STRUCTURAL SYSTEM ENABLING PROMPT RECOVERY AFTER EARTHQUAKES

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ABSTRACT :

After experiencing catastrophic earthquakes in major cities worldwide in 1990's and 2000's, the general public recognized that the economical loss due to the out-of-service period for repairing the damaged building was more significant than the cost to rehabilitate the damaged building itself. The base isolation system is one of the solutions to keep building functions after earthquakes, but the initial and maintenance costs are too high to apply to all kinds of buildings. The authors proposed a new economical structural system which enables prompt recovery after earthquakes using precast prestressed concrete frames with energy dissipating elements. Precast prestressed concrete structures show high self-centering characteristics with negligible damage and enable prompt recovery, if the excessive drifts due to nonlinear elastic behavior are reduced by using some energy dissipating elements. The structural system with precast concrete frames and energy dissipators satisfy the social demand with much less cost compared to that of the base isolation system. This paper introduces two types of the structural system and describes the design concepts. The focal point is the optimization of self-centering and energy dissipating properties. An FEM model was developed to simulate experimental results with high accuracy. From this analysis, a simplified calculation method was proposed to estimate hysteretic characteristics of the structures with each types of the system. Finally, design procedures for optimization of the restoring performance and the amount of energy dissipators were introduced.

KEYWORDS: Precast prestressed concrete structure, Damage control, Residual deformation, Energy dissipation, Optimization of hysteresis loop

1. INTRODUCTION

When major earthquakes attacked major cities in the world in 1990's and 2000's, even if structures do not collapse, many damaged reinforced concrete (RC) buildings did not function continuously without long term repair period. The economical loss in this period was more serious than the cost to rehabilitate damaged buildings. Though conventional seismic design codes require little or no damage for minor or medium earthquakes and prevent collapse of structures for major earthquakes, the demand of society is shifting to the higher level. The general public started to pursue structures which experience no or minor damage, hence necessitates no repair, and can be used immediately after the earthquake regardless of its intensity. For this reason, the base isolation system has been attracting attention. However, the base isolation system ordinarily needs much higher initial and maintenance cost and it is not very realistic to apply them to all sorts of structures.

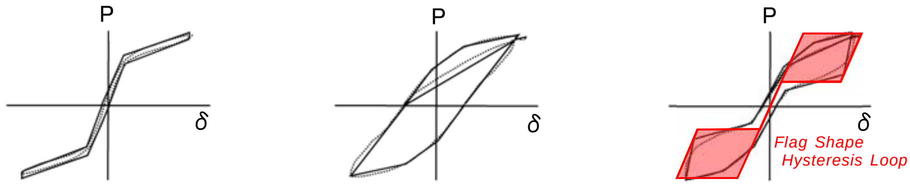
The U.S. PRESSS (PREcast Seismic Structural System) program, coordinated by the University of California, San Diego[1], [2], [3] proposed hybrid systems with precast prestressed concrete structures and energy dissipating elements. The hybrid systems showed excellent performances with limited or negligible seismic damage and some of them were used in California for buildings up to 39 stories[4]. This system also have been applied to the bridge structures[5]. However, the hybrid framing system proposed by PRESSS has complicated beam sections. The authors proposed some internal and external energy dissipators for precast concrete structures which enable the section much simpler.

This paper introduces graded composite strands as an internal dissipator and corrugated steel shear panels as an external one, and explains how to optimize hybrid structural systems with these energy dissipators. A relatively simple calculation method was proposed based on FEM analytical results considering gap opening motions and bond-slip behaviors of tendons for estimating hysteretic behaviors of the structures with proposed system. Using the numerical model, the design procedures for optimization of the seismic performance of proposed structural systems were established.

2. PRECAST PRESTRESSED CONCRETE STRUCTURES WITH ENERGY DISSIPATORS

Precast prestressed concrete structures show nonlinear elastic behavior as shown in Figure 1(a) and the residual deformation remains very small if the gap openings and rocking motions at the interfaces are allowed. However, the large degradation of stiffness causes excessive drift of structures under earthquakes. Hysteretic energy dissipating elements take advantage of the excessive deformations and reduce maximum responses (Figure 1(b)). Combination of nonlinear elastic frames and energy dissipators produce so-called *flag shape* hysteresis loops (Figure 1(c)).

