SEISMIC PERFORMANCE OF STEEL BRIDGE PIERS WITH CORROSION DAMAGES

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ABSTRACT

Many steel structures have been faced the problem of deterioration in Japan. Severe damages will be caused in such deteriorated structures subjected to huge earthquake. It is necessary to secure safety of such structures against earthquakes. However, 2 dimensional horizontal behavior of seismic response of structures with damages by corrosion has been hardly researched. Therefore, in this study experiments intended for rectangular steel bridge piers with damages by corrosion in the corners were conducted in order to evaluate two-dimensional behavior. It was found that local buckling occurred at not only the stiffened plates but also the corners in the piers which have corrosion at the corners. Therefore, compared with a pier without corrosion, deterioration of strength of the pier with corrosions was remarkable. As a conclusion, suitable maintenance is necessary so that structures may not receive severe damage in huge earthquake.

Keywords: Steel bridge pier, Corrosion damage, Seismic Performance.

1. INTRODUCTION

The earthquake occurs frequently, and huge earthquakes such as Hyogoken-Nanbu Earthquake in 1995 and Niigata Chuetsu Earthquake in 2004 occurred in Japan in recent years. Furthermore, the 9.0-magnitude earthquake inflicted unprecedented damage in Tohoku region in 2011. Many steel structures in Japan were built in the period of rapid economic growth. Most of them have reached the age of aging in recent years. As such steel structures are designed according to the earthquake resistance standards of those days, the seismic performance is low. Damage of such as pier with a low seismic performance is concerned. Figure 1 shows corrosion in the corner of the steel bridge pier. It is important to secure the earthquake resistant safety of the superannuated steel structures during earthquakes. However, judging from a current Japanese financial status, the rebuilding of the steel structures is difficult. Therefore, it is necessary in order to extend its life to maintain corroded

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steel structures (Abe et al., 2007). Studies on seismic behavior of steel bridge pier considering the influence of two horizontal directions have been carried out since Hyogoken-Nanbu earthquake (Watanabe et al., 2000, Nagata et al., 2004, 2006, Goto et al., 2005, 2007, 2009, Aoki et al., 2007). However, studies of corroded steel bridge piers have not been conducted. Therefore, in this study experiments were carried out in order to clarify the behavior of corroded steel bridge piers subjected to horizontal load in two directions.

Figure 1: Corrosion of the steel bridge pier

2. STEEL BRIDGE PIER FOR THIS STUDY

As a steel bridge pier constructed in design criteria before Hyogoken-Nanbu Earthquake, the T-shaped single-column steel bridge pier with rectangular thin-walled hollow sections shown in Figure 2 was assessed. In order to evaluate the seismic performance of such piers having section loss in the corners because of corrosion, a scaled model structure was fabricated for the loading test.

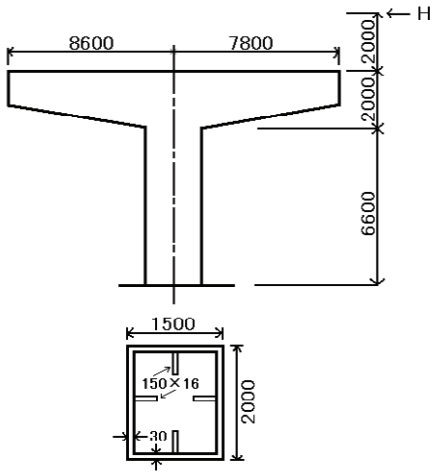


Figure 2: Steel bridge pier (unit: mm)

3. OUTLINE OF THE LOADING TEST

3.1. Material properties

In order to understand the material properties of the specimen, monotonic tensile tests were carried out. Obtained material properties are shown in Table 1.

Table 1: Material properties

Young's Modulus E(N/mm^2)	Yield Stress σ_y(N/mm^2)	Poisson's Ratio ν
2.09×10^5	403	0.282

3.2. Specimens

Specimens scaled down to 1/9 were fabricated. Side view and cross section view of specimens are shown in Figure 3 and Figure 4, respectively. As corroded specimens, plate thickness in the corners was thinned to 1.6 mm from 3.2 mm. Here, the sound specimen is called Model-1, and the specimen with corrosion is called Model-2.

