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USE OF GRADED COMPOSITE STRANDS IN PCAPC STRUCTURES FOR BETTER SEISMIC PERFORMANCE

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ABSTRACT :

When major earthquakes hit urban areas in the world in 1990's and 2000's, many damaged reinforced concrete buildings did not function continuously during a long term repair period. Base isolation is one of the solutions to reduce the seismic damage and prevent the out-of-service state, but it needs high initial and maintenance costs and cannot be applied to every building.

This study aims to propose an economical structural system with precast prestressed concrete (PCaPC) structures. PCaPC structures need no or little repair after earthquakes due to their self-centering characteristics. However, they also show excessive lateral deformations under earthquakes because of their low stiffness and small energy dissipation capability. The authors proposed to use graded composite strands (GCS-U) which has both characteristics as a tendon and an energy dissipating element. A GCS-U consists of seven high yield strength wires surrounded by twelve low yield strength wires.

In an experimental phase, cyclic loading test on three PCaPC portal frames with different types of tendons (GCS-U, ordinary strands with or without bond) were conducted. The specimen using GCS-U showed larger amount of energy dissipation as the specimen using unbonded strands. All specimens showed and almost no damage until 2% story drift. In an analytical phase, envelope curves of experimental lateral load-drift relations were simulated accurately with a frame analysis model. It is confirmed that PCaPC structures with GCS-U have high possibility to provide economical damage-free buildings.

KEYWORDS: Precast prestressed concrete structures, Graded composite strand, Residual deformation, Energy dissipation, Flag shape hysteresis loop

1. INTRODUCTION

After experiencing catastrophic earthquakes in big cities worldwide in 1990's and 2000's, many reinforced concrete buildings were damaged and it took long time to repair. The general public recognized that the economical losses during a long term repair period sometimes become more significant than the cost to repair the damaged building itself. Base isolation is one of the solutions to reduce the seismic damage and prevent the out-of-service state, but it needs high initial and maintenance costs and cannot be applied to every building.

PCaPC structural systems with energy dissipating elements were firstly proposed by Priestley et al. in PRESSS (PREcast Seismic Structural Systems) research program[1], [2], [3], which reduces seismic damage and needs no or little repair because of self-centering characteristics due to prestressing force or dead load with energy dissipating elements limiting the maximum displacements. A hybrid connection was one of their systems and inspired the following research. In the hybrid connection, unbonded post-tensioned tendons along the beam centerline connect beams and columns and provide restoring force. Mild steel reinforcement at the top and bottom of the beam section provides energy dissipation by yielding at the interfaces between beams and columns. This system showed excellent performance in testing of a five-story structure under the PRESSS program and was used for buildings in California[4]. However, the beam section of the hybrid connection is complicated because they need top and bottom layers of mild steel in addition to tendons.

The authors proposed the use of graded composite strands (GCS's) as an alternative to post-tensioned tendons and mild steels. The research on the original GCS was conducted by Niwa et al.[5] GCS's have the same configuration of ordinary strands with both characteristics as prestressing tendons and energy dissipating elements. They can make beam sections as simple as ordinary prestressed concrete beams and dissipate as large energy as hybrid connections proposed in PRESSS program.

In this research a new type of GCS, called "GCS-U", which has unbonded high strength strands surrounded by mild steel wires was proposed. GCS-U provides higher restoring force than the original GCS in large deformation because the high strength strand doesn't yield. This paper describes cyclic loading test on PCaPC portal frames with GCS-U compared to PCaPC portal frames with ordinary strands. The specimen using GCS-U kept residual deformations small and showed very small damage. The amount of energy dissipation was improved by using GCS-U. It is confirmed that PCaPC structures with GCS-U provide economical solutions leading to no or little repair after earthquakes.

