# PRECAST PRESTRESSED PORTAL FRAMES WITH CORRUGATED STEEL PANEL DAMPERS

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**ABSTRACT :**

This research aims to propose economical structural system which reduces seismic damage and needs no or little repair combing precast prestressed concrete (PCaPC) structures and corrugated steel panel dampers. PCaPC structures show elastic behaviors and very little damage even after experiencing large deformation. However, the lateral displacement under earthquakes tends to be large because of their low stiffness. Corrugated steel panels improve their seismic performances with high capabilities of dissipating energy as dampers even after yielding. This system is economical by using ordinary materials and existing construction technologies.
In an experimental study, seismic loading tests were conducted on four portal frames with corrugated steel panel dampers. Experimental variables were the types of frame structures (RC, bonded PCaPC, and unbonded PCaPC) and the yield strength of corrugated steel panels (100MPa, 225MPa, and 300MPa). All PCaPC frames showed much smaller residual deformations and less damage than RC frames. Energy dissipation was almost identical for two types of steel. In an analytical study, it was proved that superposition of hysteretic loops of frames and dampers agreed well with experimental results. Equivalent viscous damping ratios and residual displacements were well simulated by using simple $M$-$\theta$ model.

**KEYWORDS:** Corrugated steel panel, Precast prestressed concrete structure, High energy dissipation, Residual deformation, Flag shape hysteresis loop

## 1. INTRODUCTION

New seismic structures, which experience no or little damage and need no repair, hence are able to function immediately after earthquakes, have been attracting significant attention since major earthquakes attacked big cities in the world last two decades. When public buildings, such as hospitals and office buildings, were damaged and not able to continue their service, their long term repair period caused serious social damage and economic losses. Some methods such as base isolation are developed to solve this problem, but their initial and maintenance costs are too expensive for every building to employ.

PCaPC structures need no or little repair after earthquakes since they show high restoring force from prestressed tendons and little damage concentrating at interfaces between precast members. However, they also show low stiffness after gap openings at interfaces and lateral displacements of structure tend to be large under earthquakes. In order to reduce the seismic response, it was proposed to add energy dissipating elements to PCaPC structures. Priestley et al. proposed some structural systems using PCaPC frames with energy dissipating devices in PRESSS (PREcast Seismic Structural Systems) research program[1], [2], [3]. They proved that PCaPC structures with energy dissipating devices showed excellent performance, and the system used for 39-story buildings[4].

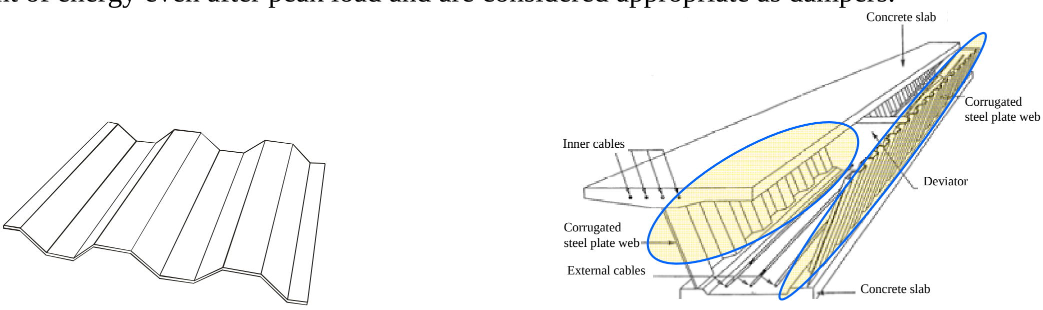
The authors developed new energy dissipating devices for PCaPC frames using corrugated steel panels. It was concerned that Corrugated steel panel showed high capabilities of energy dissipation even after peak load by Mo and Perng[5] and Chosa et al.[6]. This system is economical by using ordinary materials and existing construction technologies.

Cyclic loading test on four portal frames with corrugated steel panel dampers were conducted to investigate their performances. Corrugated steel panel dampers yielded at the expected drift angle and dissipate a sufficient amount of energy. Good self-centering behaviors were observed when the lateral load contribution of damper was optimized. A calculation method to determine the adequate contribution of the damper was derived from a simple *M-θ* model.

