Strengthening of steel plate by carbon fiber sheet under axial compression force

Yuya Hidekuma[1], Kazuo Ohgaki[2], Yusuke Okuyama[3], Takeshi Miyashita[4], and Akira Kobayashi[1]

[1] Nippon Steel & Sumikin Materials Co., Ltd, Tokyo, Japan
[2] Institute of Technologists, Saitama, Japan
[3] Nagaoka University of Technology, Niigata, Japan
[4] National Institute of Technology, Nagano College, Nagano, Japan

ABSTRACT: In recent years, a repairing method, which bonds carbon fiber sheets to corroded steel members, has been applied. However, its behavior under large deformation, such as buckling, has not been clarified sufficiently. This paper presents the buckling behavior of a steel plate strengthened by a carbon fiber sheet under axial compression force. A compression test was carried out for specimens that carbon fiber sheets were bonded on both sides of a steel plate. These specimens were configured such that overall and local buckling took precedence over other failures. Obtained results showed that the buckling strength of the steel plate was improved by the effect of the carbon fiber sheet, and the location of buckling was able to be controlled depending on the design of the strengthening. This indicates that strengthening by carbon fiber sheets is quite effective for the retrofitting of steel members such as girder, pier, truss and steel stack.

1 INTRODUCTION

In Japan, the design standards of highway bridges were revised owing to increasing of traffic live load and some huge earthquakes. Therefore, the load capacity of the steel members which constructed before revision of the design standards is not enough. Especially, the strengthening of the buckling resistance is difficult because it is necessary to consider about overall buckling and local buckling. Under such circumstances, a simple and economical strengthening method against buckling of a steel member is desired.

On the other hands, in recent years, a repairing method, which bonds carbon fiber sheet to corroded steel members, has been applied, e.g. Hidekuma et al (2012), Wakabayashi et al (2013) or Nagai et al (2012). The carbon fiber sheet is light weight, high strength and high rigidity, and it has good workability compared with steel plates bolting or welding method. Taking advantage of these benefits, the carbon fiber bonding has been applied to repair of corroded steels. However, the researches about the strengthening against buckling using carbon fiber sheet are not studied. Although, in some papers, e.g. Shaat et al (2013) or Haedir et al (2012), it was studied about the overall buckling of rectangular or circular steel column, the basically research for overall or local buckling is not enough in order to establish the design method of steel member using carbon fiber sheet.

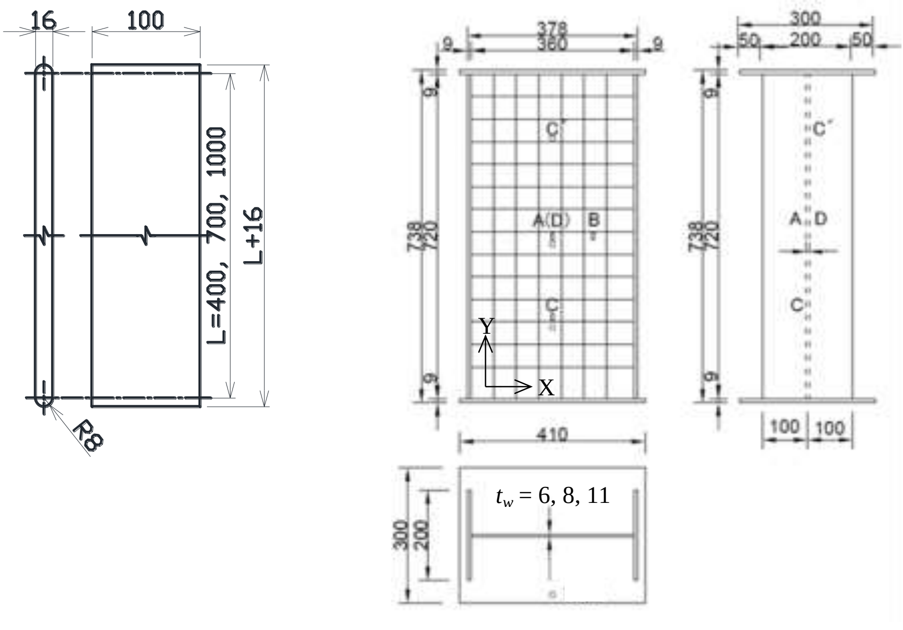
Therefore, in this paper, the buckling behavior of a steel column strengthened by a carbon fiber sheet under axial compression force was studied. Two types of steel column specimens, the overall buckling of simple support column and the local buckling of four sides supporting plate were used. As the overall buckling steel column, the steel plates which have three different length were used. And as the local buckling steel column, the H-shaped section steels which have three different thickness of web plate were used. These specimens were configured such that overall and local buckling took precedence over other failures. A compression test was carried out for specimens that some layer of carbon fiber sheets were bonded on both sides of a steel plate in order to the strengthening effect of carbon fiber sheet on the each specimen.