2. GRADED COMPOSITE STRANDS

A Graded Composite Strand (GCS) consists of two types of wires of high and low yield strengths. As shown in Figure 1, the high strength wires remain elastic and provide restoring force, while the low strength wires yield and dissipate energy under seismic loading. Prestressing force is introduced so that low strength wires yield before experiencing earthquakes and they dissipate energy from the early stage. Figures 2 and 3 show configurations of two types of GCS's. The original GCS in Fig. 2 consists of twisted wires of two different strengths. GCS-U in Fig. 3 consists of seven high strength wires and surrounding twelve low strength wires. GCS-U provides higher restoring characteristics than original GCS because its high strength wires are unbonded. Low strength wires of GCS-U are placed in the form and concrete is cast. The prestressing force is produced only to the central high strength wires after concrete hardens.

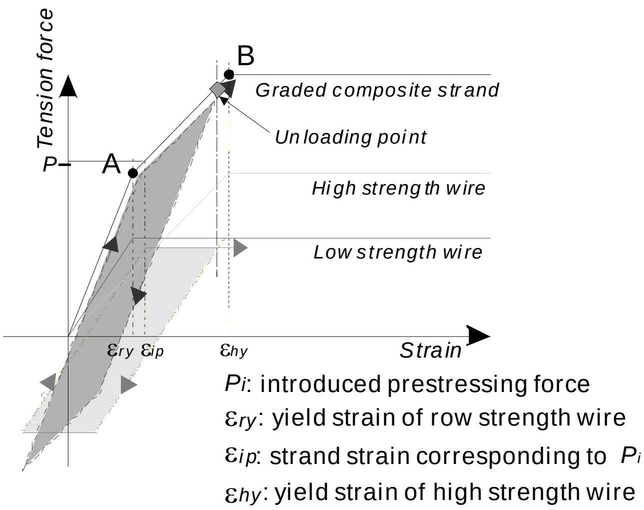


Figure 1 Behavior of a GCS

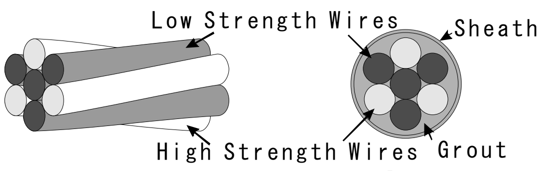


Figure 2 Original GCS

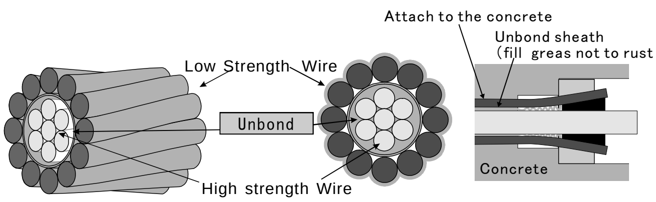


Figure 3 GCS-U

3. OUTLINE OF THE EXPERIMENT

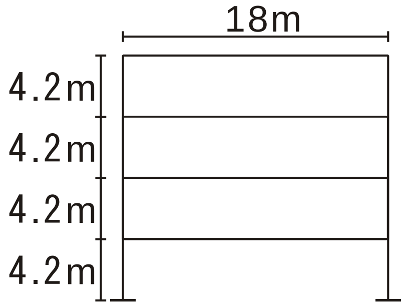


Figure 4 Prototype structure

Cyclic loading tests on three PCaPC portal frames with different strands (GCS-U, bonded ordinary strands and unbonded ordinary strands) were conducted. Objectives of the experiment are as follows:

- To observe damage progress as the story drift angle increases.
- To measure the amount of energy dissipation and residual deformation.
- To confirm the ultimate failure mode and ductility.
- To develop a numerical model to simulate the behavior of the specimens.

The first story of a prototype four-story building was modeled. The sections of columns and beams of the original building was 900mm×900mm and 1050mm×750mm. A four story frame with a single span was designed based on the Calculation of Response and Limit Strength [6]. Nonlinear static analysis was conducted to design the frame, in which each member was modeled as an elastic beam-column element with nonlinear rotational springs at both ends. The rotational spring had *M-θ* relations proposed for bonded prestressed members by Okada et al.[7]. It was confirmed in the analysis that lateral load capacities of the buildings satisfied required capacities at repairable damage limit state and safety limit state. The former state was defined by the point when at least one member reached the yield moment, and latter state was defined by a story drift angle of 1/50.