Objectives of this research are follows:
1. To investigate the seismic behavior of PCaPC portal frames with corrugated steel panel dampers through cyclic loading tests. To confirm that corrugated steel panel dampers yield from a small drift angle and improve energy dissipating capabilities with small residual deformations. Ductility of frames and dampers and damage conditions were also checked.
2. To establish a numerical method to estimate the seismic behavior of proposed structural system. To investigate lateral load capacity of corrugated steel panel dampers and simulate behaviors of PCaPC frames with corrugated steel panel dampers with superposition of hysteresis loops of frames and dampers.

## 2. CORRUGATED STEEL PANEL DAMPER

Corrugated steel shear panels have been used in box girder bridge structures since 1990's. They weigh less and decrease prestressing loss due to their configurations. Corrugated steel shear panels have high shear stiffness with negligible axial and flexural stiffness. In 2000, Mo and Perng[5] reported a use of corrugated steel shear panels as a main lateral load carrying component for building structures. They proved that corrugated steel shear panels are effective to delay buckling of shear panels. Chosa et al.[6] confirmed that the shear capacity and stiffness of corrugated steel shear panels are fully utilized if sufficient anchorage is provided at the interface between shear panels and surrounding frames. They also proved that corrugated steel shear panels dissipate large amount of energy even after peak load and are considered appropriate as dampers.




(a) Corrugated steel panel (b) Box girder bridge with corrugated steel panel web
Figure 1 Configuration of a corrugated steel shear panel and practical use in a bridge

## 3. EXPERIMENTAL SETUP

### *3.1 Specimens*

Specimens consisted of RC or PCaPC portal frames and corrugated steel panel dampers. Experimental variables were the types of frame structure (RC, bonded PCaPC and unbonded PCaPC) and the yield strength of corrugated steel panel dampers (300 MPa, 225 MPa and 100 MPa). The types of specimen are shown in Table 1. Initially introduced prestressing forces, $F_i$, were determined so that the stress equal to 85% of the yield strength in all specimens. Constant 900 kN axial load was introduced to each column. Axial force ratios were calculated with prestressing forces in beams and with prestressing force and axial force (900 kN, as a long term load) in columns.

Table 1 The types of specimen

| Specimen | Frame type | Tendon type | Fi (kN) | Axial force ratio | | | | Damper type |
|---|---|---|---|---|---|---|---|---|
| PCbS | bond PC | Intended 9.0mm* | 277 | column | 0.26 | beam | 0.08 | Ultra low steel (LY100*) |
| PCbL | bond PC | Intended 9.0mm* | 277 | | 0.26 | | 0.08 | Low steel (LY225*) |
| RC | RC | – | – | | 0.20 | | 0.00 | Mild steel (300 MPa) |
| PCu | unbond PC | Intended 11.2mm* | 434 | | 0.30 | | 0.12 | Mild steel (300 MPa) |

$F_i$: Initial prestressing force per a tendon   Axial force ratios: The ratio of axial force to compressive strength of members
*LY100: $f_y$=105MPa, LY225: $f_y$=235MPa   Intended tendon 9.0mm*, 11.2mm*: Diameter of tendon is 9.0mm, 11.2mm

### *3.2 Corrugated steel panel dampers*

Configurations of dampers of four specimens were identical as shown in Figure 2. The thickness of flat steel plates was determined to regard them as rigid plates and to concentrate shear deformation to corrugated steel panel. Triangle panels extending from both sides of flat plates were designed to reduce flexural deformation of flat plates. The height of corrugated steel panel, $h_D$ (= 190 mm), was the minimum height to have at least one wave so that the corrugated steel panel yields from a small drift. The thickness and width of peripheral flange plates were determined so that they were still elastic when the corrugated panel carried 1.5 times lateral load at shear yielding. Flanges were welded to corrugated steel panel or flat plates and they were connected with high-strength bolts each other. A damper and a frame were connected through mortar with high-strength bolts. Mechanical properties of plates are shown in Table 2. The expected drift angle and lateral load carried by damper at damper yielding are shown in Table 3.

