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RESIDUAL STRENGTH OF DAMAGED STEEL BRIDGE PIER WITH CIRCULAR CROSS SECTION AND ITS REPAIR METHOD

Moriaki Suzuki[1)], **Yoshiyuki Shimaguchi**[2)] **and Tetsuhiko Aoki**[3)]

1) Associate Professor, Department of Civil Engineering, Aichi Institute of Technology, Japan
2) Graduate Student, Graduate School of Engineering, Aichi Institute of Technology, Japan
3) Professor, Department of Civil Engineering, Aichi Institute of Technology, Japan
suzuki-moriaki@aitech.ac.jp, f09703ff@aitech.ac.jp, aoki@aitech.ac.jp

Abstract: After HYOGOKEN-NANBU Earthquake in 1995 at Kobe, Japan, many researches for seismic resistance design have become actively. Especially seismic resistance design researches of steel bridge piers tend to how to strengthen them to against to severe earthquakes. For example, researches of improving the strength and the ductility by strengthen the cross section and proportion or by applying high performance materials, such as low yield steel, and so on.

But, most of the above researches are only for new bridge piers or constructed by old design codes, and these piers are not experienced severe damages caused by earthquakes. Therefore there is no guideline about repairing methods for damaged steel bridge piers. And there is no assessment techniques retrofitted piers are established until now.

In this study, firstly, we introduce repairing methods for local buckled of steel bridge piers after cyclic loading experiments. We prepared 6 damaged steel pier specimens, which had elephant foot bulge buckling at the bottom of pier, and repair them by filling concrete inside. After repairing, perform cyclic loading experiments are conducted under same load sequence, and by comparing the seismic resistance capacity between before and after repaired to discuss the reliability of repairing methods.

1. INTRODUCTION

After severe earthquake it generally needs large amount of cost and time to reconstruct infrastructures such as bridges. It is very important topics to make sure of rescue action. In Japan, many elevated bridges have been constructed in large city which have steel bridge piers. Once these kinds of infrastructures have been damaged under severe earthquake and it will make immeasurable social loss. For example, in HYOGOKEN-NANBU Earthquake in 1995 at Kobe, Japan, it takes more than one year to repair and reconstruct the highway before reopen.

Many steel bridge piers using as elevated highway bridges have circular cross section. Because which have advances on isotropic bending capacity and slenderness appearance in comparison with rectangular cross section. But after earthquake, many damages such as elephant foot bulge buckling and cracks have observed on circular cross section piers at the bottom of piers. Many researchers have been conducted to improve strength and ductility or strengthen cross section and proportion by applying high performance materials and so on. But, the subjects of these researches are only for new bridge piers or constructed bridges designed by old design codes, which have not experienced severe damages in earthquakes. Therefore, there is no guideline about repair method for damaged piers. And no assessment techniques retrofitted piers are established until now.

In this study, firstly, we introduce repairing methods for local buckled of steel bridge piers after cyclic loading experiments. We prepared 6 damaged steel pier specimens, which had elephant foot bulge buckling at the bottom of pier, and repair them by filling concrete inside. After repairing, perform cyclic loading experiments are conducted under same load sequence, and by comparing the seismic resistance capacity between before and after repaired to discuss the reliability of repairing methods.

2. SPECIMEN AND EXPERIMENT SETUP

2.1 Specimen

Table 1 shows the specifications of specimens and Figure 1 shows the general shape and cross section of specimen. And these specimens are about 1/4 scale down model from real structure. The Diameter D=600mm and the height of specimen h(=2890mm) is from bottom to loading point. These specimens have prepared for our previous experiments (Susantha et al. 2005, Hattori et al. 2006). In this table, "NC" of the specimen name means "No Core", and "CR" means "CoRe column" as previous experiment.

In this study 6 specimens have been repaired and do the same experiment, which will be described later.

