# SEISMIC STRENGTHENING OF PIERS WITH PARTIAL USE OF HIGH DUCTILITY CEMENT

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## Abstract

It has been known that the ductility of bridge piers can be improved if they are constructed of high ductility cement, but the use of this cement is not so widespread because of cost problems. To find the most efficient use of this material for seismic strengthening of bridge piers, the authors performed a loading test using specimens with varying cover concrete thicknesses. From the experiment, it was found that if the cover concrete of a pier is constructed of high ductility cement, it can provide a horizontal confinement effect as much as the pier whose entire cross section is constructed of this material. The deformation capacity and the energy absorption capacity will also be significantly improved compared with a pier constructed of ordinary concrete.


## 1. Introduction

It has been known from past researches that addition of high ductility cement to reinforced concrete (RC) structures will improve not only seismic resistance but also durability. However, its use is not so widespread for technical and economic reasons. Technically, both production of cement and its application to structures require special equipment. Economically, this cement is more expensive than ordinary concrete because of use of fibers.

In the Japanese Specifications for Highway Bridges: Seismic Design, the cover concrete is ignored when calculating the ultimate strength of ordinary RC piers, assuming that it is unable to carry the stress in the ultimate stage by spalling off from the pier. But, we considered that if the cover concrete is constructed of high ductility cement, it will suffer little damage and can carry the stress even in the ultimate stage. Based on this concept, our study aimed to confirm that the seismic resistance of RC piers can be improved by the partial application of high ductility cement, namely, to the cover concrete area of the pier. The parameter adopted was the application thickness of high ductility cement.

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## 2. Evaluation by Calculation

### 2.1 Attributes of specimens

Figure 1 and Table 1 show the configuration and attributes of specimens, respectively. The specimen was constructed to 1/8 scale of an ordinary RC single column pier. The main reinforcement ratio and the hoop tie ratio were identical to those of ordinary piers. The specimens were designed to fail by bending.

Table 2 shows the cross sections studied. No. 1 is the control type with its entire cross section constructed of ordinary concrete. No. 2 has a cross section constructed of high ductility cement. In No. 3～No. 5, high ductility cement was applied to the cover concrete area only, but their application thickness varied. These specimens were intended to compare the effectiveness of the cover concrete and the behavior of the compressive range near the main reinforcement.

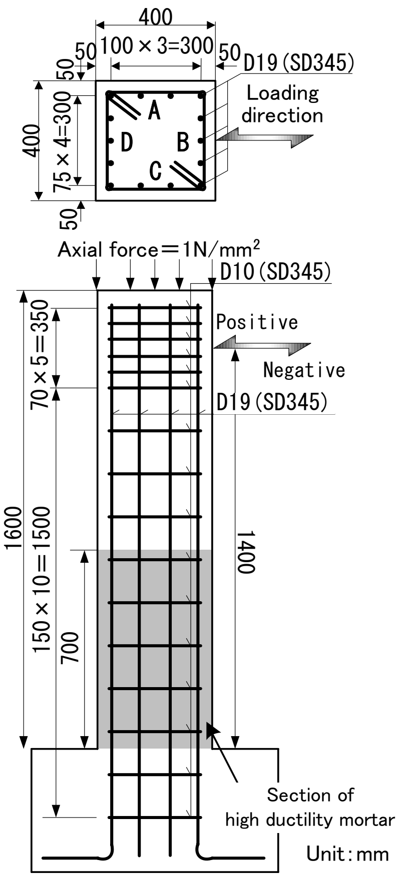
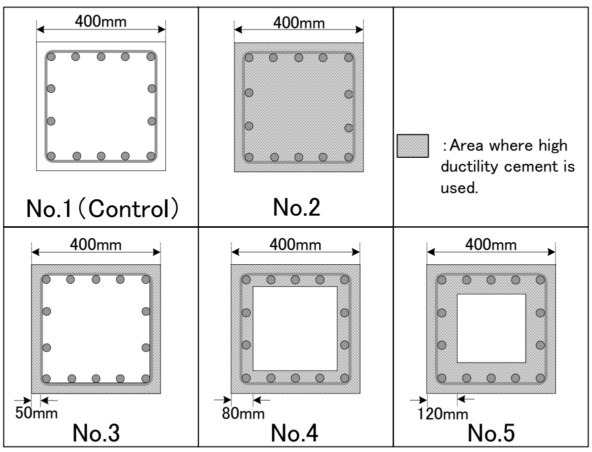