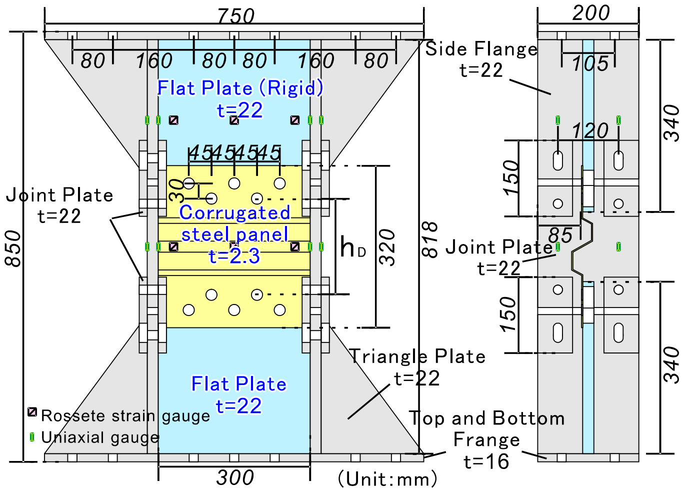



Figure 2 Configuration and dimensions of corrugated steel panel damper

Table 2 Mechanical properties of steel plates

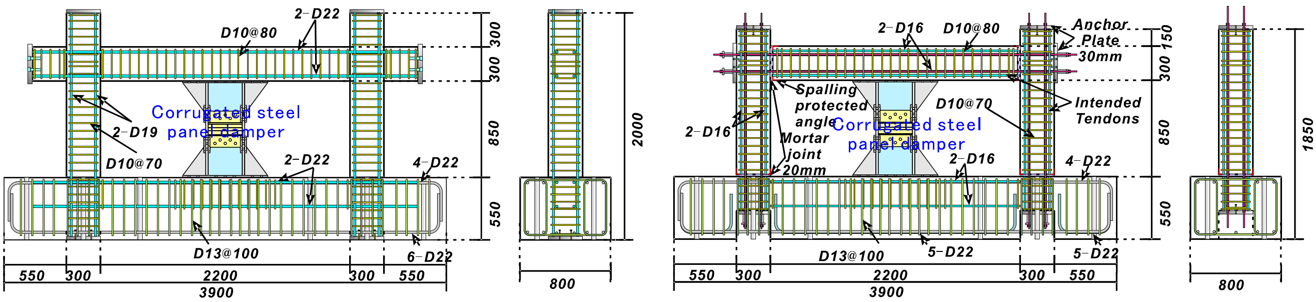
| Specimen | Plate type | Thickness (mm) | Yield strength (MPa) | Tensile strength (MPa) | Young's modulus (GPa) |
|---|---|---|---|---|---|
| PCbS | Corrugated steel panel | 2.09 | 105 | 247 | 181 |
| PCbL | Corrugated steel panel | 2.09 | 235 | 324 | 209 |
| RC, PCu | Corrugated steel panel | 2.09 | 307 | 400 | 193 |
| All specimen | Flat plate | 16.0 | 268 | 442 | 208 |

Table 3 The expected drift angle and lateral load carried by damper at yielding

| Specimen | Damper type | Expected drift angle at damper yielding (%) | Expected lateral load at damper yielding (kN) |
|---|---|---|---|
| PCbS | Ultra low steel (LY100) | 0.03 | 38.0 |
| PCbL | Low steel (LY225) | 0.07 | 85.1 |
| RC | mild strength (300 MPa) | 0.10 | 111.1 |
| PCu | mild strength (300 MPa) | 0.10 | 111.1 |