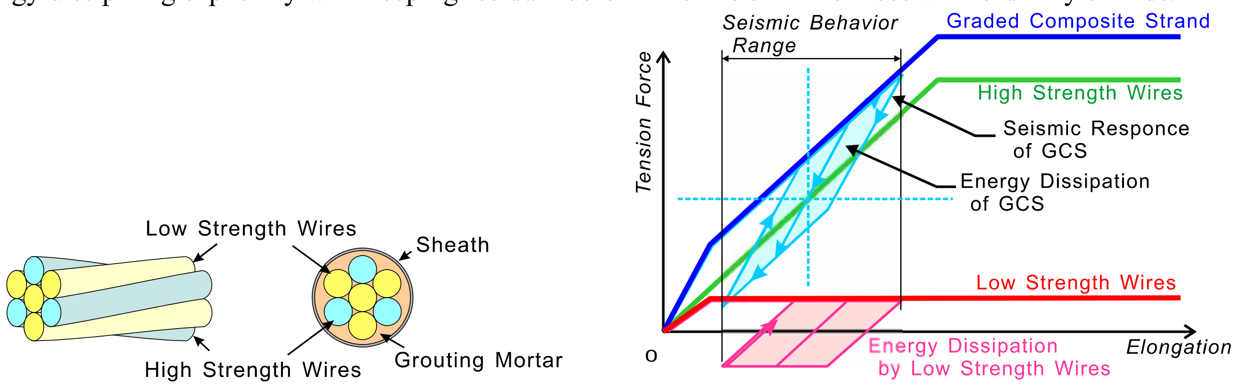
Two types of hybrid precast prestressed concrete structural systems with energy dissipating elements are introduced in this section. One is precast concrete frames using graded composite strands as prestressing tendons and internal dissipators work with gap opening motions. The other is precast prestressed concrete frames with corrugated steel shear panel dampers as external dissipators.



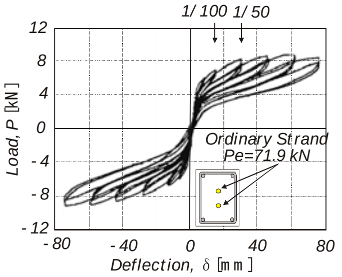
(a) Nonlinear elastic behavior (b) Plastic behavior (c) Flag shape behavior
Figure 1 Hysteresis loops of precast prestressed concrete structures and energy dissipating elements

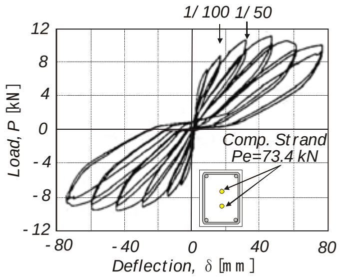
2.1 Precast Prestressed Concrete Members Using Graded Composite Strands as Tendons

A graded composite strand (GCS) consists of two types of wires with different yield strengths. Figure 2(a) shows a GCS which consists of four low strength wires and three high strength wires. When used as prestressing tendons in precast concrete members, GCS's experience large elongation due to gap opening motions between precast members. Under cyclic deformation at the gap, low strength wires yield and dissipate energy, while high strength wires are elastic and provide restoring force as shown in Figure 2(b). Cyclic loading tests on precast prestressed concrete cantilever beams with GCS's were conducted from 1993 to 2005[6]. Figure 3 shows load-displacement relations of cantilever beams tested by Niwa et al.[6] It was confirmed that GCS's increased energy dissipating capability with keeping residual deformation as small as those with ordinary strands.



