanical properties of steels.

	SS400	SM490Y	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	829
Poisson's ratio ν	0.3	0.3	0.3

As external force, forced displacement u_0 is applied at the end of the model (see in Fig.1). As boundary conditions, the rotations are free about the y-axis and z-axis for the outstanding panel in the xy-plane and xz-plane, respectively and other rotations are fixed.

3. Results and Discussion

3.1 Ultimate strength curves for Mn outstanding plates

Figure 3 shows the ultimate strength curves for the Mn outstanding plates of the SMC column assembled with Mn steel and the DMHC column assembled from Mn steel and carbon steels obtained by FEM analysis. In this figure, Euler's and Basler's ultimate strength curves for the plate with one edge free and other three edges simply supported [6] are shown together. The vertical axis is the non-dimensional strength from the yield stress of Mn steel, and the horizontal axis shows the width-thickness ratio parameter R_{OS} given by Eq.(4).

The notation Mn/SS(Mn) in Fig.3 indicates the Mn outstanding plate of the column assembled by Mn steel and SS, and the other one means the same. The buckling coefficient k is calculated using Chawalla's approximation formula for the plate with one edge free and other three edges simply supported[7].

Euler :

$$\frac{\sigma_U}{\sigma_Y} = \begin{cases} 1 & (R_{OS} < 1.0) \\ 1/R_{OS}^2 & (1.0 \leqq R_{OS}) \end{cases} \qquad (2)$$

Basler :

$$\frac{\sigma_U}{\sigma_Y} = \begin{cases} 1 & (R_{OS} \leqq 0.45) \\ 1-0.53\ (R_{OS}-0.45)^{1.36} & (0.45 < R_{OS} < \sqrt{2}) \\ 1/R_{OS}^2 & (\sqrt{2} \leqq R_{OS}) \end{cases} \qquad (3)$$

where,

$$R_{OS} = \frac{b}{t}\sqrt{\frac{\sigma_Y}{E}\frac{12(1-\nu^2)}{\pi^2 k}} \qquad (4)$$

R_{OS}: width-thickness ratio parameter
b : width of the panel (mm)
E : Young's modulus (MPa)
t : thickness of the panel (mm)
k : buckling coefficient
σ_Y: yield stress (MPa)
ν : Poisson's ratio

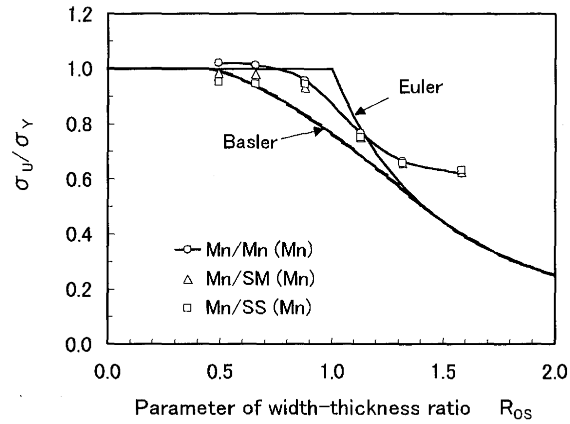


Fig.3 Ultimate strength of outstanding Mn steel in hybrid cruciform column.

The important findings in Fig.3 are as follows:

(1) The region of elastic buckling ($R_{OS} > 1.0$)
There is no significant difference in the ultimate strength of the Mn outstanding plate assembled with similar steels or dissimilar steels.

(2) The region of elastic-plastic buckling ($R_{OS} \leqq 1.0$)
The ultimate strength of the Mn outstanding plate assembled with dissimilar steels seems to be slightly smaller than that of the plate assembled with similar steels.

In any case, it is found that the Mn steel shows its own characteristic whether Mn steel is connected with the steels of smaller strength or not.