Figures 5 and 6 show the configuration and dimension of the specimens. Prestressing tendons in the beam were placed so that they canceled flexural moment due to the long term vertical load. The initial prestressing force introduced to tendons was 105.3 kN in the beams and 143.6 kN in the columns. Material properties are shown from Table 1 to 4.

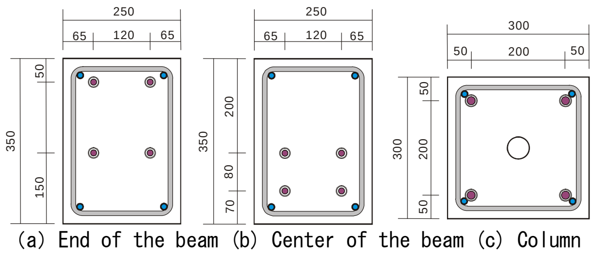


Figure 6 Cross sections of specimens (unit: mm)

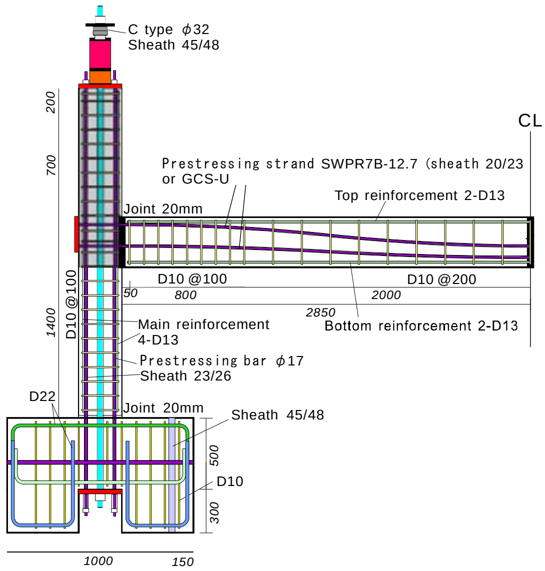


Figure 5 Specimen dimensions (unit: mm)

The variable of the experiment were the types of tendons. As shown in Table 5, Specimens BOND and UNBOND used bonded or unbonded ordinary strands and Specimen GCS used GCS-U. Reinforcing arrangements were identical in all specimens. In all members of BOND and UNBOND, stubs and columns were cast separately and connected by tendons. However, second-story columns and a beam of GCS were cast in one time because GCS-U needed directly embedded at the ends of the beam.

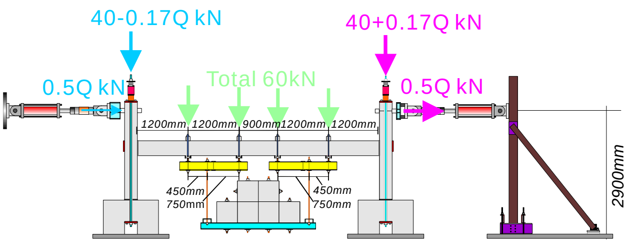


Figure 7 Loading system

Figure 7 shows the loading system. Both stubs were fixed to the reaction floor. The beam was vertically loaded firstly with a 6.0 ton concrete block weight at four points, simulating the moment distribution due to long term vertical load.