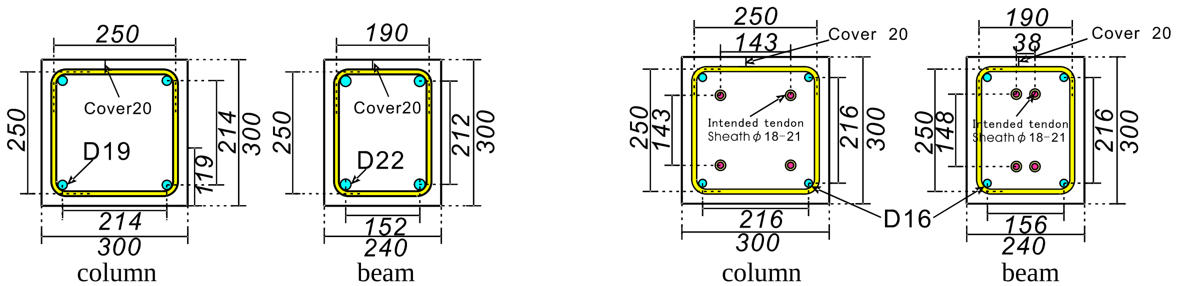
### *3.3 RC or PCaPC Frames*

Frames were designed in 40% scale and modeled internal span in first story of a mid or low-rise building. Dimensions, reinforcing arrangement and cross-section configurations are shown in Figures 3 and 4. In PCaPC specimens (PCu, PCbL and PCbS) columns, beams and stubs were cast separately and connected through mortar joint with tendons. RC specimen was cast monolithically. Material properties of reinforcements, concrete and mortar are shown in Tables 4 through 6.




(a)RC (b)PCu, PCbL and PCbS

Figure 3 Arrangement of reinforcement and dimensions




(a)RC (b)PC

Figure 4 Cross-section dimensions of columns and beams

Table 4 Material properties of reinforcement

| Bar type | Area ($mm^2$) | Yield strength (MPa) | Tensile strength (MPa) | Young's modulus (GPa) |
|---|---|---|---|---|
| D10 | 71.33 | 360 | 499 | 184 |
| D13 | 126.7 | 327 | 470 | 172 |
| D16 | 198.6 | 349 | 527 | 184 |
| D19 | 286.5 | 389 | 585 | 196 |
| D22 | 387.1 | 381 | 587 | 189 |
| Intended tendon 9.0mm | 64.0 | 1410 | 1500 | 200 |
| Intended tendon 11.2mm | 100 | 1410 | 1500 | 200 |

Table 5 Material properties of concrete

| Specimen | Type of member | Compressive strength (MPa) | Tensile strength (MPa) | Young's modulus (GPa) |
|---|---|---|---|---|
| RC | Column, Beam | 52.7 | 2.90 | 26.8 |
| Pcu | Column, Beam | 45.4 | 3.40 | 25.7 |
| | Stub | 45.7 | – | 25.6 |
| PCbS | Column, Beam | 45.6 | 3.23 | 24.4 |
| | Stub | 38.8 | – | 27.4 |
| PCbL | Column, Beam | 46.2 | 3.09 | 24.7 |
| | Stub | 40.2 | – | 26.0 |

Table 6 Material properties of mortar

| Specimen | | Compressive strength (MPa) | Tensile strength (MPa) | Young's modulus (GPa) |
|---|---|---|---|---|
| RC | Damper-Frame | 81.2 | 5.8 | 27.7 |
| PC | Damper-Frame | 49.2 | 2.2 | 16.7 |
| | Beam-Column | 52.6 | 3.6 | 23.4 |
| | Column-Stub | 42.4 | 3.2 | 29.6 |
| PCbS | Damper-Frame | 51.4 | 2.7 | 14.7 |
| | Beam-Column | 33.1 | 3.8 | 18.9 |
| | Column-Stub | 71.3 | 3.6 | 26.9 |
| | Grouting in Beam | 58.2 | 3.1 | 15.7 |
| | Grouting in Column | 47.2 | 2.3 | 15.0 |
| PCbL | Damper-Frame | 55.9 | 2.3 | 15.5 |
| | Beam-Column | 45.7 | 4.3 | 21.7 |
| | Column-Stub | 62.8 | 4.0 | 32.3 |
| | Grouting in Beam | 54.2 | 2.9 | 16.4 |
| | Grouting in Column | 55.4 | 2.7 | 16.5 |

### *3.4 Loading Arrangement*

Loading system is shown in Figure 5. Constant 900 kN axial load was introduced to each column (axial load ratio was 0.20). Equal magnitude of lateral load was applied to both ends of the beam by two 1000 kN hydraulic jacks. One cycle of lateral load less than cracking capacity was applied. Then two cycles of preselected drift angle, R, was enforced at R=±0.1%，±0.2%，±0.4%，±0.6%，±0.8%，±1.0%，±2.0%，±3.0%, etc.