Buckling parameters of this specimen is shown in Table 2. Since this specimen has been designed with reference to the pier has been designed previously Hyogoken-Nanbu Earthquake, it found that these specimens are inferior to the seismic performance.

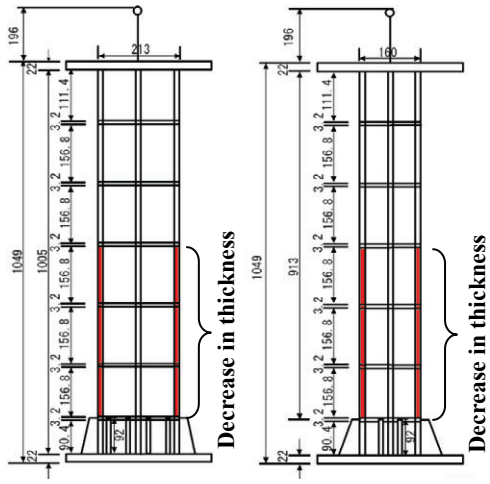
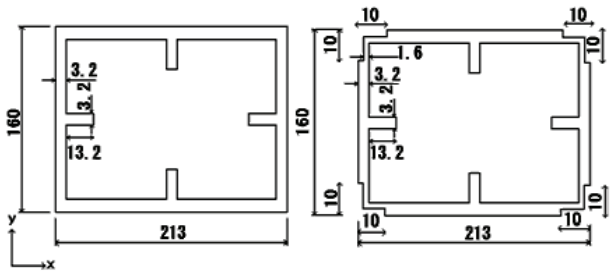


Figure 3: Specimen (unit: mm)



(a) Sound (Model-1) (b) Corroded (Model-2)

Figure 4: Cross section (unit: mm)

Table 2: Buckling parameters

	X direction	Y direction
Width-thickness ratio parameter R_r	0.569	0.762
Width-thickness ratio parameter R_f	0.656	0.766
Slenderness ratio parameter λ	0.388	0.484
Stiffness ratio of longitudinal stiffener γ/γ^*	0.687	0.984

3.3. Three-dimensional testing machine

The testing system utilized in this research is shown in Figure 5 and schematically illustrated in Figure 6. This system, which was developed jointly by Kyoto University and the Shimadzu Corporation, which has nine electrically controlled hydraulic actuators to test the six degrees of freedom of the structures; that is, the displacements in the X, Y, and Z directions of 100 mm and the rotations along the X, Y, and Z axis of 10.3 degrees. The capacity of corresponding loading are 100 kN in the X and Y directions, 500 kN in the Z direction 300 kN (in tension); 100 kN-m for all bending forces. All actuators are synchronized with each other and digitally controlled so as to have an accurate trace of the displacement or force path prescribed in the computer program. The loading frame is also stiff enough to have accurate displacement control.

Figure 5: Three-dimensional testing machine

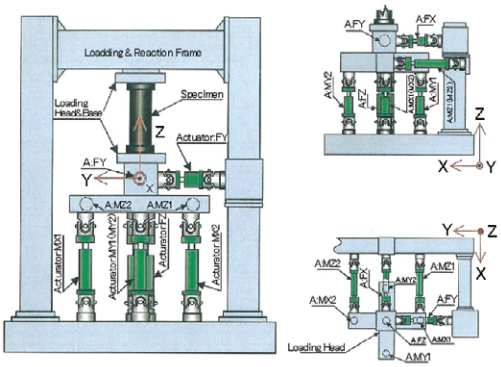


Figure 6: Loading apparatus

3.4. Procedure of the loading test

Procedure of the loading test is shown in Figure 7. First, the axial force of 15% of yield axial force was loaded by load control. Next, torsion of approximately 80% of torsional yield was loaded by displacement control. Then, the bending was loaded by horizontal cyclic bi-directional Loading by displacement control. Here, horizontal cyclic bi-directional Loading shown in Figure 8 was carried out. Initial horizontal yield displacement δ_y and load H_y are shown in Table 3.