(a) Configuration of a seven-wire-GCS (b) Tension force-elongation relations of a GCS
Figure 2 Configuration and seismic behavior of a GCS



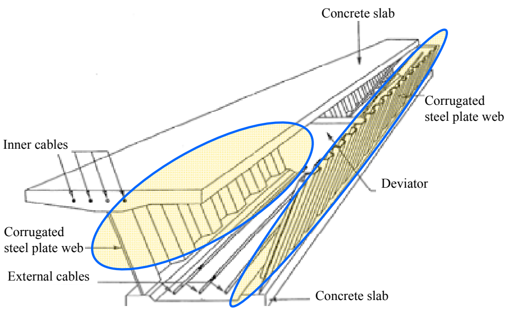


(a) Specimen with ordinary strands (b) Specimen with GCS's

Figure 3 Load-displacement relations of cantilever beam tests[6]

2.2 Precast Prestressed Concrete Frames with Corrugated Steel Shear Panel Dampers

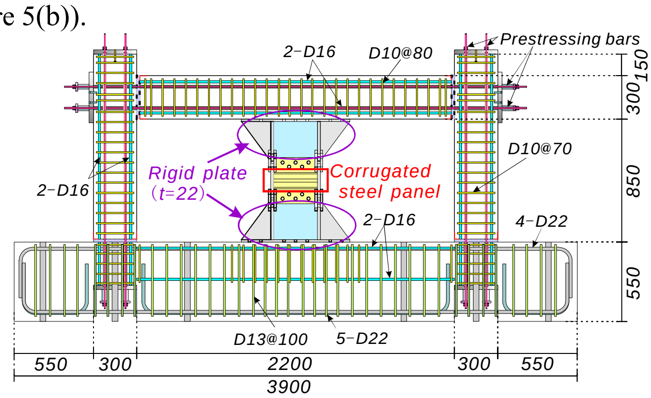
Corrugated steel shear panels are mainly used as webs of box girder bridges as shown in Figure 4(a) because they weigh less and decrease prestressing loss due to their negligible axial stiffness. Mo and Perng[7] suggested the use of corrugated steel shear panels instead of RC shear walls as main lateral load resisting components in building structures. Though their experimental results showed the poor seismic performance because of insufficient anchorage between the shear panel and the peripheral frame, Chosa et al.[8] confirmed that the shear capacity and stiffness of corrugated shear panels were fully utilized with the amount of anchorage satisfying the Japanese design guideline[9]. Corrugated steel shear panels have been already used as shear walls in Japan (Figure 4(b)).

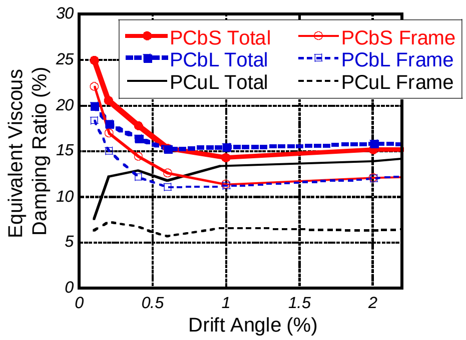


(a) Use as webs of a bridge (b) Use as a shear wall in a school building

Figure 4 Practical uses of corrugated steel shear panels

It is also confirmed that corrugated steel shear panels dissipate much greater energy even after the peak load. Therefore, a damper using corrugated steel panel was proposed. The damper consists of a corrugated steel panel and two rigid flat steel plates connected upper and lower beams as shown in Figure 5(a), so that the story drift concentrates at the corrugated steel panel. Under static cyclic loading tests, the equivalent viscous damping ratio of a precast prestressed concrete frame with the damper was doubled at maximum compared to its bare frame (Figure 5(b)).





(a) Dimensions of a specimen (b) Experimental results of equivalent viscous damping ratio

Figure 5 Experiment on portal precast prestressed concrete frames with corrugated steel panel dampers

Frame analyses were conducted for these experiments using portal frames with corrugated steel shear panels as shear walls or dampers. Analytical results proved that hysteretic characteristics of frames with dampers were calculated by superposition of respective characteristics of frames and dampers. The results are shown in the companion papers[10], [11].

3. ANALYTICAL METHOD TO ESTIMATE THE BEHAVIORS OF PROPOSED STRUCTURAL SYSTEMS

Two structural systems using precast concrete frames with energy dissipating elements were proposed as shown in the previous chapter. Experimental results proved their usefulness. However, there was no simple method to estimate hysteretic characteristics of these structures, because existing design methods do not assume large deformation at the interfaces between precast members. This paper describes an FEM analysis on proposed structural systems. The FEM model clarified the behaviors of each structural elements and factors influencing hysteretic characteristics. Based on these analytical results, a relatively simple method for estimation of hysteretic load-deformation relations was proposed.