2 OUTLINE OF TESTS

2.1 Specimen and test method

2.1.1 Overall buckling column

Figure 1 shows the dimension of the column specimens. The length of steel plate model was 400 mm, 700 mm and 1000 mm. The pexis of both ends was simple pin support. Five layers of carbon fiber sheets were bonded throughout its length and width of the both sides, and the direction of carbon fiber sheet was longitudinal of steel plate. The number of layer was same in all strengthened specimens as shown in Table 1. The poly urea putty that has low elastic modulus and high elongation was inserted between steel and carbon fiber sheets in order to improve the debonding resistance. The uniaxial compressive tests of steel plate model as simple support column were conducted as shown in Figure 2.



(A) Steel plate model (B) H-shaped model

Figure 1. Demension of the column specimens.

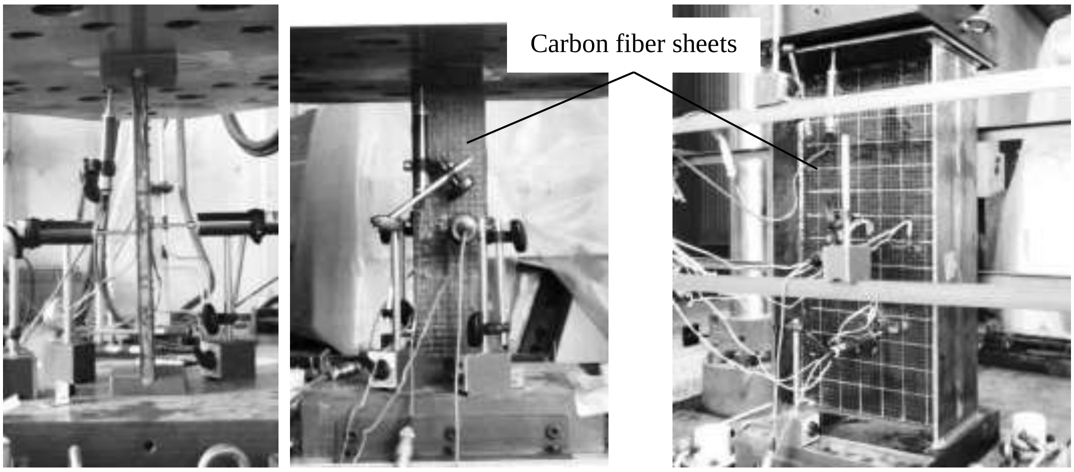
Table 1. Experimental parameter of the column specimens.

(A) Steel plate model

CASE	Length of plate L (mm)	Number of ply
L400-0	400	0
L400-5		5
L700-0	700	0
L700-5		5
L1000-0	1000	0
L1000-5		5

(B) H-shaped model

CASE	Tickness of web t_w (mm)	Number of ply
S6-0	6	0
S6-6		X: 6, Y: 6
S8-0	8	0
S8-6		X: 6, Y: 6
S11-0	11	0
S11-6		X: 6, Y: 6



(A) Steel plate model (simple support) (B) H-shaped model (4-sides suport)

Figure 2. The column specimens under compressive load carring.

2.1.2 Local buckling column

As local buckling column specimens, H-shaped section steels that the end-plates were welded on the both ends were used. The thickness of web plate was 6 mm, 8 mm and 11 mm as show in Figure 1. The dimension of all specimens was same except thickness. Six layer of carbon fiber sheets were bonded all over the both sides of web panel, and the direction of carbon fiber sheet was vertical (Y) and horizontal (X) direction. The number of layer was same in both Y and X direction and they were laminated alternately. The specification of strengthening was same in all strengthened specimens as shown in Table 1. The poly urea putty was also used same as steel plate column. The uniaxial compressive tests of H-shaped column as four sides supporting plate were conducted until buckling occurred as shown in Figure 2.