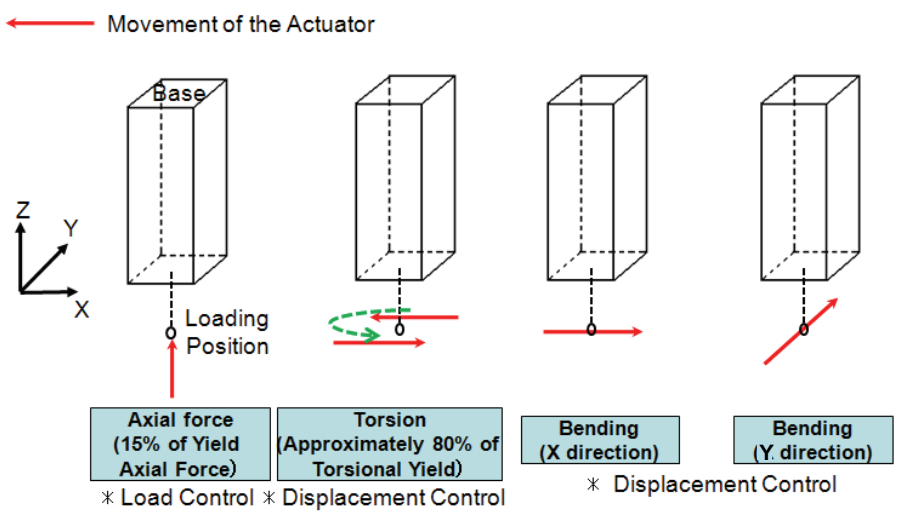


Figure 7: Loading procedure

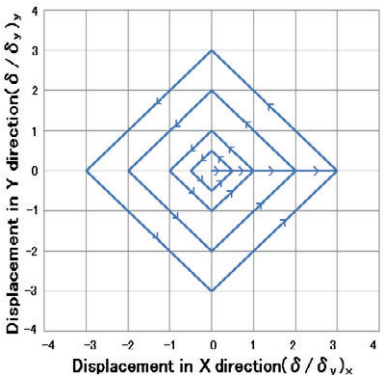


Figure 8: Loading path

Table 3: Horizontal yield displacement δ_y and load H_y

	δ_y(mm)	H_y (kN)
X direction	6.53	47.7
Y direction	8.69	40.6

3.5. Overview of the loading test

Overview of loading test is shown in Figure 9. Displacement transducers were used to control external displacement in order to experiment with high accuracy. Additional deformation of base of column was removed by displacement transducers attached to crossed angles from base of column.

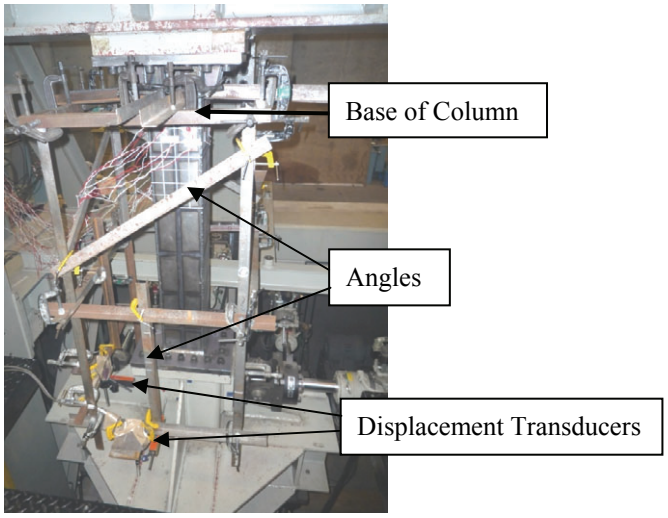


Figure 9: Overview of the loading test

4. OUTLINE OF ELASTO-PLASTIC FINITE DISPLACEMENT ANALYSIS

4.1. Analytical model

In order to perform the parametric analysis, the test results are compared with those obtained by the elasto-plastic finite displacement analysis using a general-purpose FEM code called ABAQUS. The discretization of a steel bridge pier model is shown in Figure 10.