3.2 Effects of buckling forms on ultimate strength of outstanding plate

Focusing on the combination of Mn/SS which shows the largest difference in strength, the effects of buckling forms on the ultimate strength of the Mn outstanding plate are investigated.

Case IA : the case when the ultimate state becomes, after elastic buckling, (R_{OS}=1.33)

Case IB : the case when the ultimate state becomes, after elastic-plastic buckling, (R_{OS}=0.66)

Figure 4 shows the relation between the mean stress $\bar{\sigma}$ of the Mn panel and the deflection w at the center of the free edge (x=a/2, y=b, z=0). **Figure 5** shows the relation between $\bar{\sigma}$ and the displacement in the axial direction u. The mean stress $\bar{\sigma}$ is normalized by the yield stress σ_Y of the Mn steel, the deflection w and the displacement u in the axial direction are normalized the plate thickness t and the displacement u_Y in axial

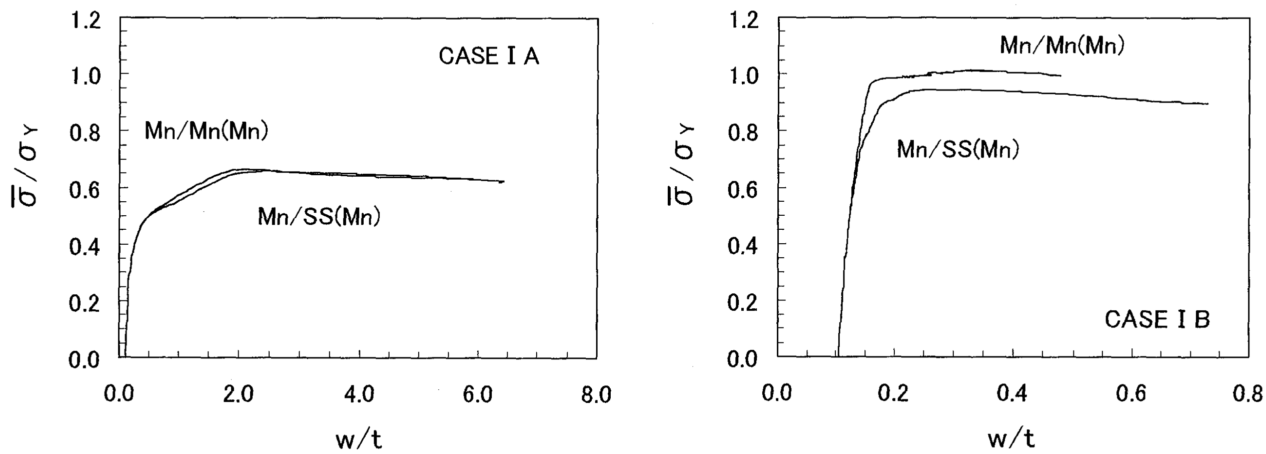


Fig.4 Relation between mean stress and deflection (Mn panel).