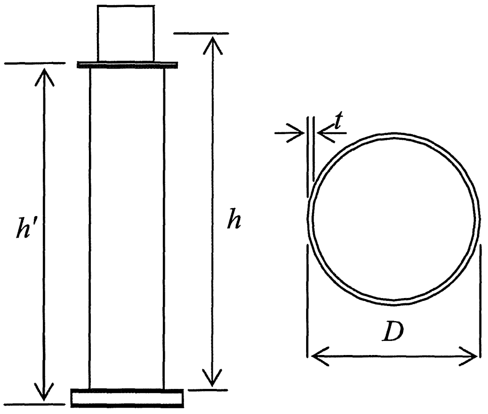
Table 1 General information of specimens (Susantha et al. 2005, Hattori et al. 2006)

Specimen Name (Former exp.)	R4.5-NC/CR	R6.0-NC/CR	R12.0-NC/CR
Specimen Name (Repaired in This Study)	C1.5D-T4.5A C1.5D-T4.5B	C1.5D-T6.0A C1.5D-T6.0B	C1.5D-T12.0A C1.5D-T12.0B
Material	SS400		
Diameter : D (mm)	600		
Thickness: t (mm)	4.26	5.90	11.9
Loading Height: h (mm)	2890		
Specimen Length: h' (mm)	2600		
Moment of Inertia: I (mm^4)	3.534×10^8	4.859×10^8	9.509×10^8
Diameter Thickness Parameter: R_t	0.190	0.137	0.053
Slenderness Ratio Parameter: λ	0.351	0.354	0.316
Yield Lateral Load: Hy(kN)	118.5	158.5	250.7
Yield Lateral Displacement: δy(mm)	12.8	12.9	10.1

2.2 Experiment Setup

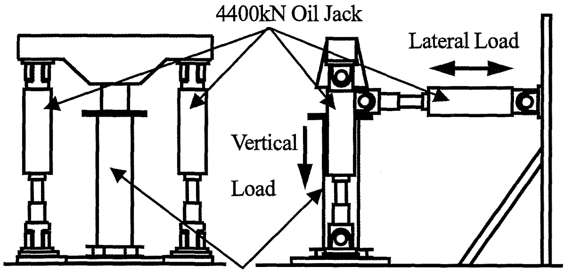
Figure 2 and Photo 1 shows the setup of the experiments. Vertical load is supplied by two 4400kN oil jacks connecting in a loading beam and horizontal load is supplied by one 4400kN oil jack.

In this study cyclic loading sequences have been selected. Figure 3 shows the details of loading sequences.