3.1 FEM Analysis on Cantilever Beams with GCS's

3.1.1 Outline of the Model

Behaviors of cantilever beams with GCS's were simulated using an FEM analysis. The model considers two distinctive behaviors in precast prestressed concrete structures: bond-slip behaviors of strands, and gap opening motions at interfaces between precast members. The geometry and dimensions of the FEM model are shown in Figure 6. Four-node plane stress elements were used to represent concrete and anchor plates. Reinforcing bars were modeled with truss elements. Except strands, reinforcing bars share the same nodes of concrete elements (assuming perfect bond). In order to simulate the bond-slip behavior, nonlinear *bondlink* springs were used between nodes of strands and concrete elements. Bond-slip hysteretic characteristics are described in section 3.1.2. For the gap opening motion at the fixed end of the beam, interface elements were used. The interface element was defined between surfaces of the beam end and the stub. It allows opening and resists penetrations with 0.6 friction coefficient at the contacted region.

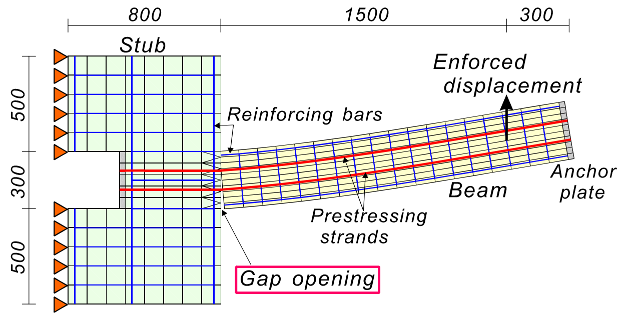
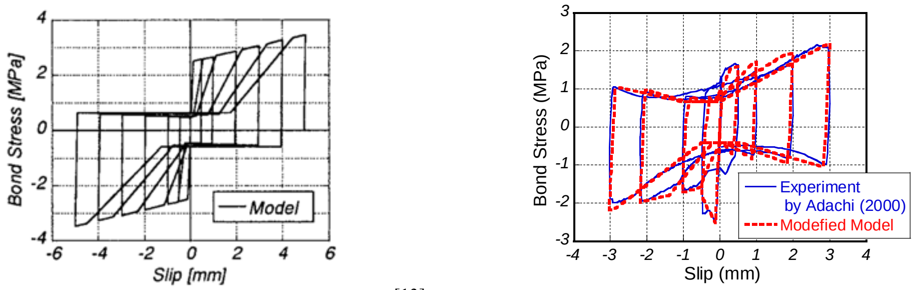


Figure 6 FEM Model of the cantilever beam

3.1.2 Materials

Stress-strain relation under uniaxial loading conditions of concrete was determined based on cylinder test results. The mechanical behavior of the concrete material is modeled using the concrete damaged plasticity constitutive model which provides a general capability under cyclic loading. Unloading path is defined so that the residual strain is equal to half of the strain at the unloading point. Simple bilinear stress-strain relations were used for steel reinforcements. For *bondlinks*, the hysteretic bond-slip model proposed by Adachi et al.[12] was used with some modification to simplify and complement the cyclic behavior. Adachi's model was made for prestressing strands based on the model for deformed prestressing bars proposed by Morita and Kaku[13] (Figure 7(a)). Modified bond-slip model is compared to an experimental result tested by Adachi et al.[12] in Figure 7(b).

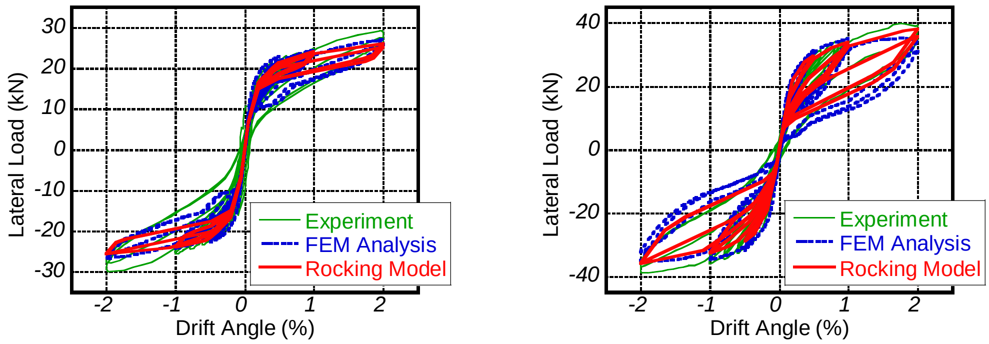


(a) Bond-slip model by Morita and Kaku[13] (b) Bond-slip relations on cyclic test