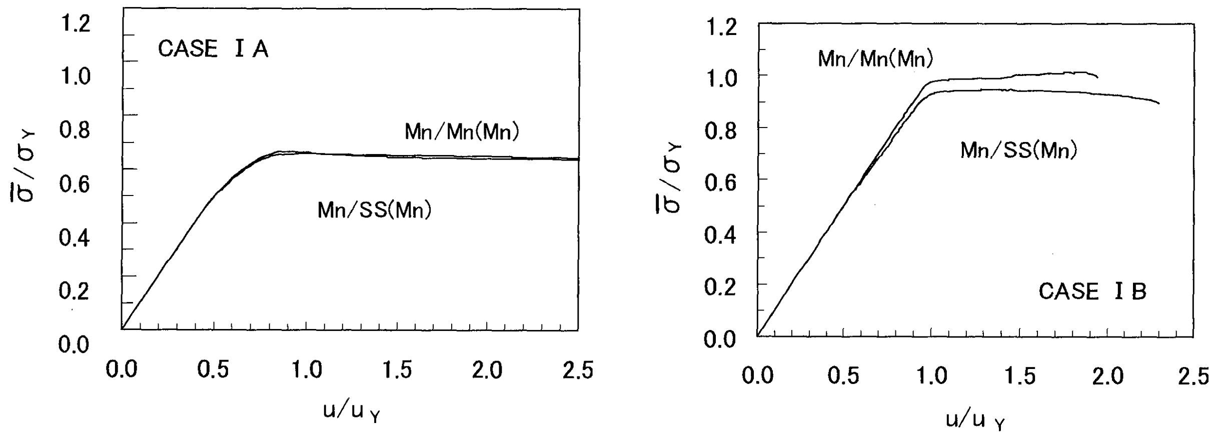


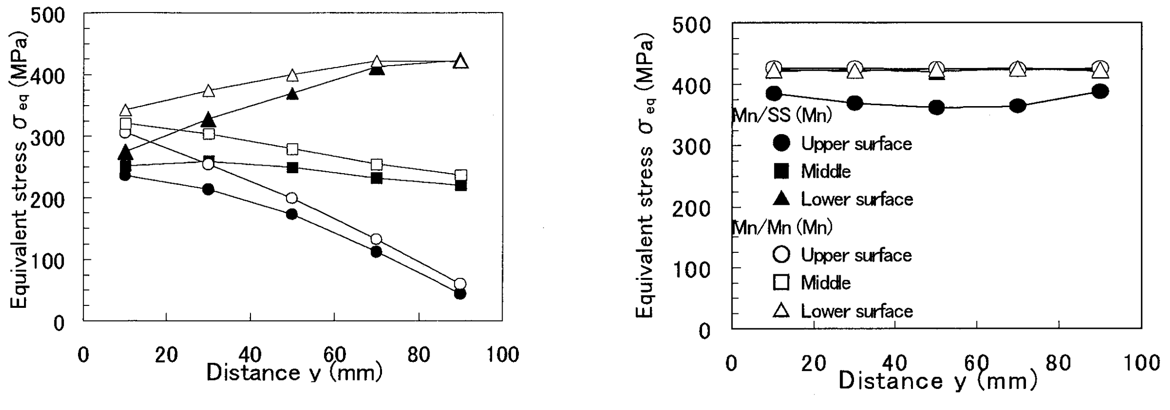
Fig.5 Relation between mean stress and axial displacement (Mn panel).

direction at ultimate state, respectively. $\bar{\sigma}$ is obtained by dividing the loads that the outstanding Mn panel carries by the cross-sectional area of the Mn panel.

In the case that the ultimate state becomes after elastic buckling (Case IA), the buckling behavior of the Mn outstanding plate is almost same whether similar steels or dissimilar steels are combined.

On the other hand, in the case in which ultimate state becomes after elastic-plastic buckling (Case IB), the Mn outstanding plate assembled with dissimilar steels shows the same buckling behavior as that of the plate assembled with similar steels in the elastic range. The difference in buckling behavior between both occurs and the strength of the Mn outstanding plate assembled with dissimilar steels is about 10% smaller than that of the plate assembled with similar steels in the region where $\bar{\sigma}/\sigma_Y$ is larger than 0.7.

Discussing the reason why different behavior occurs depending on the difference of buckling form at the ultimate state, the distributions of the equivalent stress and the progress of the plasticity are examined. **Figure 6** shows the distribution of the equivalent stress in the central cross-sectional plane (x=a/2, yz-plane) at the ultimate state. The notation ●○, ■□ and ▲△ indicate the equivalent stress in the upper plane, central plane and lower plane, respectively. In the Case IA, the equivalent stress of the Mn outstanding plate combined with dissimilar steels is about 20% smaller than that of the plate assembled with similar steels (**Figure 6(a)**) near the joining plane (y=0). Because the Case IA is elastic buckling, the buckling is the dominant deflection. In the case of DMHC column, under the condition that the deflection is the same ; the larger stress occurs in SS steel having larger Young's modulus, that is, the bending rigidity of the plate is larger. Because of this, it is considered that the equivalent stress of the Mn outstanding plate combined with dissimilar steels becomes smaller than that of the plate combined with similar steels, near the joining plane. In the width direction, the equivalent stress of the Mn outstanding plate assembled with dissimilar steels has



(a) CASE IA (b) CASE IB

Fig.6 Distributions of equivalent stress in ultimate state (Mn panel).