2.2 Construction procedure and materials

The construction procedure of the carbon fiber sheet system was as follows; grinded the surface of steel with disk grinder, and cleaned the surface with acetone, then applied the urethane primer coating, next applied the poly urea putty to be about 0.8 mm thickness after dry tack of primer, finally bonded the some layer of carbon fiber sheets with epoxy resin after dry tack of putty. And the mechanical properties of steel, carbon fiber sheet and resins are shown in Table 2.

Table 2. Mechanical properties of (A) steel, (B) carbon fiber sheet and (C) resins.

(A) Steel

Thickness	mm	6	8	11	16
Elastic modulus	N/mm^2	2.0×10^5			
Yield stress	N/mm^2	298	301	287	283

(B) Carbon fiber sheet

Elastic modulus	N/mm^2	4.23×10^5
Tensile strength	N/mm^2	4102
Design thickness	mm	0.165

(C) Resins

Resins		Epoxy	Poly urea
Elastic modulus	N/mm^2	-	61
Tensile strength	N/mm^2	64	11
Lap shear strength	N/mm^2	15.7	-
Elongation	%	-	368

3 RESULTS AND DISCUSSION

3.1 Overall buckling column

The maximum load and the increasing ratio of each specimen obtained from compressive load tests were shown in Table 3. Here, the increasing ratio is the value obtained from dividing the maximum load after strengthening by that of non-strengthening of each length. From this table it is found that the maximum load after strengthening was improved more than 60 % compared to non-strengthening specimens. In L400 series, the maximum load increased to nearly full plastic axial force (452 kN).

Figure 3 shows that the relationship between load and vertical displacement of each specimen. The displacement at the maximum load of strengthened specimens was almost twice as large as non-strengthened one. Furthermore, it is found that the rapid drop of load after maximum load did not occur. Normally, when the carbon fiber sheet bonding to steel undergoes the large defamation such as buckling, the debonding of carbon fiber sheet occurs. And then, the debonding leads the rapid drop of load. However, in this test, the debonding did not occur after buckling as shown in Figure 4. This seems to be caused by poly urea putty that has low elastic and high elongation.

Figure 5 shows that the relationship between load and vertical strains of each specimen. The strain gages were attached at both sides of center. In this figure, it is found that the strain increase ratio of strengthened specimens is smaller than that of non-strengthened one. Furthermore, the linear part of strengthened specimens is larger than that of non-strengthened one. When the specimen undergoes bending deformation, linearly increasing strains are divided into a tension side and a compression side. Therefore, the buckling deformation was reduced by the carbon fiber sheet.

Table 3. Maximum load of overall buckling columns

CASE	Maximum load (kN)	Increasing ratio
L400-0	261	-
L400-5	445	1.74
L700-0	146	-
L700-5	252	1.72
L1000-0	70	-
L1000-5	113	1.61

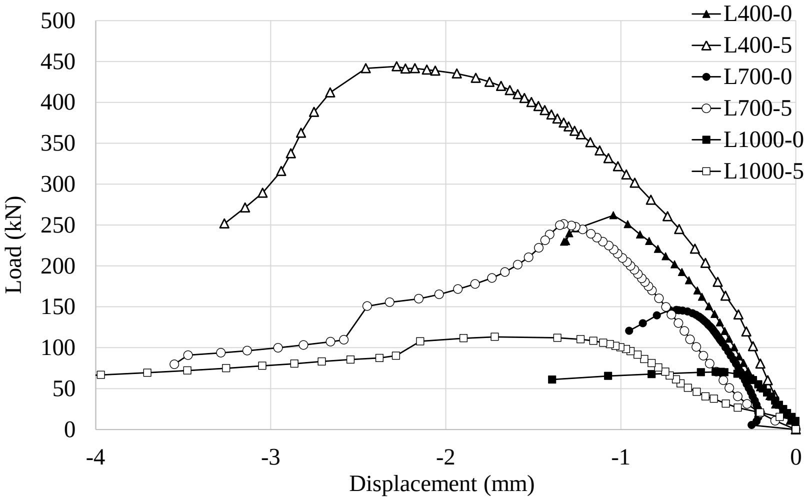


Figure 3. Load – displacement curves of overall buckling column.