Fig. 1. Configuration of specimen

Table 1. Attributes of specimen

| | | | |
|---|---|---|---|
| Cross section[mm] | | 400×400 | |
| Thickness[mm] | | 50 | |
| Shear span[mm] | | 1400 | |
| Shear span ratio[mm] | | 4.0 | |
| Concrete strength [N/mm$^2$] | High ductility type | 56.9(Cal.) | 80.8(Exp.) |
| | Ordinary type | 27.0(Cal.) | 24.8(Exp.) |
| Main reinforcement | Steel | SD345 | |
| | Diameter | D19 | |
| | Tensile rein. ratio[%] | 1.43 | |
| Hoop tie | Steel | SD345 | |
| | Diameter | D10 | |
| | Spacing[mm] | 150 | |
| | Vol. ratio[%] | 0.63 | |
| Compressive stress[N/mm$^2$] | | 1.0 | |

Table 2. Cross sections studied

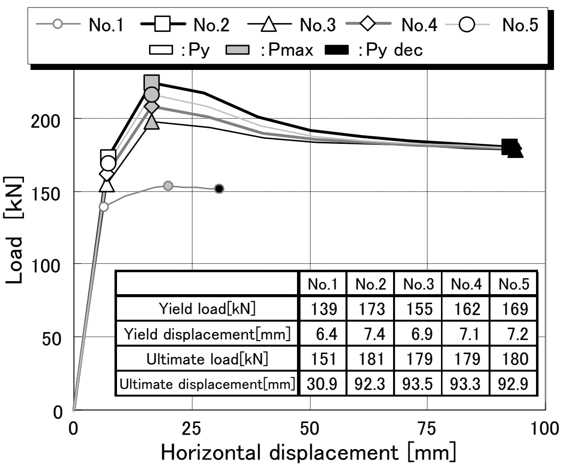


## 2.2Calculation method

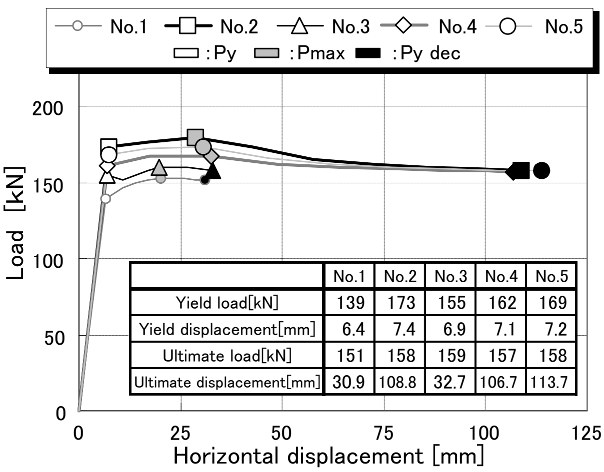
For comparison with experimental results, the ultimate strength of columns was calculated in accordance with the Japanese Specifications for Highway Bridges: Seismic Design [1]. Although the cover concrete is ignored in this specification, it was taken into account in the current calculation, assuming that the cover concrete constructed of high ductility cement could carry the stress even in the ultimate stage [2].The stress-strain relationship on the tensile side was also taken into account, assuming that the high ductility cement used could also carry the stress on the tensile side [2]. The ultimate strain was defined as the strain at the time the stress decreased to 50% of the maximum compressive stress. This is based on the research results that a value very close to an actual ductility factor could be obtained from the evaluation at the time of 50% decrease [3].