Table 1 Concrete

Type	Compressive strength (MPa)	Strain at compressive strength (%)	Tensile strength (MPa)	Young's modulus (GPa)
GCS	60.9	0.250	3.42	29.8
Other concrete	61.0	0.236	3.10	30.2

Table 2 Mortar and grout mortar

Beam		Column
Compressive strength (MPa)	Tensile strength (MPa)	Compressive strength (MPa)
49.6	3.36	60.5

Table 3 Ordinary steel

Type	Yield strength (MPa)	Strain at yield strength (MPa)	Tension strength (MPa)	Young's modulus (GPa)
D10	347	0.225	464	173
D13	356	0.192	498	185
D22	373	0.232	569	182

Table 4 Prestressing bar and strand

Type	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
Prestressing bar ϕ17	1195*2	1274	200
Prestressing strand ϕ 12.7*1	1773*2	1975	193
Low strength wire of GCS-U	144*2	152.0	195

*1Used as prestressing tendons in Specimens UNBOND and BOND. It is also used a central unbonded strand of GCS-U in Specimen
*2 0.2% offset value

Table 5 Specimens and variables

Specimens	Structure	Column	Beam
BOND	Precast	Bonded	Bonded
UNBOND	Precast	Unbonded	Unbonded
GCS	Precast	Unbonded	GCS-u

Equal magnitude of lateral load was applied to the both ends of the frame. The axial force of the columns was varied depending on the magnitude of lateral load (axial load, $N = 40 \pm 0.17\,Q$ kN, Q: lateral load (kN)). Lateral displacement at the midspan was controlled with preselected story drift angle with two cycles each at ±0.1, ±0.2, ±0.4, ±0.6, ±0.8, ±1.0, ±2.0, ±3.0, ±4.0, ±5.0, ±7.5%.