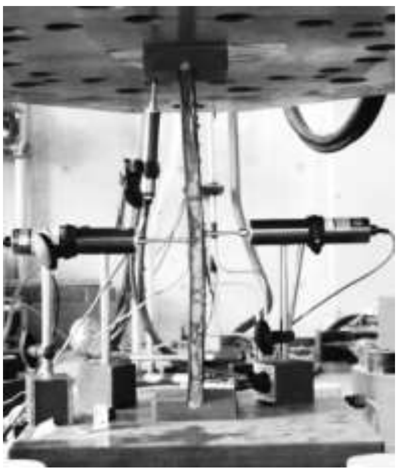
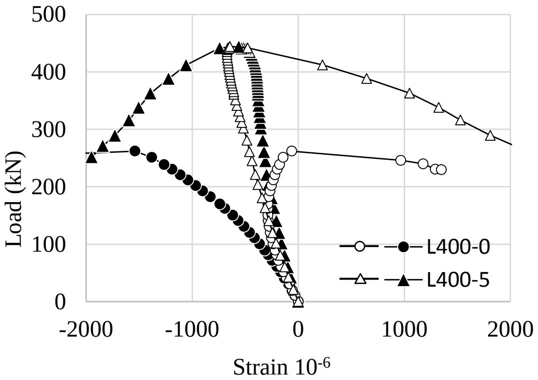
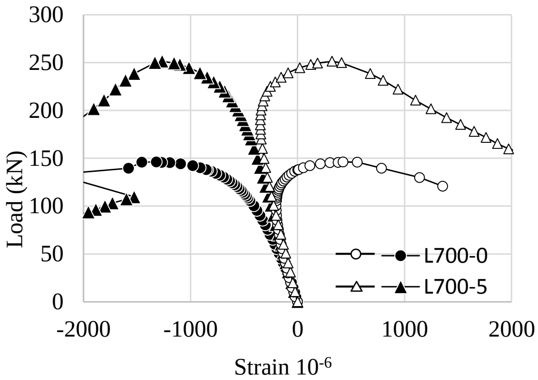


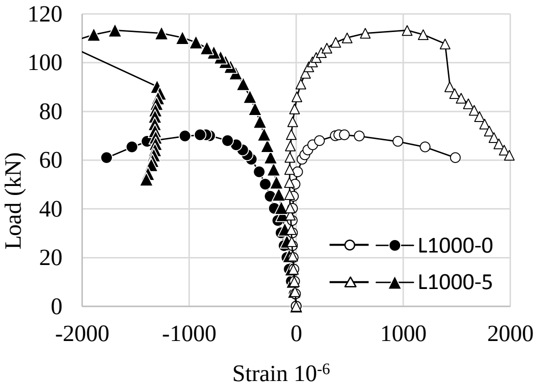
Figure 4. L400-5 after test.



(A) L400 series



(B) L700 series



(C) L1000 series

Figure 5. Load – strain curves of overall buckling column (A) L400, (B) L700 and (C) L1000.

3.2 Local buckling column

The maximum load and the increasing ratio of local buckling column specimens obtained from compressive load tests were shown in Table 4. The increasing ratios were calculated by same method as overall buckling column. From this table, it is found that the maximum loads after strengthening were improved by almost 25% compared to non-strengthening specimens.

Table 4. Maximum load of local buckling column

CASE	Maximum load (kN)	Increasing ratio	Bucklimg load of web (kN)	Increasing ratio
S6-0	1497	-	959	-
S6-6	1858	1.24	1259	1.31
S8-0	1888	-	1154	-
S8-6	2394	1.26	1350	1.17
S11-0	2231	-	1437	-
S11-6	2807	1.26	2138	1.49

Figure 6 shows that the relationship between load and displacement of local buckling columns. In this figure, it is found that there are two points where changed the increase ratio of displacement. The first point was around 1000 to 1500 kN, the second point was near the maximum load. As shown in Figure 7, not only web panel buckling but also flanges buckling occurred after maximum load. First, the web panel buckling occurred at around the one quarter of the height. And then, the flanges buckling occurred with twisting.