## 2.3 Calculation results

Figure 2 shows the load-displacement (P- δ )relationship obtained from calculation for the two cases when the cover concrete was and was not taken into account. The maximum load increased by 10 to 20 % when the cover concrete was taken into account. In Specimens No. 2, No. 4, and No. 5, there was no difference in the ultimate displacement regardless of the cover concrete being taken into account or not. But, in Specimen No. 3, the difference was about 50 mm. This is because, in the case of this specimen, ignoring the cover concrete means ignoring all the range constructed of high ductility cement, leads to small deformation capacity.




a) When the cover concrete thickness is taken into account




b) When the cover concrete thickness is ignored

Fig. 2. P-δ relationship by calculation

## 3. Experimental program

From the calculation results, it is predicted that if high ductility cement is applied up to inside the main reinforcement on the cross section, the deformation capacity will be improved regardless of inclusion or exclusion of the cover concrete in the capacity evaluation. Based on this, three specimens were chosen for the loading test: No. 1 which is the control specimen with its entire cross section constructed of ordinary concrete; No. 2 whose entire cross section is constructed of high ductility cement; and No. 4 which contains the smallest amount of high ductility cement among the specimens presumed to have seismic strengthening effect.

To produce high ductility cement, Vinylon fibers, 15 mm long, were added at a volumetric ratio of 1.3%. The application range of this cement along the column height was the plastic hinge section only, but the actual height of the application range was made to 700 mm to include the transition range.

Loading was applied by the reverse manner, with the load control method up to the yield load obtained by calculation and then with the displacement control method at each integral multiple of the yield displacement ( $\delta_y$ ). Each loading step was repeated just once and loading was terminated when the load decreased to $0.5P_{max}$. In consideration of the dead load of an actual structure, a uniform axial load equivalent to $1.0N/mm^2$ was applied to the top of the column. The displacement meters were installed at the column bottom on sides B and D of each specimen to find the effect of main reinforcement pullout from the footing.

## 4. Experimental results

### 4.1 Damage

Figure 3 shows damage to the specimens at the end of $\pm 9\delta_y$ loading. In Specimen No. 1, loading was terminated at this load. The cover concrete mostly spalled and main reinforcement buckled. Numerous cracks with a width of 3 mm or more appeared in the area not yet spalled.

In specimen No. 2, cracks with a width of 3 mm or more did not occur, but fine cracks appeared widely. Bulging of concrete was not found. Cracks continued to expand slowly under subsequent loadings. Bulging became conspicuous after $10\delta_y$ but concrete spalling was virtually none even at the ultimate stage.

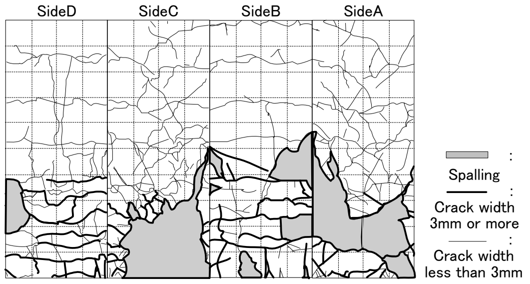
In Specimen No. 4, cracks with a width of 3.0mm or more did not occur, but many fine cracks appeared widely, more than the number in Specimen No. 2. The behavior after this loading was rather identical to that of No. 2, meaning that the seismic strengthening effect of these specimens is rather identical.

### 4.2 Comparison of load-displacement relationship

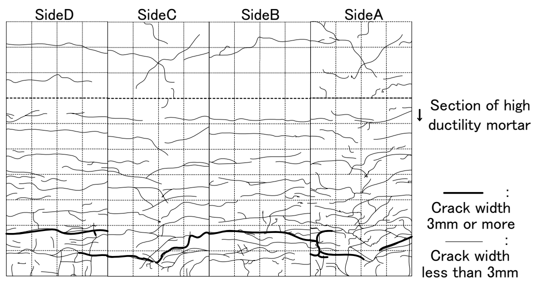
Figure 4 shows the load-displacement (P-$\delta$)hysteresis loops of each specimen. In Specimen No. 1, the main reinforcement strain exceeded the yield strain at a loading of 150 kN and reached the maximum load (201 kN) at $3\delta_y$ (26.6 mm). The load was retained until $7\delta_y$ (62.1 mm). But, with the spalling of the cover concrete, the load quickly decreased and fell below 0.5 $P_{max}$ at 9 $\delta_y$ (81.2 mm).

In Specimen No. 2, the main reinforcement strain exceeded the yield strain at 136 kN and reached the maximum load (209 kN) at 7 $\delta_y$ (63.8 mm). After this, the load slowly decreased as the horizontal displacement increased. Then, after the column bottom bulged, the load fell below 0.5 $P_{max}$ at 14 $\delta_y$ (129.8 mm).