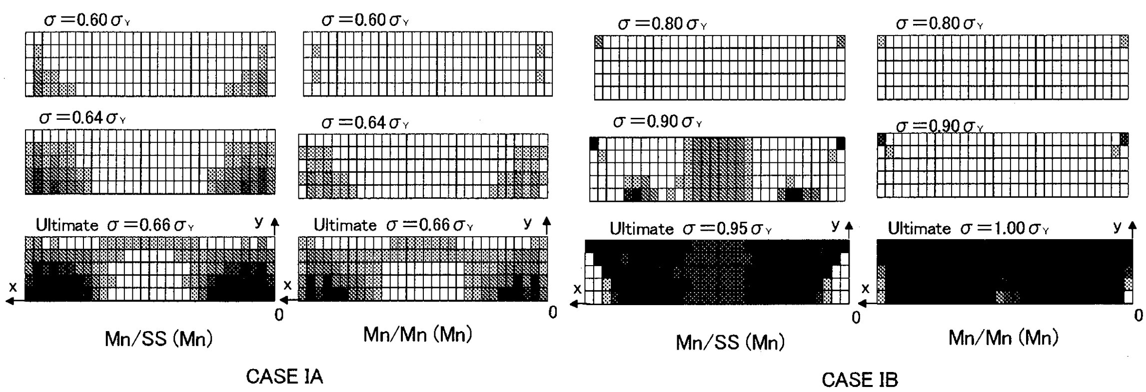


Fig.7 Progress of plasticity.

the same distribution as that of the plate assembled with similar steels.

On the other hand, in the case of elastic-plastic buckling, that is, Case IB, the equivalent stress of the Mn outstanding plate combined with similar steels takes a constant value in the width direction. However σ_{eq} of the Mn outstanding plate is slightly distributed in the width direction in the case that the plate is assembled with a steel of lower strength (**Figure 6 (b)**), the magnitude of σ_{eq} is 20% smaller than that of the Mn outstanding plate assembled with similar steels. The reason is considered below.

Since elastic-plastic buckling depends on yield stress, the progress of plasticity from the initial yielding to the ultimate state is examined. **Figure 7** shows the progress of plasticity for the outstanding plates at several stress levels. In Fig.7, the upper edges indicate the free edges of the outstanding plates. The white color represents the elastic range. The darker the color becomes the more the plasticity is progressed.

In Case IA, there is no significant difference in the progress of plasticity of the Mn outstanding plate between DMHC column and SMC column. On the other hand, in Case IB, the outstanding plates yield initially at the stress level of $\sigma = (0.7\sim 0.8)\sigma_Y$, and after that, a difference in the progress of plasticity for the Mn outstanding plate is found between DMHC column and an SMC column. In the DMHC column, after the SS outstanding plate yield, the Mn outstanding plate carries most of the load, and as a result, the plate progresses in plasticity from the central portion to reach the ultimate state. On the contrary, in an SMC column, the Mn outstanding plate does not become plastic until the Mn steel itself yields, and the Mn plate reaches to the ultimate state immediately after the Mn steel yields. As mentioned above, it is found that there is difference in the progress of plasticity between the cases assembled with dissimilar steels and similar steels. For that reason, σ_{eq} of the Mn outstanding plate assembled with SS having lower strength becomes smaller than that of the plate assembled with similar Mn steels.