(a)Front View (b) Cross Section

Figure 1 General shape of Specimen



(a) Front View (b) Side View

Figure2 Experiment Setup

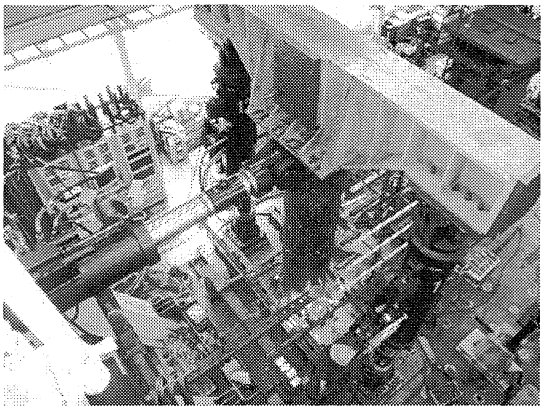


Photo 1 Experiment Setup

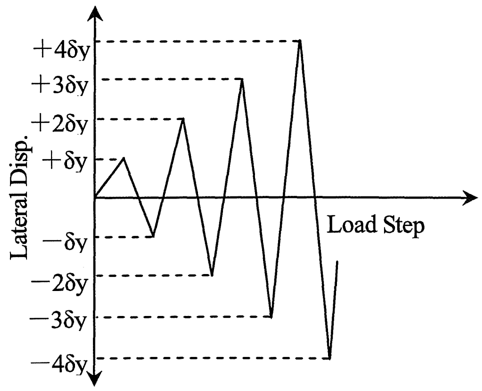


Figure 3 Loading Sequence

3. RESIDUAL STIFFNESS AND REPAIR METHOD

3.1 Damage Size and Residual Stiffness

Before the repair process, buckling damage size and residual stiffness are measured. Table 2 shows the size of damages about elephant foot bulge buckling for all specimens. Figure 4 shows the general positions of buckling damages. The residual stiffness is also measured, and both the initial and the residual stiffness are listed in Table 3. In this table, the initial stiffness indicates the strength of brand new specimen. That is, these values were obtained from former previous experiments (Susantha et al. 2005, Hattori et al. 2006). On the other hand the residual stiffness is obtained from damaged specimens. That is, the strengths obtained from the specimens before repair. And the set up of this experiment is the same system as former experiments.

From these Tables and Figure, the damages of specimens have a correlation of stiffness ratio with radius of curvature (see in Figure 5).

3.2 Repair Method

In this study the concrete-filled repair method is selected as following reasons (see Figure 6).

1) Concrete-filled column experiments for seismic retrofit have been performed in many research institutes. And the diaphragms welded inside the column have an important part in seismic performance. 2) The filled height of concrete is more effective in comparison with the concrete strength. 3) Too much amount of filled concrete will sometimes increase the strength too much. 4) Some of the material of old steel bridge piers do not suit for welding.

The purpose of this study is, recovering the stiffness to the same level as new specimen but not increasing the strength too much. And the desirable maximum strength is ±10% different from the value of a new specimen. In addition, the time cost in repairing work will not take long. Therefore, in this study Concrete-filled repair method and the height of filling in 1.5D are adopted. Table 4 shows the strength of specimens filled by concrete (Suzuki et al.1998, 1999, 2005, Morishita et al. 2000, Imanaka et al. 2004).

Table 2 Size of Damages

Specimen	Buckling Size		Radius of Curvature		
	hb (mm)	Bb (mm)	ρt (mm)	ρm (mm)	ρb (mm)
C1.5D-T4.5A	100.3	14.5	43.7	23.8	30.0
C1.5D-T4.5B	116.3	16.0	23.9	19.7	18.7
C1.5D-T6.0A	98.8	17.0	19.6	18.7	31.6
C1.5D-T6.0B	89.1	30.0	20.5	13.9	17.5
C1.5D-T12.0A	116.6	20.0	43.7	34.1	70.1
C1.5D-T12.0B	109.7	33.0	40.3	29.5	45.2

Table 3 Initial and Residual Stiffness

Specimen	Initial Stiffness	Residual Stiffness	Stiffness Ratio
	K_0 (kN/mm)	K (kN/mm)	K/K_0
C1.5D-T4.5A	8.18	5.11	0.625
C1.5D-T4.5B	8.18	3.72	0.454
C1.5D-T6.0A	10.6	5.77	0.544
C1.5D-T6.0B	10.6	4.45	0.419
C1.5D-T12.0A	18.6	14.2	0.766
C1.5D-T12.0B	18.6	10.9	0.588

Table 4 Strength of Filled Concrete

Specimen	Strength of filled concrete (N/mm^2)
C1.5D-T4.5A	30.7
C1.5D-T4.5B	34.0
C1.5D-T6.0A	35.4
C1.5D-T6.0B	26.3
C1.5D-T12.0A	34.3
C1.5D-T12.0B	27.2