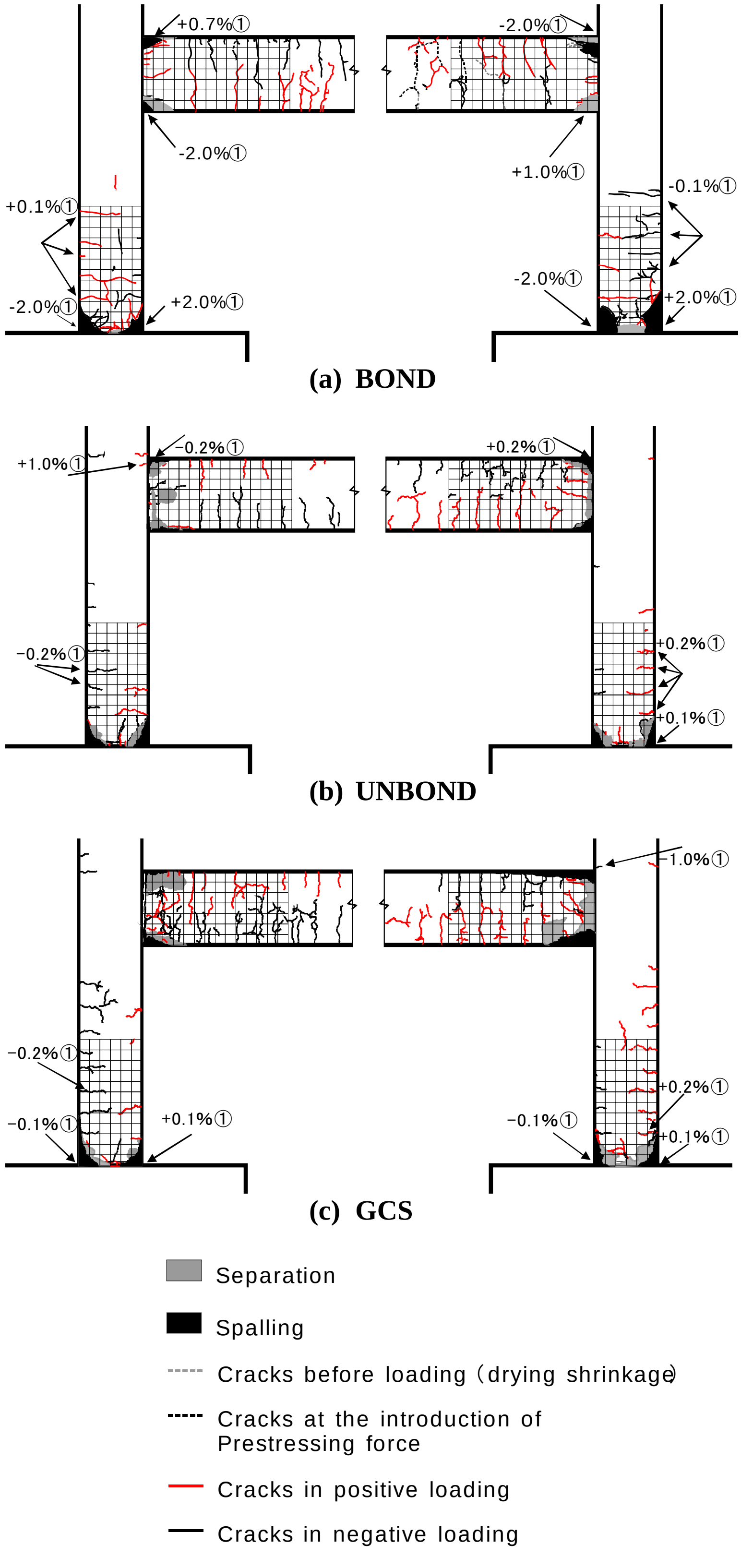


Figure 8 Damage and crack patterns

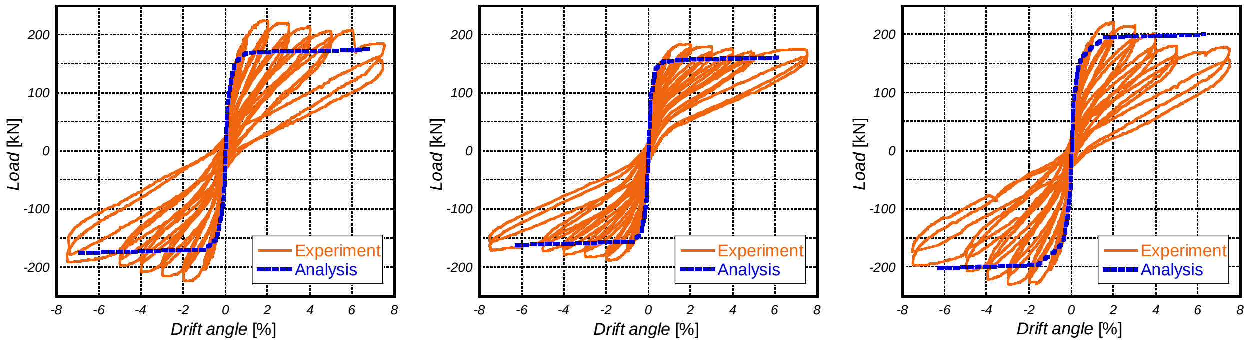
4. RESULT OF THE EXPERIMENT

4.1 Damage progress and crack pattern

Damage and crack patterns are shown in Figure 8. Cracks are shown with drift angle, R, and the cycle number when the crack took place. GCS had more cracks than UNBOND, but damage conditions of both specimens were not very different. Flexural cracks appeared at outside of the columns and bottom of the beams, but severe damage such as concrete spalling at beam and column ends did not occur until R = 2.0%. The residual crack widths were invisible at R =1.0% and less than 0.2 mm at R = 2.0%.

4.2 Lateral load-story drift angle relations

Lateral load-story drift angle relations are shown in Figure 9. All specimens provided self-centering behavior. The residual drift angle at R =3.0% were smaller than 1/600 corresponding to the deformation at repairable damage state. Hysteresis loops of BOND and GCS were fat compared to that of UNBOND. Lateral load capacity degradation after the peak load was very small in UNBOND, and not intensive in BOND and GCS. All specimens had enough ductility. The lateral load capacity of GCS at R =7.5% was similar to that of UNBOND. This is because the low strength wires of GCS-U had bond deterioration at large deformation and the specimen showed a similar behavior and ultimate capacity to the unbonded structure.