In case of the elastic buckling, there is no significant difference between the ultimate strength of the Mn outstanding plate assembled with dissimilar steels and that of the plate assembled with similar steels. Conversely, in case of the elastic-plastic buckling, the progress of plasticity for the Mn outstanding plate assembled with dissimilar steels is different from that for the plate assembled with similar steels. Owing to this, it is found that the ultimate strength of the Mn outstanding plate assembled with dissimilar steels becomes slightly smaller compared with that of the plate assembled with similar steels.

3.3 Effects of materials combination on ultimate strength

In the case where elastic-plastic buckling occurs, the effects of material combination on the ultimate strength of the Mn outstanding plate for the DMHC columns in the region of $R_{OS} \leq 1.0$ is investigated here.

Figure 8 shows the relation between the mean stress $\bar{\sigma}$ and the axial displacement u for the outstanding plate assembled with similar steels with a width-thickness ratio parameter R_{OS} equal to 0.88. It is known that stress-axial displacement behavior much depends on Young's modulus. Even if the yield stress of Mn and SM is almost equal, axial displacement at yield state of SM having larger Young's modulus is smaller than that of Mn. The influence of the mechanical properties on the ultimate strength of the outstanding plate is elucidated below.

The elastic-plastic large deformation analysis is carried out on the DMHC columns with a width-thickness ratio parameter R_{OS} equal to 0.88 for the following three cases:

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

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

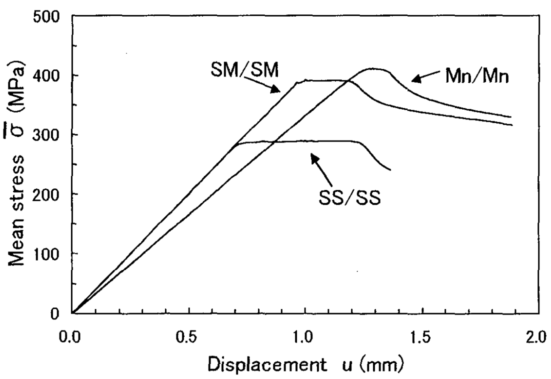


Fig.8 Relation between mean stress and axial displacement.

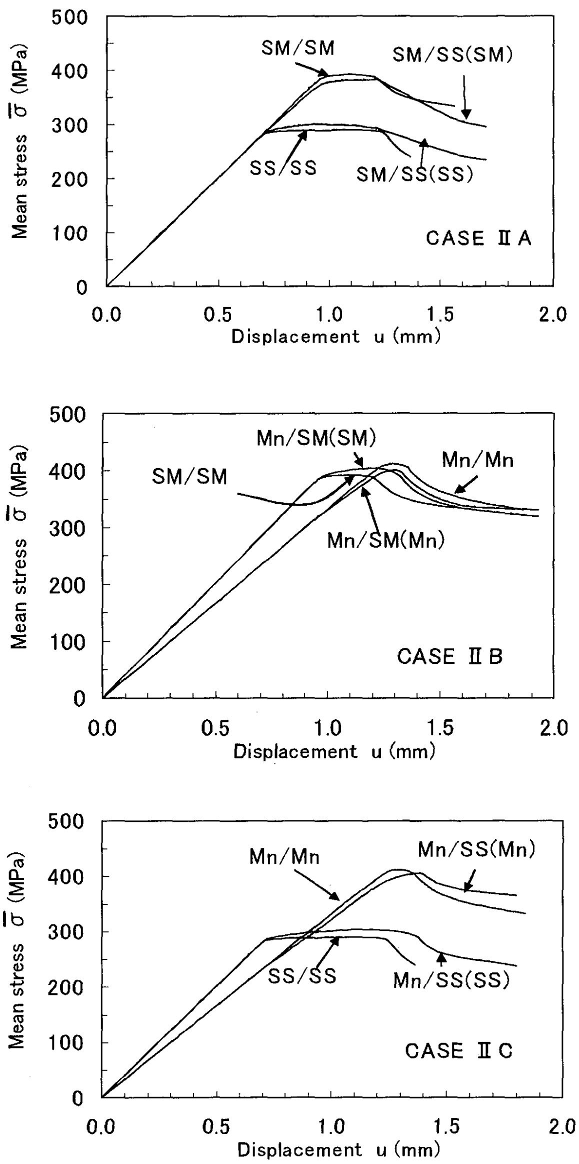


Fig.9 Relation between mean stress and axial displacement.