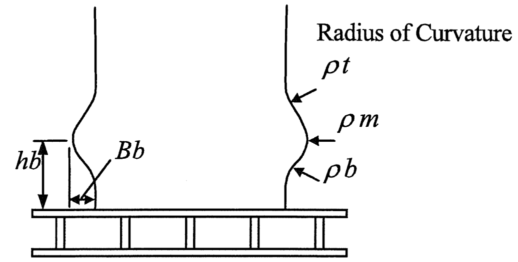


Figure 4 Schematic Drawing of Damages

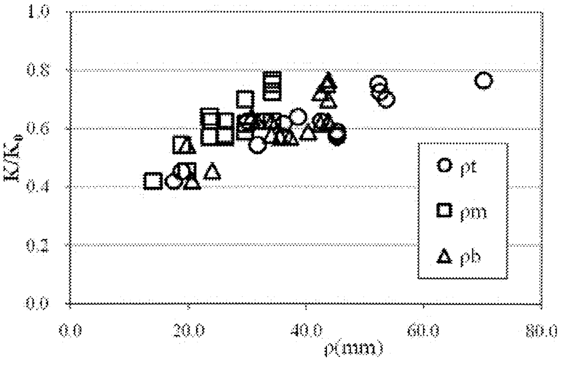


Figure 5 Stiffness Ratio - Radius of Curvature Relationship

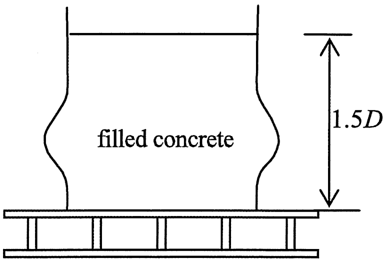
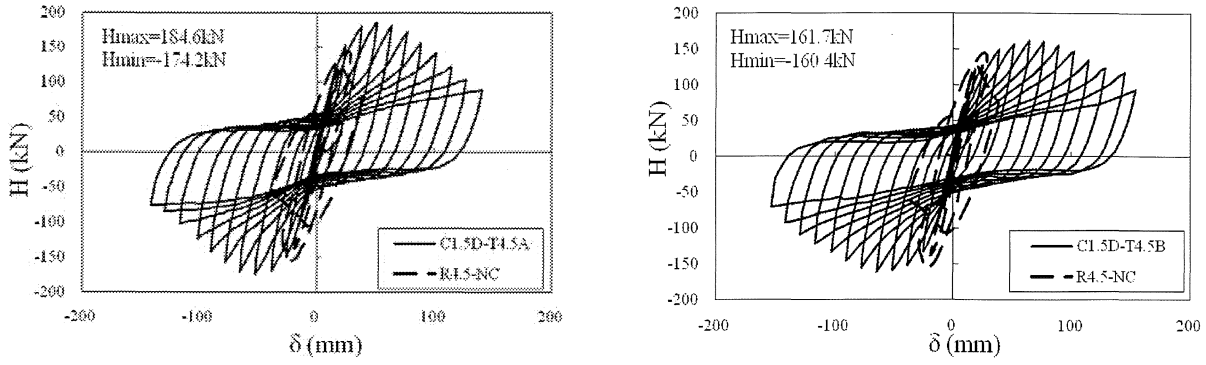
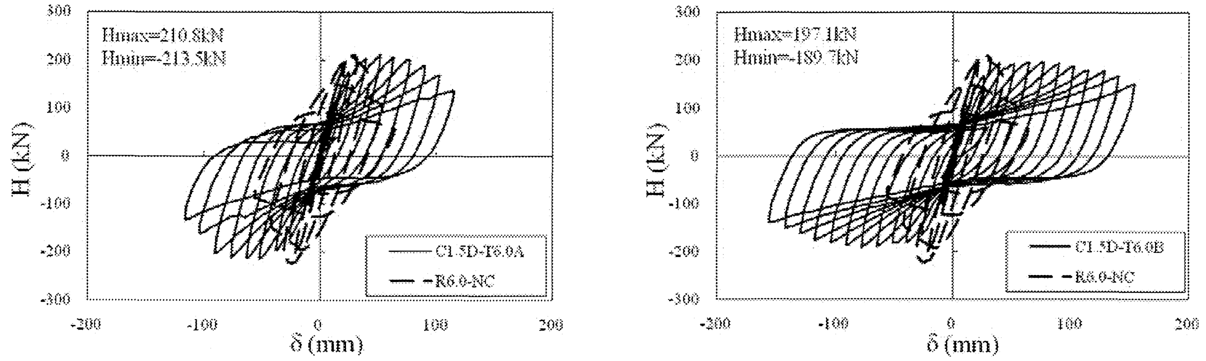