Figure 7 Bond-slip relations applied to *bondlinks*

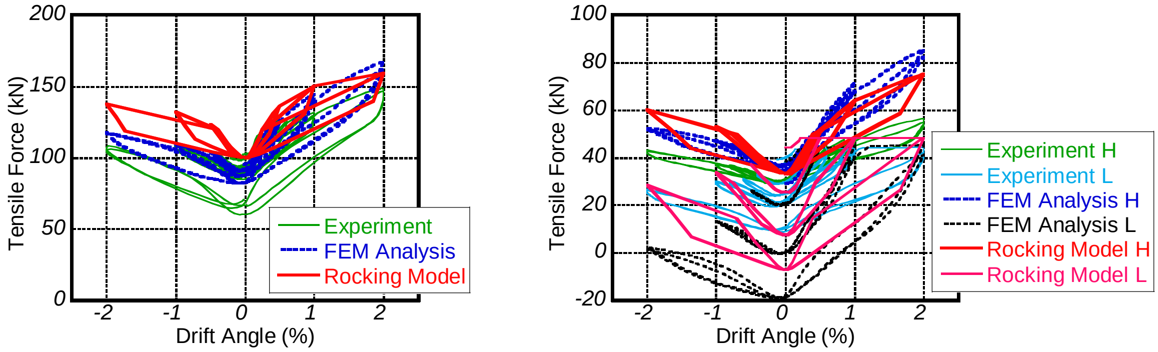
3.1.3 Analytical Results

Figure 8 and Figure 9 show the simulation of cantilever beam specimens with ordinary strands or GCS's. According to the loading protocol of experiment, cyclic deformation was enforced at the free end of the beam in the FEM model. Both applied lateral load (Figure 8) and tensile force of prestressing strands (Figure 9) well simulated hysteresis loops of experimental results.



(a) Specimen with ordinary strands (b) Specimen with GCS's

Figure 8 Load-rotation angle relations of cantilever beam test



(a) Specimen with ordinary strands (b) Specimen with GCS's

Figure 9 Tensile force-rotation angle relations of cantilever beam test

3.2 Rocking Model for Precast Prestressed Concrete Cantilever Beams

3.2.1 Outline of the Model

This model has been developed for a precast prestressed concrete member that has a large gap opening between members. In this section, a cantilever beam shown in Figure 10 is taken as an example for explanation. It is assumed that the beam shows rocking behavior and tendons experience elongation with the vertical load, P. The vertical displacement, δ, is calculated by summation of displacement due to beam elastic displacement, δ_b, and displacement due to the gap opening motion, δ_r. The moment at the gap is calculated with the gap opening width,

δ_j. Since P is obtained from the moment at the gap, a P-δ relation is determined.