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

Figure 9 shows the relation between the mean stress and the axial displacement. From the general point of view, it seems that the steel sufficiently demonstrates its own original performance, even if it is combined with other steels. The behavior is investigated in detail below.

In the case that Young's modulus is the same (Case IIA), if the steels of different strength are combined, the strength for the outstanding plate having lower strength (SM/SS(SS)) of the DMHC column slightly becomes higher than that of the SMC

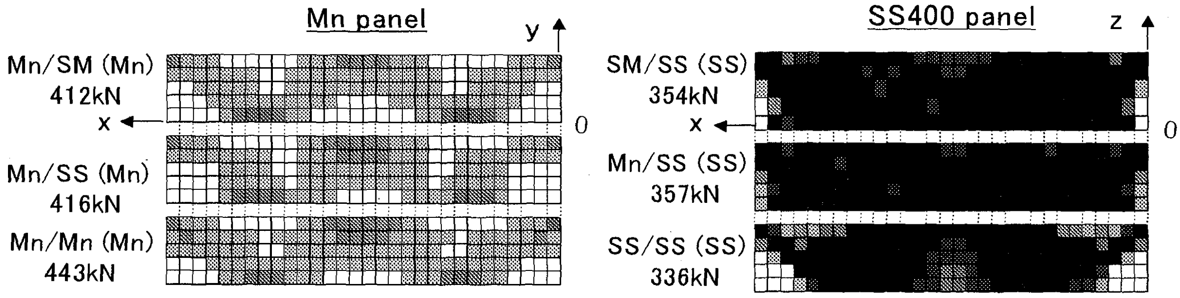


Fig.10 Feature of plasticity in ultimate state.

column. This is probably because the SM panel (SM/SS(SM)) of the DMHC column having larger strength can carry the loads even after yielding of SS panel. Furthermore, the strength of the SM outstanding plate being combined with the SS panel slightly decreases in comparison with that of the SM outstanding plates comprising an SMC column. The tangential rigidity of the SM outstanding plates decreases after the SS panels yield, and the SM outstanding plates reach the ultimate strength when the SM steels themselves yield.

On the other hand, in the case that Young's modulus is different (Case IIB and Case IIC), each outstanding plate shows almost same stress-axial displacement behavior. So, Case IIC is considered. Because of the difference of Young's modulus, even if the outstanding plate is combined with dissimilar steels, each plate shows the same stress-axial displacement behavior as the plate combined with similar steels.

The strength of the SS outstanding plates combined with the Mn steel having larger strength slightly increases in comparison with that of the SS outstanding plate combined with similar steels.

On the other hand, the strength of the Mn outstanding plate increases till the Mn steel itself yields although the tangential rigidity decreases after the SS steel yields. In the neighborhood where the Mn plate combined with similar steels reaches the ultimate state, the Mn plate combined with dissimilar steels reaches the ultimate state, too. The strength of the Mn plate combined with dissimilar steels decreases a little in comparison with that of the Mn plate combined with similar steels, while the displacement at ultimate state of the Mn plate combined with dissimilar steels becomes slightly larger than that of the plate combined with similar steels.

Figure 10 shows the plasticity progress of the outstanding plates at the ultimate state. On the left side of the figure, the combinations of the steels and the loads are shown. Other indications are the same as Fig.7.