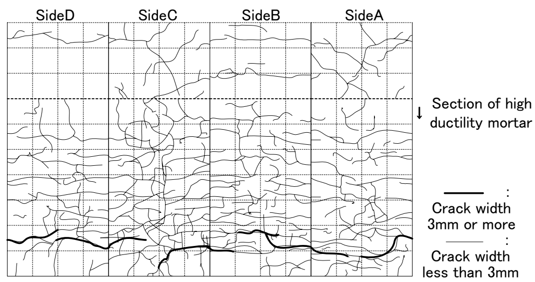
In Specimen No. 4, the main reinforcement strain exceeded the yield strain at 136 kN, like the case of Specimen No. 2, and reached the maximum load (222kN) at 5 $\delta_y$ (44.5 mm). After this, the load continued to be maintained until the displacement became 13 $\delta_y$ (115.2 mm) and then began to decrease as bulging started at the column bottom. The load fell below 0.5 $P_{max}$ at 15 $\delta_y$ (134.9 mm).




a) Specimen No. 1

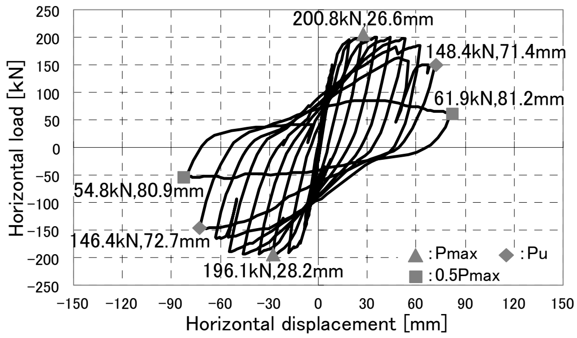



b) Specimen No.2

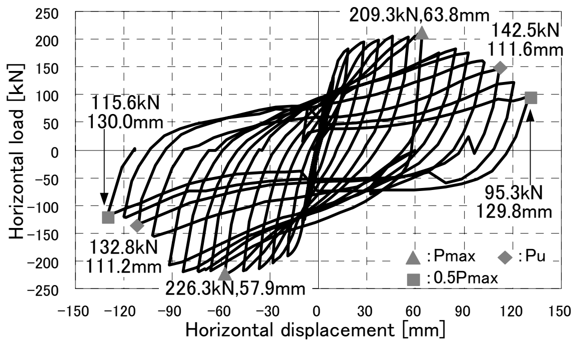



c) Specimen No. 4

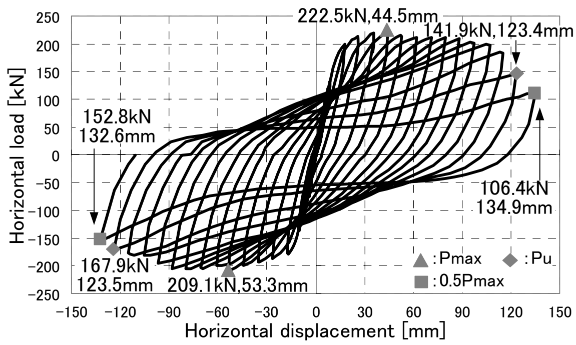
Fig. 3. Damage at the end of $\pm 9\delta_y$ loading