Figure 6 Concrete-Filled Repair



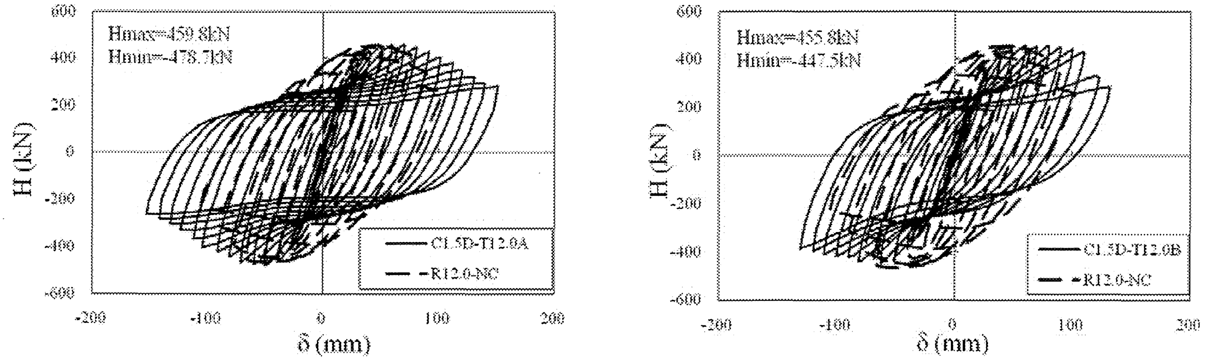
(a) C1.5D-T4.5A

(b) C1.5D-T4.5B



(c) C1.5D-T6.0A

(d) C1.5D-T6.0B



(e) C1.5D-T12.0A

(f) C1.5D-T12.0B

Figure 7 Lateral Load-Displacement Relationships

4. RESULTS

4.1 Load-Displacement Relationship

6 repaired specimens have tested by same load sequence as previous mentioned cyclic loading (see Figure 3). The horizontal load–displacement relationships are shown in Figure 7. Vertical axis represents the lateral load and horizontal axis represents the lateral displacement. The solid hysteresis curves are the results of this study's repaired series experiments and broken lines are the results of former new series experiments.

In these figures all the hysteresis curves of repaired specimens show very stable behaviors, especially after the maximum load, in comparison with the original former experiments.

4.2 Envelope Curve

Normalized envelope curves are shown in Figure 8. Vertical axes are normalized by each yield lateral load Hy shown in Table 1 and horizontal axes are normalized by each yield lateral displacement δy corresponding to experimental yield loads listed in Table 1. Normalized maximum lateral loads (Hmax/Hy) are listed in Table 5. And the normalized lateral displacement, which correspond to maximum lateral load (δmax/δy) are listed in Table 6. From these figures and tables, maximum lateral load of C1.5D-T4.5A increases about 20% from the value of former experiment. The maximum lateral loads of other specimens are no more than 10% different with former experiments. The maximum lateral load of repaired specimen appears at around after 4δy, which is about more than twice of former experiments, except in the cases of t=12.0mm (specimen C1.5D-T12.0A and C1.5D-T12.0B). In these cases the maximum loads appear at about 20% larger than former experiments. And it was observed that all lateral loads of repaired specimens would not decrease immediately after maximum lateral load.

4.3 Energy Absorption Capacity

Normalized energy absorption capacity E/Ee for each cycle is shown in Figure 9. Vertical axes are normalized by Ee(=Hyδy/2). As can be seen in these figures, except in the cases of t=12.0mm, energy absorption capacities of repaired specimens are larger than former experiments. But in cases of t=12.0mm, energy absorption capacity of repaired specimens are about half of former experiment.