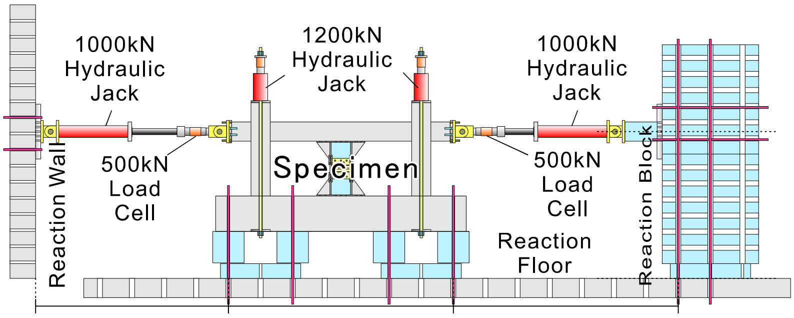



Figure 5 Loading system (unit : mm)

## 4. EXPERIMENAL RESULTS

### *4.1 Hysteresis restoring force characteristics*

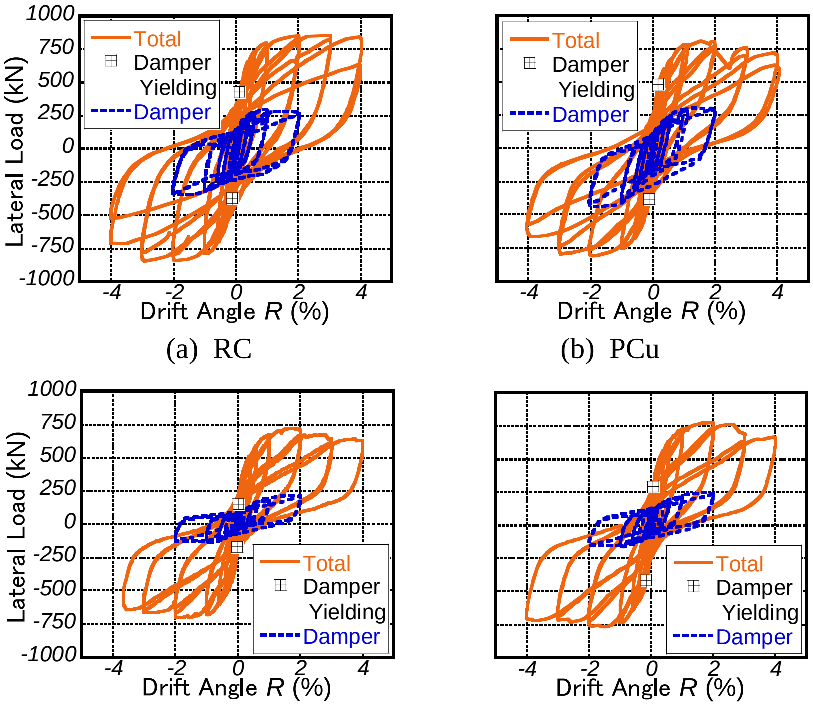
Figure 6 shows the lateral load – drift relations up to R=4.0%. The lateral load and drift angle at the yielding of shear panel and the peak load are summarized in Table 7. Each specimen had fat hysteresis loops and dissipated large amount of energy. However Residual displacements were relatively large in RC and PCu which used mild steel as corrugated steel panel, but sufficiently small in PCbS and PCbL which used low strength steels. Degradation of lateral load carrying capacity after peak load were small and eighty percent of peak load was carried even when R=4.0% in all specimens.

Table 7 The lateral load and drift angle at the yielding of shear panel and the peak load

| Specimen | At shear panel yielding | | | | At peak load | | | |
|---|---|---|---|---|---|---|---|---|
| | Drift angle (%) | | Lateral Load(kN) | | Drift angle (%) | | Lateral load(kN) | |
| | Positive | Negative | Positive | Negative | Positive | Negative | Positive | Negative |
| PCbS | 0.021 | -0.001 | 151 | -170 | 1.70 | -1.56 | 720 | -702 |
| PCbL | 0.070 | -0.140 | 292 | -416 | 1.95 | -1.57 | 775 | -768 |
| RC | 0.128 | -0.112 | 427 | -376 | 3.02 | -2.93 | 854 | -846 |
| PCu | 0.188 | -0.115 | 481 | -384 | 1.55 | -1.97 | 811 | -811 |