a) Specimen No. 1




b) Specimen No.2




c) Specimen No. 4

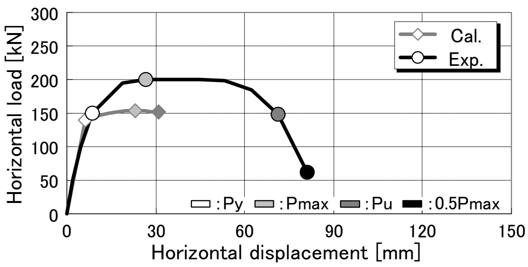
Fig. 4. P-δ hysteresis loop

## 4.3 Comparison of P- δ envelopes

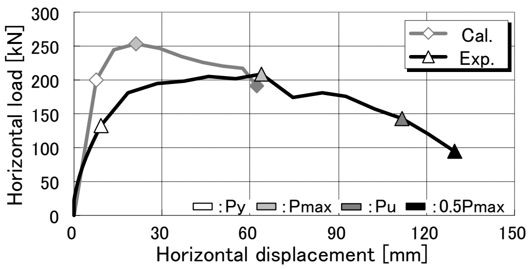
Figure 5 compares the P- δ envelopes obtained from calculation and experiments. If attention is paid to the experimental results, the ultimate displacement increased by 40 mm with the use of high ductility cement. It is also seen that the deformation capacity of Specimen No. 4 which used high ductility cement for the outer 80 mm area of the cross section was roughly identical to that of Specimen No. 2 which used high ductility cement for the entire cross section. Therefore, it can be said that efficient seismic strengthening is possible with the partial use of high ductility cement.

If Specimen No. 2 and No. 4 are compared, the load decreased gradually after reaching a maximum in No. 2, but in No. 4 the maximum load was maintained until 100 mm displacement and then decreased abruptly. This difference is attributable to the rise of the column bottom. Figure 6 shows the schematic of a rise from the footing. When the rise is conspicuous, ① the area that can carry the compressive stress becomes small because the contact plane with the footing is small, and ②fracture on the compression side, buckling of reinforcement, and plasticization are facilitated because only the reinforcement must carry the tensile force.

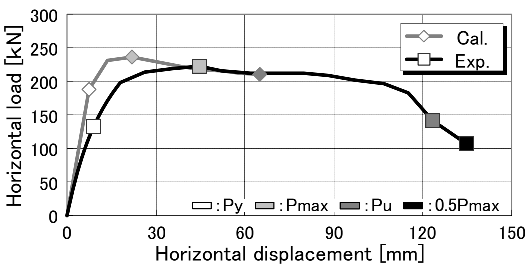
One cause of this rise is the construction method of the column. As shown in Fig. 7, the column was constructed in order of ① footing, ②lower column (high ductility cement area), and ③upper column. A marked rise occurred to Specimen No. 2 because the footing and lower column were constructed separately. In contrast, the rise was small in Specimen No. 4 because the footing and the core concrete were constructed monolithically. The displacement due to main reinforcement pullout at 6 $\delta_y$ near the maximum load was 23.4 mm (40% of horizontal displacement) in Specimen No. 2 and 16.7 mm (30% of horizontal displacement) in Specimen No. 4. It is generally said that the displacement due to main reinforcement pullout is about 20% of horizontal displacement. Therefore, the effect of main reinforcement pullout was rather serious in these specimens, especially in No. 2.



a) Specimen No. 1



b) Specimen No. 2



c) Specimen No. 4

Fig. 5. Comparison of P-δenvelopes

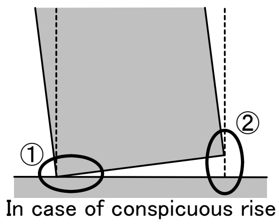



Fig. 6. Schematic of a rise at the column bottom

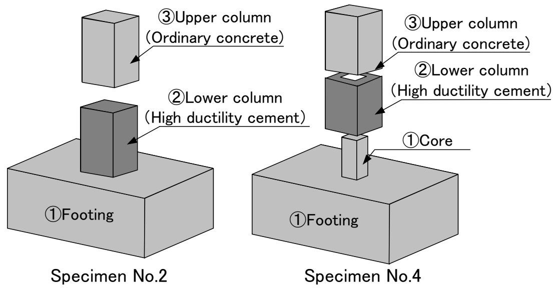



Fig. 7. Construction of column

## 4.4 Hysteresis absorption energy

Figure 8 shows the hysteresis absorption energy at each loading step. The maximum hysteresis absorption energy of Specimen No. 1 was about 20 kN・m, but that of No. 2 and No. 4 was about 30 kN・m and 35 kN・m, respectively, showing 1.5 times increase by the use of high ductility cement. Also, the maximum displacement of Specimen No. 1 was 60 mm, but that of No. 2 and No. 4 was as large as 90 mm and 110 mm, respectively. The maximum cumulative hysteresis absorption energy of Specimen No. 1 was 100kN・m, but that of No. 2 and No. 4 was 260kN・m and 300kN・m, respectively, indicating that the energy absorption capacity will increase significantly if high ductility cement is applied.