Figure 8 shows that the relationship between load and strain of Y direction of S6-0. The four points strain were measured from A to D as shown in Figure 1. In this figure, the strains rapidly changed around 1000 kN. From this data, it can be judged that the web plate buckling occurred at this load. This load agrees with the increase ratio changing point of load – displacement curve of S6-0. The buckling loads of the web panel of other specimens were judged by same method. The buckling loads of the web panel of all specimens and the increasing ratio were shown in Table 4. The web buckling loads after strengthening were improved by almost 32% on average compared to non-strengthening specimens.

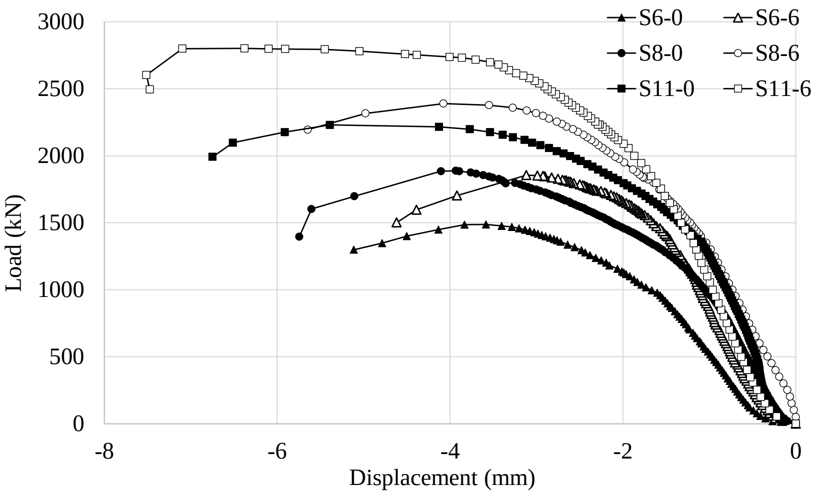


Figure 6. Load – displacement curves of local buckling column.

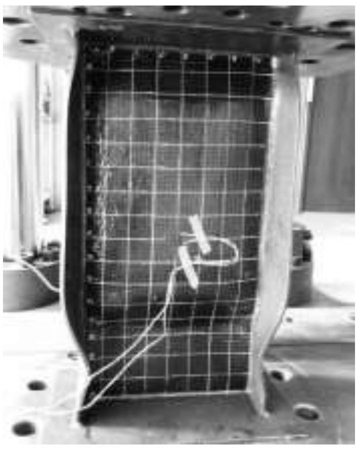


Figure 7. S6-6 after test.

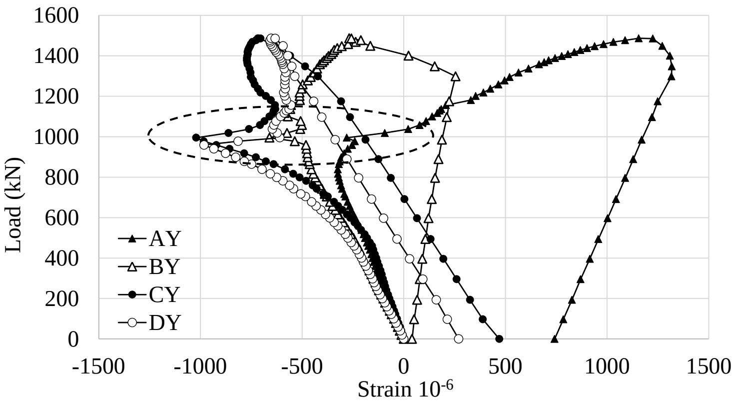


Figure 8. Load – strain curves of S6-0.

4 CONCLUSION

In this paper, the compressive behavior of the overall buckling steel column (simple support) and local buckling steel column (H-shaped section: 4-sides support) strengthened by a carbon fiber sheet under axial compression force was studied. As a result, the following knowledges were obtained.

1) The maximum loads after strengthening were improved greatly in both overall buckling and local buckling columns. In overall buckling column, the buckling load increased by 61 to 74 % with five layers of carbon fiber sheets. In local buckling column, the web buckling load increased by 17 to 49 %, the maximum load increased almost 25 % on average with six layers of carbon fiber sheets bonded in two directions.

2) The no debonding of the carbon fiber sheets occurred in all specimen after buckling deformation. This seems to be caused by poly urea putty that has low elastic and high elongation.

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