4.4 Ductility Factor

The results of ductility factor are shown in Table 7. Ductility factor is one of the most important factors that indicate seismic resistance capacities. In this study ductility factor μ95 is defined by Figure 10 and Equation (1). Here H95 is 95% of maximum lateral load after maximum load. δ95 is lateral displacement correspond to H95. From this result all the ductility factor increased, in case of t=4.5mm and t=6.0mm the ductility factor increased from around 2 to more than 5 and in case of C1.5D-T12.0B it increased more than 10.

$$\mu 95 = \delta 95 / \delta y \qquad (1)$$

Table 5 Normalized Maximum Lateral Load

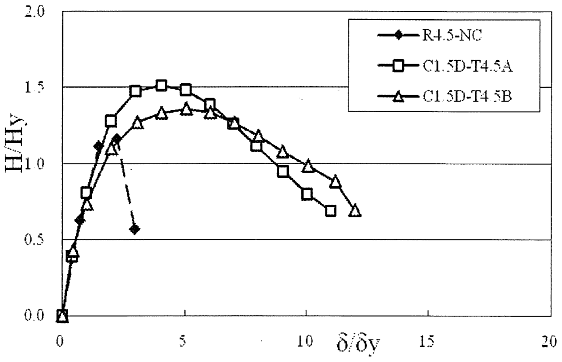
Specimen	Former (Hmax/Hy)	Repaired (Hmax/Hy)	Repaired/ Former
C1.5D-T4.5A	1.27	1.51	1.19
C1.5D-T4.5B	1.27	1.36	1.07
C1.5D-T6.0A	1.37	1.34	0.98
C1.5D-T6.0B	1.37	1.22	0.89
C1.5D-T12.0A	1.84	1.86	1.02
C1.5D-T12.0B	1.84	1.80	0.98

Table 6 Normalized Maximum Lateral Displacement

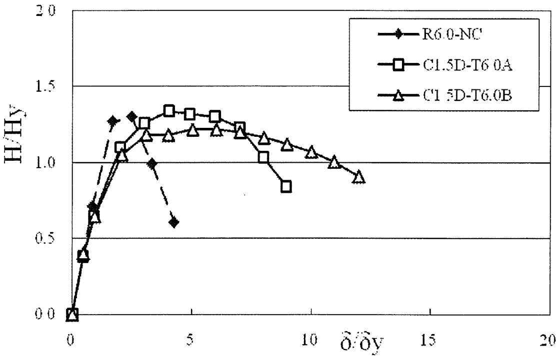
Specimen	Former (δmax/δy)	Repaired (δmax/δy)	Repaired/ Former
C1.5D-T4.5A	1.84	4.02	2.18
C1.5D-T4.5B	1.84	5.04	2.73
C1.5D-T6.0A	1.96	4.02	2.05
C1.5D-T6.0B	1.96	5.97	3.05
C1.5D-T12.0A	4.42	5.47	1.24
C1.5D-T12.0B	4.42	6.05	1.37

Table 7 Ductility Factor μ95

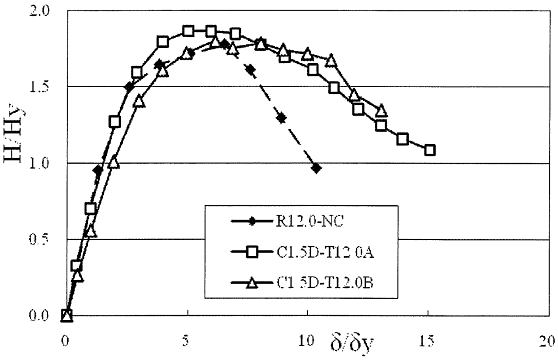
Specimen	Former	Repaired	Repaired/ Former
C1.5D-T4.5A	2.17	5.49	2.52
C1.5D-T4.5B	2.17	6.66	3.06
C1.5D-T6.0A	2.46	6.37	2.59
C1.5D-T6.0B	2.46	8.09	3.29
C1.5D-T12.0A	6.67	7.93	1.19
C1.5D-T12.0B	6.67	10.03	1.50