The Mn plate becomes plastic to an equal extent, regardless of whether the plate is combined with similar steels or dissimilar steels. On the other hand, the SS plate shows much greater plasticity when composed with SM or Mn steel, though their ultimate strength slightly increases, showing a remarkable difference from the situation of plasticity of the SS panel combined with similar steels.

4. Conclusions

For the dissimilar steels hybrid cruciform columns, the buckling experiments and the simulations of the experiment using elastic-plastic large deformation analysis were carried out. The results of analysis are in good agreement with the experimental ones. A series of analyses were performed in order to make clear the buckling characteristics of the outstanding plate assembled with dissimilar steels.

The obtained main results were as follows:

(1) The ultimate strength curves for the Mn outstanding plate of the DMHC column assembled by Mn steel and dissimilar steels (SS, SM) were obtained through the elastic-plastic large deformation analysis. The influences of the difference of buckling form on the ultimate strength of the Mn outstanding plate were elucidated. That is,

(2) In case of elastic buckling, the ultimate strength of the Mn outstanding plate assembled with dissimilar steels is nearly equal to that of the plate assembled with similar steels. On the other hand,

(3) In case of elastic-plastic buckling, the ultimate strength of Mn outstanding plate assembled with dissimilar steels of which the strength is small is 10% smaller than that of the plate assembled with similar steels, if width-thickness ratio parameter becomes smaller. However, it is not a significant decrease.

The influences of the steel combinations on each outstanding plate were investigated. According to the results;

(4) In the case that the yield stress of each panel is equal, the steel of larger Young's modulus yields earlier.

(5) Whether the plate is assembled with similar steels or dissimilar steels, each outstanding plate sufficiently demonstrates its own original performance. Therefore,

(6) It is found that when the existed steel structures are repaired or reinforced, the application of the steel whose strength is larger than that of the present steels can increase the ultimate strength of the existing structure compared with the case of being repaired or reinforced with similar steels.

References

1) Atsushi ICHIKAWA, Kiyomitsu MURATA, Genpachi ANAMI and Akio MATSUURA: Study on Application of Austenitic High Manganese Steels to Maglev Guideway, Steel Construction Engineering, Japan Society of Steel Construction, Vol.1 No.1, March, 1994, pp.63-72 (Japanese).

2) Eiji NAKAJI, Soichi IKEDA, You-Chul KIM, Yoshihiro NAKATSUJI and Kohsuke HORIKAWA: Mechanical Properties and Fatigue strength of High Manganese Non-magnetic Steel/Carbon Steel Welded Joints, Quarter Journal of the Japan Welding Society, Vol.15, No.3, August, 1997, pp.535-540 (Japanese).

3) Takumi MATSUMOTO, Soichi IKEDA, Toshiyuki OHTSUKI and Kosuke HORIKAWA: Compressive Test of High Manganese Non-magnetic Steel and Carbon Steel Hybrid Cruciform Column, Proceeding of 49th Annual Conference of the Japan Society of Civil Engineers, I-(A), September, 1994, pp.76-77 (Japanese).

4) Testuya YAO: Analysis of buckling & plastic collapse hull structure, Data of special lecture at Bonding Science Research Laboratory of Osaka University, July 1997 (Japanese).

5) You-Chul KIM, Hidetoshi TAHARA, Eiji NAKAJI and Kohsuke HORIKAWA: Buckling Characteristics of High Manganese Non-magnetic Steel and Carbon Steel Hybrid Cruciform Column, Journal of Constructional Steel, Vol.5, Japan Society of Steel Construction, November, 1997, pp.117-124 (Japanese).

6) Subcommittee on Stability Design, Committee on Steel Structures, Japan Society of Civil Engineers: Guidelines for Stability Design of Steel Structures, October, 1987 (Japanese).

7) Column Research Committee of Japan: Handbook of Structural Stability, Corona Publishing Company, Ltd., March, 1971 (Japanese)