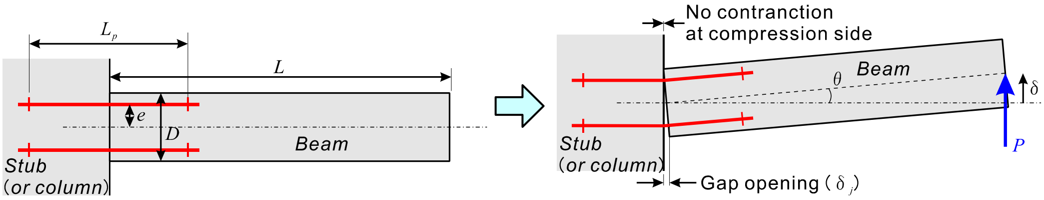


Figure 10 Rocking behavior model of a cantilever beam

3.2.2 Moment Calculation at the Fixed End of the Beam

Moment calculation at the fixed end of the beam is fundamentally based on the assumption of linear strain distribution in the section. However, strain of prestressing strands are not determined with the assumption, but with a hysteretic model of strain increment, $\Delta\varepsilon_p$, being subject to δ_j. A $\Delta\varepsilon_p$-δ_j relation consists of three regions when the deformation of the beam increases, and two regions when the deformation decreases as shown in Figure 11. The $\Delta\varepsilon_p$-δ_j relations model were developed from analytical results of the FEM model mentioned in section 3.1. Bond yielding and strand yielding is the boundary points of three regions of the $\Delta\varepsilon_p$-δ_j relation in deformation increasing situation. Bond yielding in opposite direction is the boundary point in deformation decreasing situation. $\Delta\varepsilon_p$-δ_j relations are linear in region A, C, D and E, and $\Delta\varepsilon_p$ is inversely proportional to (δ_j – *constant*) in region B. Slope of the linear regions and the proportionality coefficient determined by equations based on the parametric studies on FEM cantilever beam analyses. Those equations need geometric properties, material properties, and prestressing conditions of the member.

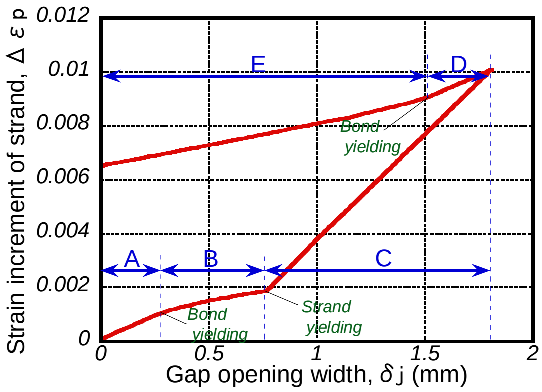


Figure 11 $\Delta\varepsilon_p$-δ_j relations in proposed rocking model

3.2.3 Comparison of results in Experiment, FEM Analysis, and Rocking Model

Figure 8 and Figure 9 show comparison of results in the experiment, the FEM analysis, and the rocking model. The results of rocking model were quite similar to the results of FEM analysis. Some errors between experimental results and rocking model results are mainly caused by imperfect grouting in the specimens. From these result, it is confirmed that rocking model reduces solution cost substantially with the same level of accuracy of FEM model. The rocking model is so simple that it can be incorporated in a frame analysis as a rotational spring at ends of a beam-column element.

4. SYMPLE METHOD FOR OPTIMIZATION OF ENERGY DISSIPATING CAPABILITY

4.1 Optimization Using Proposed Rocking Model

When GCS's are used as tendons in precast concrete members, the procedure to determine the adequate amount of GCS's is complicated, because GCS's works as both tendons and dissipators and their amount affect both properties of self-centering and energy dissipation. However, the maximum section area of low strength wires and the minimum area of high strength wires are simply defined with two conditions. One is that the resultant force of tendons keeps positive value after unloading, and the other is that high strength wires remain elastic. Using the rocking model, upper and lower limits of areas of wires are calculated easily and several optimum combinations of the number of wires are selected to meet the conditions.

The adequate amount of GCS's is decided to maximize the energy dissipating capability of the member. Figure 12 shows the results of trial calculations of equivalent damping ratios, H_{eq}. The dimensions of the member are the same in the cantilever beam specimen with GCS's shown in Figure 8(b) and Figure 9(b). The area of low strength wires of a GCS was varied. Displacements were cyclically applied to the free end of the beam corresponding to the rotation angle of the beam to 0.5%, 1.0%, and 2.0%. The results proved that the area of low strength wires is specified to provide the maximum H_{eq}, with each rotation angle.