(a) t= 4.5mm

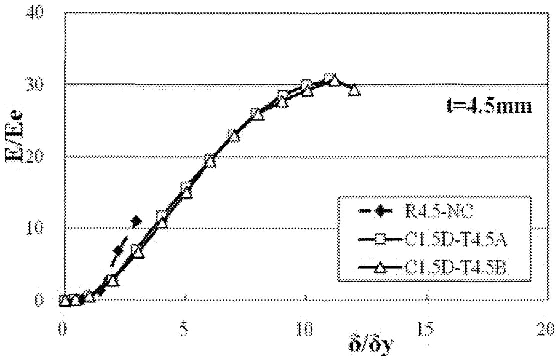


(b) t= 6.0mm

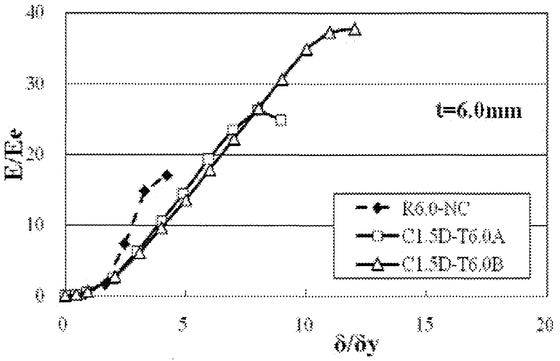


(c) t= 12.0mm

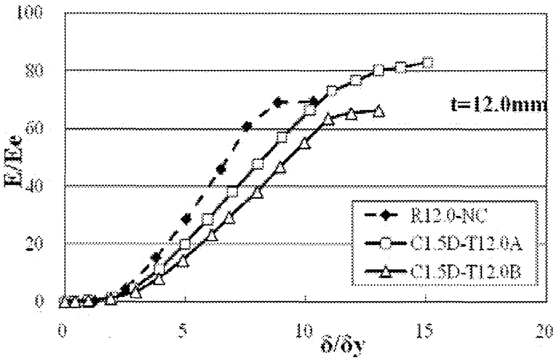
Figure 8 Envelope Curve



(a) t= 4.5mm



(b) t= 6.0mm



(c) t= 12.0mm

Figure 9 Energy Absorption Capacities

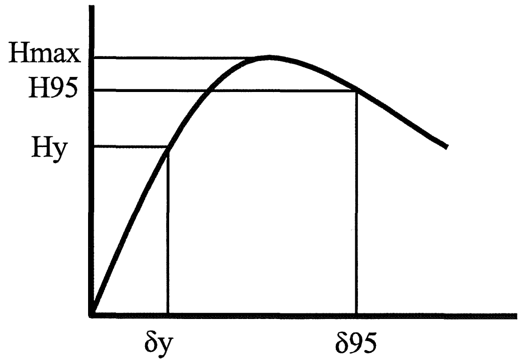


Figure 10 Definition of Ductility Factor

5. CONCLUSIONS

In this study cyclic loading tests are conducted in repaired steel bridge piers which have been damaged by loading test conducted in former researches. The conclusions are listed as below.

1) Simple Concrete-filled repair method, suggested in this study, is very effective.

2) Damage parameters such as Stiffness Ratio - Radius of Curvature have correlations with repair method.

3) All repaired specimens have good performance for maximum lateral load and energy absorption capacity in comparison with previous experiment.

4) The ductility factor increased from about 2 to more than 5, and in case of C1.5D-T12.0B it increased more than 10.

5) This repair method conducted in this study is very simple and easy method, and which have very good performances.

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