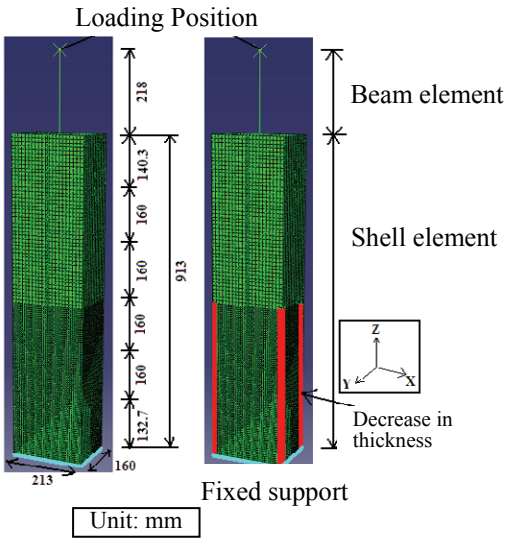


Figure 10: Analytical model

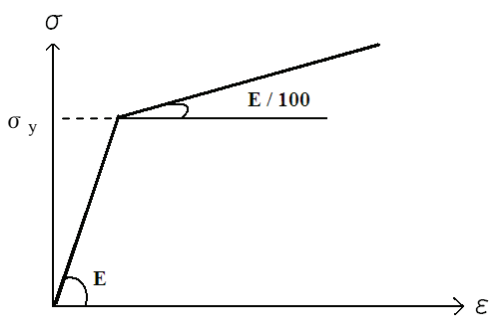


Figure 11: Stress-strain relationship

In order to evaluate the local buckling of a thin-walled section, special care must be taken regarding the size of the shell elements; namely, finer at the base of the bridge pier column. The shell

elements with 4 nodes are used with reduced numerical integration. All the displacements along the cross section at the column base are fixed, and the horizontal displacement at the top of the column in the X and Y directions is pre-specified just as in the loading test.

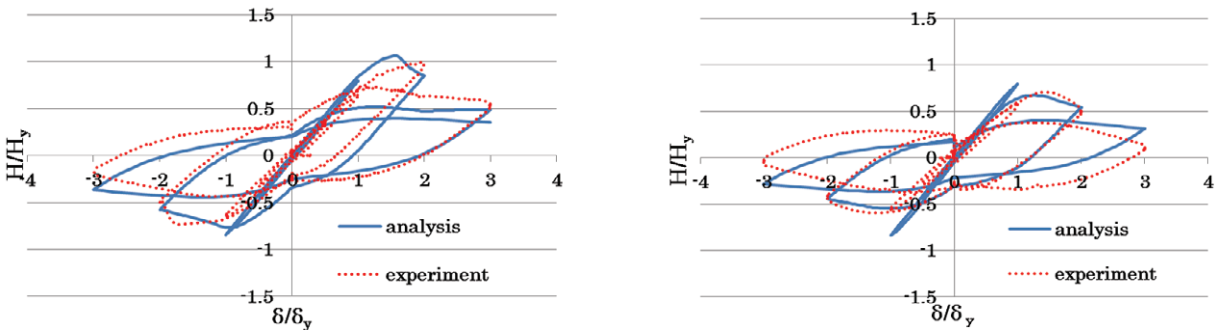
4.2. Material properties and initial imperfections

The material properties are input according to the material test results given in Table 1, and the constitutive relation of steel is assumed to be modeled by the associated flow rule in conjunction with the von-Mises yield criterion and kinematic hardening rule. Stress-strain relationship which was used in the analysis is shown in Figure 11. The initial imperfections, such as the initial out-of-plane deflection of the thin plate and residual stress in the thin plates, are not considered.