### *4.2 Lateral load carried by damper*

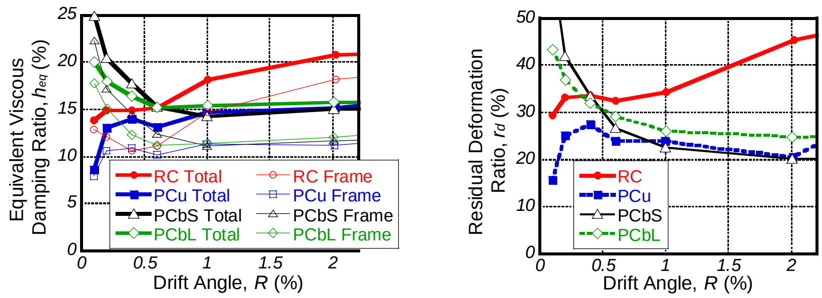
Lateral load carried by damper – drift relations are shown in Figure 6. Damper yielding points were also plotted. The shear stress of the corrugated steel panel was computed from strains assuming the plane stress and the Von Mises yield criteria. The shear force of the damper was calculated by multiplying the shear stress and the cross-section area. The ratio of load carried by damper to the total load was 30% to 35% in four specimens. The computed contribution was 25% by considering the story shear force at the formation of collapse mechanism of the frame and the shear force of the damper at yielding. It is conducted that the damper carried larger lateral load than expected. Lateral load carried by damper increased after damper yielding until R=1.0%. The increment was the largest in PCbS with used ultra low steel (LY100).




(a) RC (b) PCu

(c) PCbS (d) PCbL

Figure 6 Lateral load – drift angle relations




(a) Equivalent viscous damping ratio (b) Residual deformation ratio

Figure 7 Equivalent viscous damping ratio and residual deformation ratio

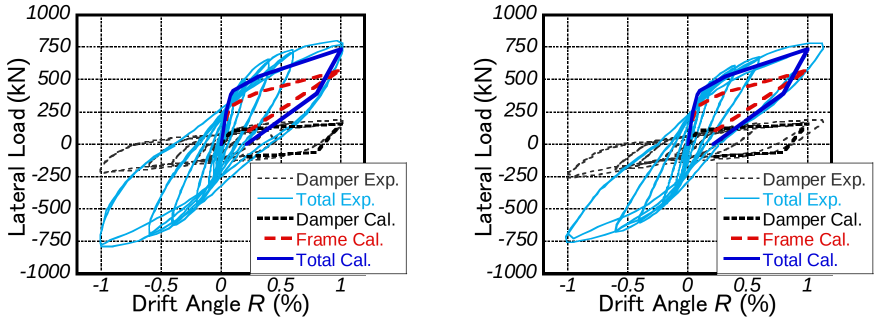
### *4.3 Equivalent viscous damping ratio and residual deformation ratio*

Figure 7(a) shows equivalent viscous damping ratio – drift angle relations. The equivalent viscous damping ratio, $h_{eq}$, was calculated from the second hysteresis loop of lateral load – drift relations. $h_{eq}$ of bare frames were computed from hysteresis loops of lateral load carried by frame – drift relations. Lateral load carried by frame was obtained by subtracting lateral load carried by damper from total lateral load. $h_{eq}$ of PCaPC specimens increased about 4% compared with that of bare frames, while $h_{eq}$ of RC increased about 2%. The difference between $h_{eq}$ of PCbL and PCbS were not so large as the difference of yield strengths (LY225,100). The energy dissipation was almost identical for two types of steel.