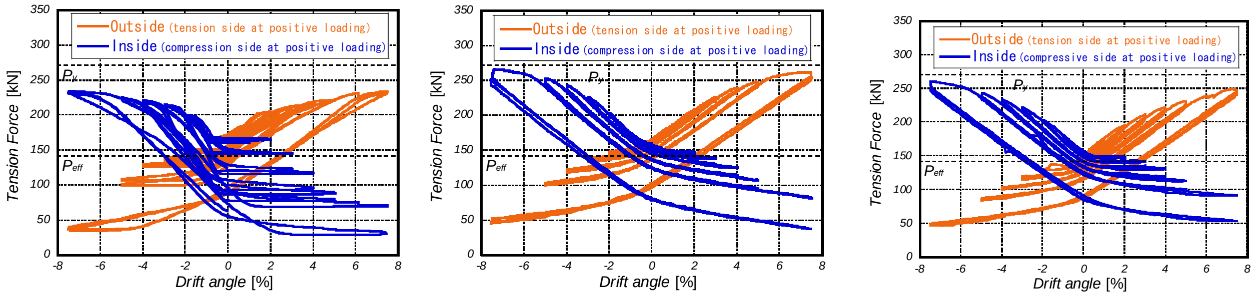


(a) BOND (b) UNBOND (c) GCS

Figure 9 Lateral load-story drift relationships

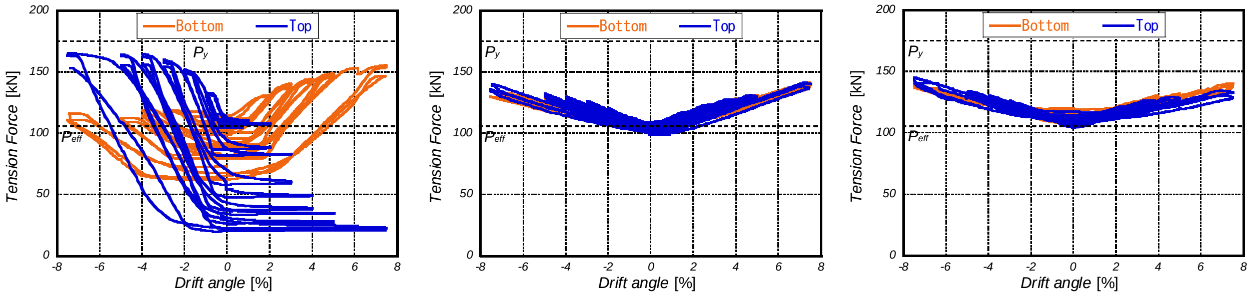
4.3 Tensile force of prestressing bars and strands

Tensile force of prestressing bars in columns and strands in beams-story drift angle relations are shown in Figures 10 and 11. Tensile force of tendons in columns didn't reach the yielding force, P_y, in all specimens. However, evaluated from envelope curves, it is highly possible that prestressing bars in columns yielded around R = 4% in Specimens UNBOND and GCS, and around R = 2% in Specimen BOND. The differences between experimental results and P_y were due to measuring errors. Residual tensile force of prestressing bars in all columns decreased as the deformation increased. This is because tendons yielded and additionally, the columns shortened due to damage at the column bases. In beams, tendons yielded in Specimen BOND, but didn't yield in Specimens UNBOND and GCS.



(a) BOND (b) UNBOND (c) GCS

Figure 10 Tensile force of prestressing bars and strands (column)



(a) BOND (b) UNBOND (c) GCS

Figure 11 Tensile force of prestressing bars and strands (beam)

4.4 Equivalent viscous damping ratio and residual drift angle

Equivalent viscous damping ratios at second loops are shown in Figure 12. An analytical result by Eq. (1) according to Japanese guideline [8] is also shown.