5. ASSESSMENT FOR STEEL BRIDGE PIERS WITH CORROSION DAMAGES

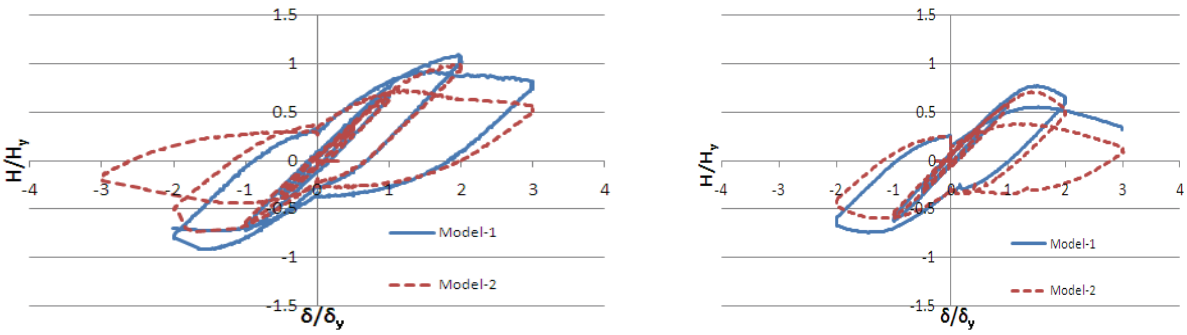
5.1. Load-displacement curves by the experiment and the analysis

Load-displacement curves obtained by the experiment and the analysis are shown in Figure 12 (Model-2(Corroded)). The results of the experiment and analysis are generally consistent in these figures. Therefore, the validity of the experiment and the analysis in this study is confirmed.



(a) X direction **(b) Y direction**

Figure 12: Load-displacement curves (Model-2(Corroded))



(a) X direction **(b) Y direction**

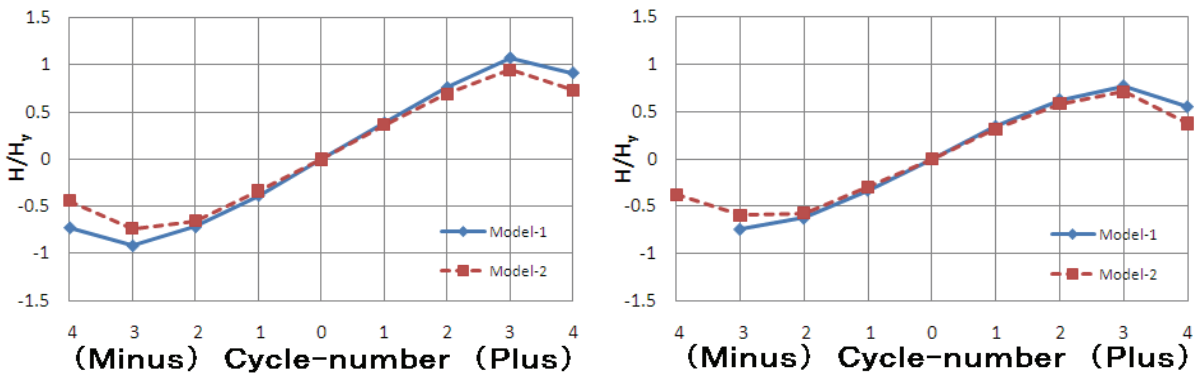
Figure 13: Load-displacement curves (Experiment)

5.2. Comparison between Model-1(Sound) and Model-2(Corroded)

Load-displacement curves in X direction and Y direction obtained by the experiment are shown in Figure 13 (a) and (b), respectively. It is found that the difference of Model-1 and Model-2 is small until 1δy. It is also found that maximum load of Model-2 is low 10% in comparison with Model-1. Moreover, decrease in load is remarkable in Model-2 compared to Model-1 after maximum load.

5.3. Envelope curves

Envelope curves in X direction and Y direction obtained by the experiment are shown in Figure 14 (a) and (b), respectively. Until maximum load the difference is small, the difference becomes larger after maximum load. It is proven that cross-section loss due to corrosion affects load-carrying capacity.