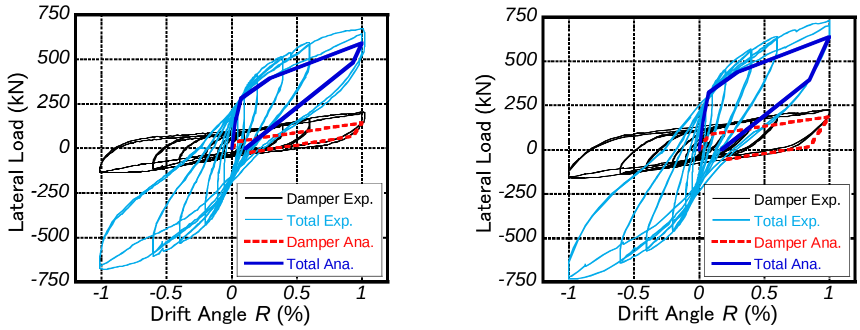
Residual deformation ratio, $r_d$, was discussed to evaluate the self-centering characteristics and calculated from average of positive and negative magnitude of residual deformations divided by the maximum deformations. Figure 7(b) shows residual deformation ratio – drift angle relations at the second loop. With increase of drift angle, $r_d$ of RC increased and reached 40% at R=2.0%, but $r_d$ of PCaPC frames were about 20～25 % at R=2.0%. The columns and beams of PCaPC suffer very little damage irrespective of the bond of tendons. PCbS using bonded tendons kept $r_d$ as small as PCu using unbonded tendons. And, PCbS kept $r_d$ smaller than PCbL. since the small shear force carried by the shear panel (LY100) can be easily offset by the restoring force of the PCaPC frame.

## 5. NUMERICAL SIMULATION USING *M-θ* MODEL

A simple mechanical model was developed to simulate the hysteric behavior of specimens. The model is expressed by the superposition of two independent resisting force due to the damper and the frame. Since it was confirmed that the hysteretic behavior of RC frames with corrugated steel shear panels were simulated by superposition of hysteresis loops of frames and shear panels by Chosa et al.[6], the same procedure is employed. The hysteresis loop of the damper was expressed by a simple bilinear curve. The stiffness of the second branch was defined 0.03 times of initial stiffness. The hysteresis loop of the frame was computed based on the *M-θ* model proposed by Okada et al.[7] in 1990. The ultimate moment was 1.15 times and the factor for unloading stiffness was modified based on experimental results[8]. Figure 8 shows analytical results of hysteresis loops. Each specimen showed good simulation of lateral load capacities and residual deformations with the same modified factors in the *M-θ* model. Figure 9 shows equivalent viscous damping ratios and residual deformation ratios computed from simulated hysteresis loops. They showed good agreement with experimental results.

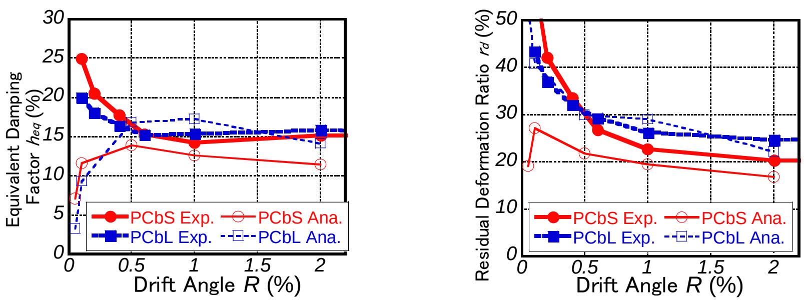



(a) RC (b) PCu




(c) PCbL (d) PCbS

Figure 8 Simulation of lateral load – drift angle relations




(a) Equivalent viscous damping ratio (b) Residual deformation ratio

Figure 9 Simulation of equivalent viscous damping ratio and residual deformation ratio

## 6 CONCLUSIONS

Statically cyclic loading tests on four portal frames with corrugated steel panel dampers were conducted, and the following conclusions were obtained.

(1) The behavior that high restoring force added fat hysteresis loops were showed by combining the corrugated steel shear panels with the precast prestressed concrete frame. The performance of specimens with bonded tendons was as good as that with unbonded tendons. Four tested specimens showed very ductile behavior and the degradation of the load carrying capacity was less than 20% even at R=4.0%.
(2) Performance of LY100 steel panel damper was as good as that of LY225 steel panel damper. The energy dissipation was almost identical for two types of steel. However, the LY100 steel had smaller residual displacement since the small shear force carried by the shear panel can be easily offset by the restoring force of the precast prestressed frame.
(3) The precast prestressed columns and beams suffer very little damage irrespective of the bond of tendons.
(4) The hysteretic behavior of the hybrid frame can be accurately predicted by superposing the hysteretic behaviors of the precast prestressed frame and dampers, separately. The computed hysteretic model was also able to accurately predict the energy dissipation and the residual displacement.

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