$$h = \gamma_1 (1 - 1/\sqrt{D_f}) + 0.05 \qquad \textbf{(1)}$$

$$\gamma_1 = 0.06 + 0.19\sqrt{\eta}$$

$$\eta = M_r / (M_p + M_r)$$

$$D_f = \Delta_s Q_d / \Delta_d Q_s$$

h : Equivalent viscous damping ratio

M_r : Flexural strength contributed from reinforcing bars

M_p : Flexural strength contributed from prestressing bars

Δd : Displacement at damage limit state

Q_d : Share force at damage limit state

Δs : Displacement at safety limit state

Q_s : Share force at safety limit state

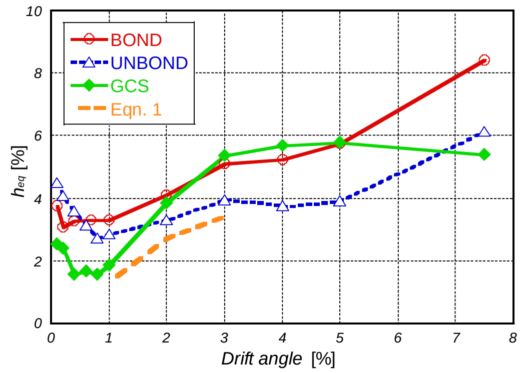


Figure 12 Equivalent viscous damping ratios

Equivalent viscous damping ratio of GCS was similar to that of BOND and larger than that of UNBOND between R=1.5% and 3.0%. GCS and UNBOND used the same unbonded seven-wire strand, so the difference of equivalent viscous damping ratio was caused by energy dissipation due to yielding of mild steel wires of GCS-U. GCS showed smaller damping ratio than BOND before R=1.5%, because mild steel wires didn't yield due to imperfect anchorage. Developing effective anchorage and introducing initial prestressing force to mild steel wires, GCS-U would have dissipated larger energy at small drift angle.

Calculation results of Eq. (1) were smaller than three experimental results. This proved that damping ratio according to the Japanese guideline gives under-estimate of seismic response of PCaPC structures irrespective of the bond characteristic of tendons.

The residual drift angle of each specimen at the end of second cycle is shown in Fig. 13. The values are under 1/600 even after *R*=3.0%. *R*=1/600 corresponds to the drift angle at repairable damage state, and all specimen were regarded as repairable. However, the residual drift angle of GCS was not small compared to that of BOND. The result have not been investigated yet, but the residual drift angle of GCS became smaller than that of BOND after *R*=3.0% when tendons of BOND probably yielded. When high initial prestressing force is introduced and bonded tendons yield at early state under seismic loading, GCS-U probably can demonstrate advantages compared to ordinary strands.