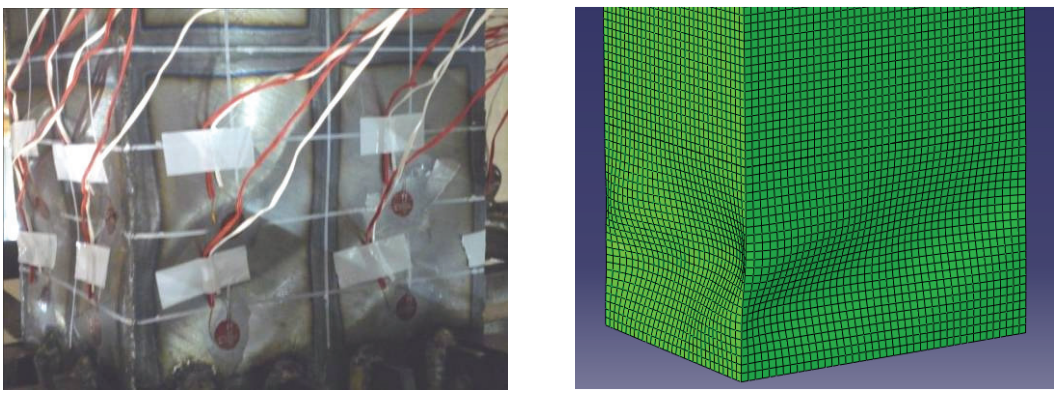


(a) X direction **(b) Y direction**

Figure 14: Envelope curves (Experiment)

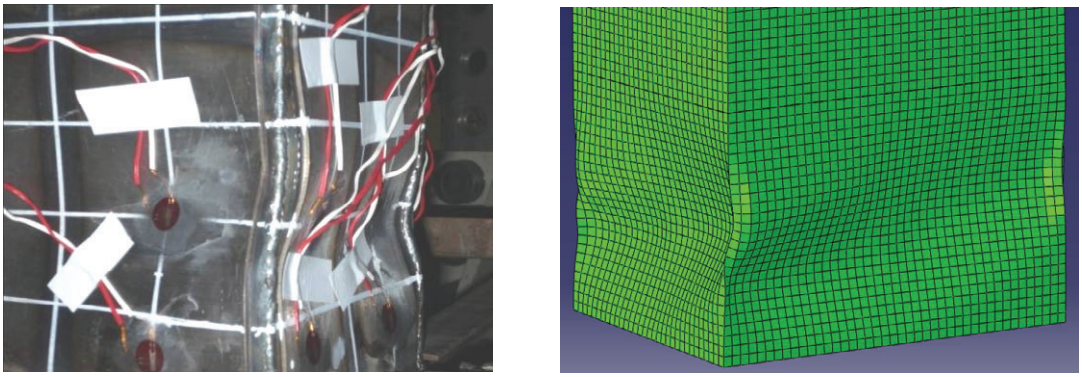
5.4. Damages of columns

Damages of columns after loading are shown in Figure 15 and 16, respectively. Local buckling was observed in plates in Model-1. Local buckling was observed in the corners in addition to the plates in Model-2. The progress of damages of Model-2 was earlier than Model-1 due to local buckling in the corners.



(a) Experiment **(b) Analysis**

Figure 15: Damage of column (Model-1(Sound), after loading)



(a) Experiment **(b) Analysis**

Figure 16: Damage of column (Model-2(Corroded), after loading)

6. CONCLUSIONS

In this study experiments and analyses for rectangular steel bridge piers with damages by corrosion in the corners were conducted in order to evaluate two-dimensional behavior. It was found that local buckling occurred at not only the stiffened plates but also the corners in the piers which have corrosion at the corners. Therefore, compared with a pier without corrosion, deterioration of strength of the pier with corrosions was remarkable. As a conclusion, suitable maintenance is necessary so that structures may not receive severe damage in huge earthquake.

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