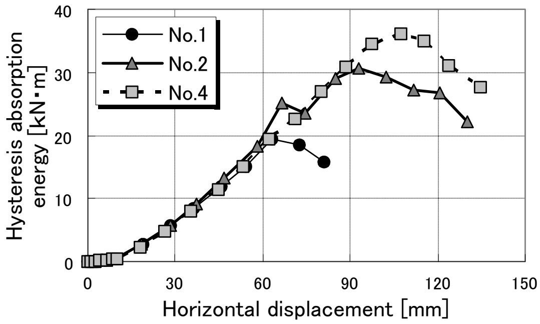
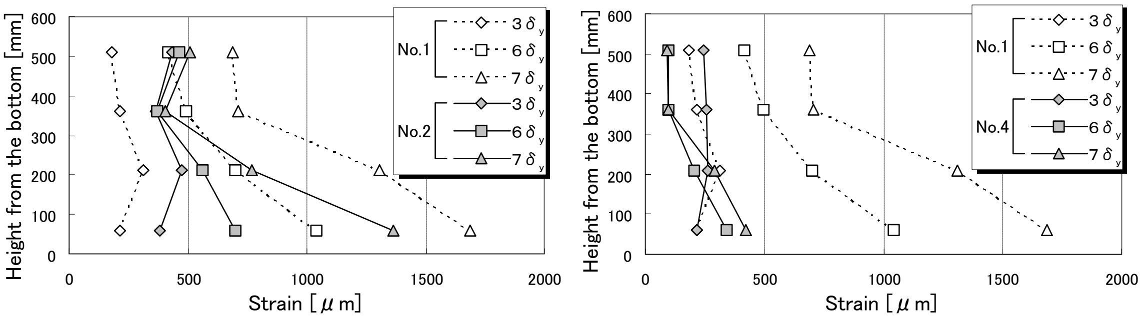



Fig. 8. Hysteresis absorption energy at each loading step

## 4.5 Distribution of hoop tie strain

Figure 9 shows the distribution of hoop tie strain. In Specimen No. 1, the hoop tie strain increased markedly with the increase of deformation, exceeding the yield strain at $7\delta_y$ (62.1 mm). In contrast, the strain developed little in Specimen No. 2 and the hoop tie strain at $7\delta_y$ (84.7 mm) was less than that of Specimen No. 1. The hoop tie strain of Specimen No. 4 was less than 1000$\mu$ at the time of $7\delta_y$ (80.0 mm). The hoop tie strain was kept this low level by the lateral confinement effect provided by the high ductility cement placed at the cover concrete. It restrained buckling of main reinforcement and damage to the core concrete, carried load until a major deformation occurred, and improved the ultimate displacement significantly. As the tendency of hoop tie strain was roughly similar in Specimen No. 2 and No. 4, it is possible to say that the use of high ductility cement only for the outer 80 mm area of the cover concrete can provide a sufficient confinement effect to the main reinforcement in the column.




a) Comparison of Specimens No. 1 and No. 2

b) Comparison of Specimens No.

Fig. 9. Distribution of strain in hoop tie

## 5. Conclusions

The following conclusions were drawn from this experiment.

(1) It was found that use of high ductility cement at the plastic hinge section of a column will increase the ultimate displacement by 60% and the maximum strength by 10% compared with a column not using this cement.

(2) It was confirmed that use of high ductility cement at the outer 20% area of the cross section can attain roughly identical seismic strengthening effect with the case the entire cross section is constructed of high ductility cement.

(3) It can be said that the cover concrete constructed of high ductility cement can provide a horizontal confinement effect, from the experimental results that the propagation of hoop tie strain and bulging of Specimen No. 2 and No. 4 were slower and smaller than those of Specimen No. 1.

## References

1)Road Association of Japan (2002) Specifications for Highway Bridges, Seismic Design

2) Suwada, H. et al. (2003) Basic Research on the Restoring Force Characteristics of Response Control Elements Constructed with High Ductility Cement-based Composite Material, Proc. of JCI, Vol. 25, No. 2, pp. 1375-1380 (in Japanese)

3)Taguchi, J. (2003) Study on the Deformation Capacity of RC Piers, Thesis for MS, Kyushu Institute of Technology (in Japanese).