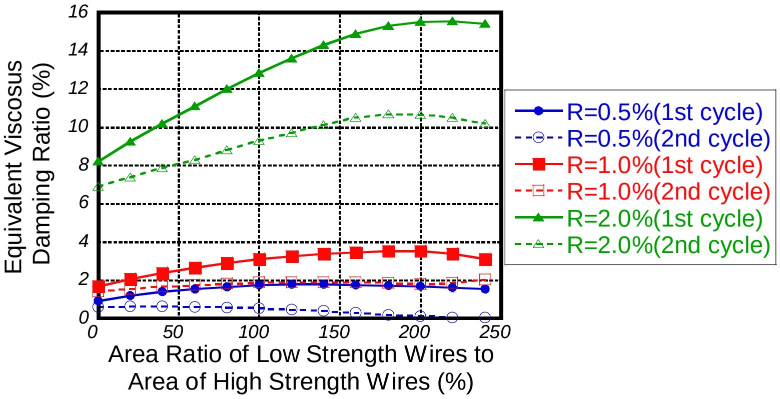
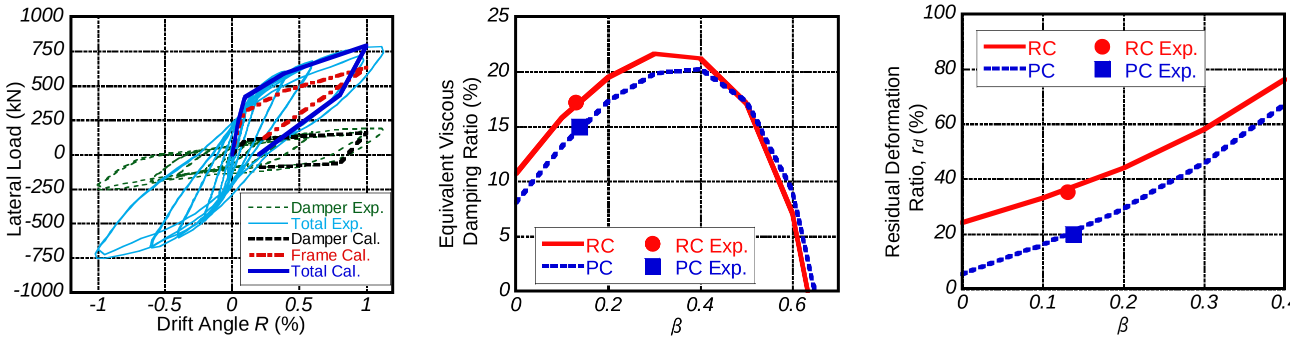


Figure 12 Effect of the area of low strength wires on equivalent viscous damping ratio

4.2 Optimization of the Parallel System

Optimization of energy dissipating performance and restoring performance is relatively simple in *parallel* system in which frames and dampers work independently for a given story drifts. Hysteretic characteristics of *parallel* systems are estimated by superposition of hysteresis loops of dampers and frames. The system of precast prestressed concrete frames with corrugated steel panel dampers is one of the *parallel* systems. Figure 13 shows simulated hysteresis loops of the system. The damper was modeled with a simple bilinear skeleton curve, and the frame was modeled with a hysteretic moment-curvature relation model proposed by Okada et al.[14] In Figure 13(b) and (c), β is the lateral load contribution of dampers to the whole structures (frames and dampers). Residual deformation ratio, r_d, is the average of positive and negative magnitude of residual displacements divided by the maximum displacement. To maximize energy dissipating capability, load contribution of a damper is defined from Figure 13(b), however, residual deformation ratio in Figure 13(c) sometimes gives limitation of β. For example, β=0.4 maximize energy dissipating capability in "PC" model, but 65% of r_d at β=0.4 is too large. The amount of corrugated steel panel damper of "PC Exp." specimen was defined to achieve maximum energy dissipating capability on condition that r_d was kept less than 20%.



(a) Load-drift angle relations (b) Equivalent viscous damping ratio-β relations (c) r_d-β relations

Figure 13 Optimization of the amount of corrugated shear panel dampers

5. CONCLISIONS

This paper introduced the concepts of precast prestressed concrete structural systems with energy dissipating elements to achieve economical structures which enable prompt recovery after earthquakes. Design procedures to optimize the performances of proposed structures were developed. The following summarizes conclusions.

1. Two structural systems using graded composite strands and corrugated steel shear panel dampers showed sufficient energy dissipating capabilities with small residual deformations in cyclic loading tests.
2. An FEM analytical model which considers gap opening motions and bond-slip relations of tendons was developed and it was confirmed that experimental results were simulated with high accuracy. Based on the FEM analysis, the simplified calculation method was proposed. Experimental and FEM analytical results were estimated accurately with the calculation method.
3. Design procedures were proposed to optimize restoring performances and energy dissipating capabilities of precast prestressed concrete structures with energy dissipating elements.

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