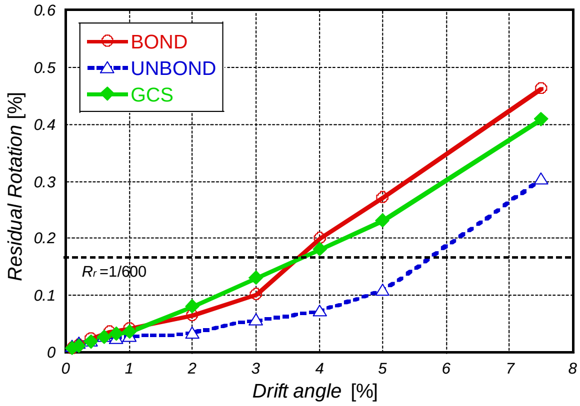


Figure 13 Residual drift angles

5. ANALYSIS

5.1 Analytical model

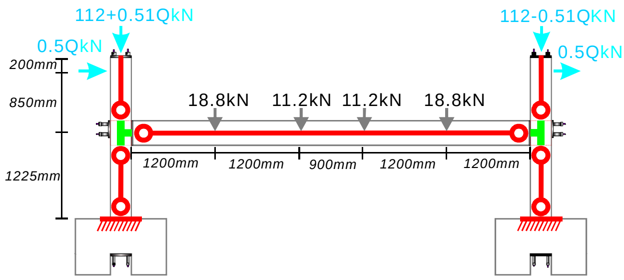
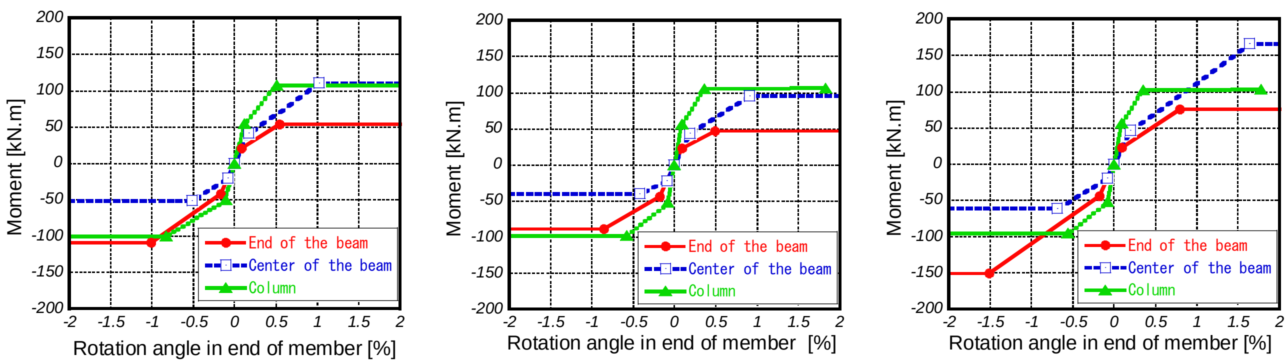


Figure 14 Analytical model

The analytical model is shown in Fig.14. The columns and the beam were modeled as an elastic line element with nonlinear rotational springs at both ends. Nonlinear rotational springs were modeled with trilinear envelope curves proposed by Okada et al. [6] The trilinear model was proposed for bonded prestressed concrete members. The column-beam joints were assumed to be rigid and the column bases were fixed. Vertical and lateral loads were applied to simulate the loading conditions of the experiments. Prestressing force was determined corresponding to the experimental values measured before the specimens experienced lateral deformation. The nonlinear characteristics of the rotational springs are shown in Fig.15. Bottom tendons are in tension and columns are in compression at positive rotation angle in the figure.



(a) BOND (b) UNBOND (c) GCS

Figure 15 Restoring force characteristic in ends of members

5.2 Analytical results

The analytical results are compared to the experimental results in Fig.9. The initial stiffness and the curve before the peak load were well simulated. However, the computed capacities were smaller than the experimental results in three specimens. The simulation on GCS is not as good as other two specimens because the bond characteristics of GCS-U were not correctly modeled.

6. CONCLUSIONS

1. The specimen using GCS-U dissipated as large energy as the specimen using bonded ordinary strands due to yielding of mild steel wires. Developing effective anchorage and introducing initial prestressing force to mild steel wires, GCS-U would show higher energy dissipating performance. The equivalent viscous damping ratio can be estimated according to the Japanese guideline irrespective of bond properties and types of strands.
2. Precast prestressed concrete structures designed by Calculation of Response and Limit Strength method showed high ductility even when tendons were unbonded. Lateral load capacity of precast prestressed concrete portal frames remained more than 80 % of the peak load until the drift angle of 7.5%.
3. All precast prestressed concrete specimens showed good self-centering behaviors. The damage of the structure concentrated at interfaces between members. Crack widths were less than 0.2 mm after experiencing 2.0% story drifts. The residual story drifts were less than 1/600 until experiencing 3.0% drift angle. However, tensile force of prestressing bars in columns deteriorated at drift angle over 2.0% due to yielding of bars and compressive failure of concrete.
4. The frame analysis using the M-θ model proposed for bonded prestressed members well simulated experimental envelope curves regardless of bond properties of strands.

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REFERENCES

[1] Priestley, M., J., N. (1991), Overview of the PRESSS Research Program. *PCI Journal*, **36(4)**, 50-57.
[2] Priestley, M., J., N. (1996), The PRESSS Program Current Status and Proposed Plans for Phase III. *PCI Journal*, **41(2)**: 22-40.
[3] Priestley, M., J., N., Sritharan, S., Conley, J., R. and Pampanin, S. (1999), Preliminary Results and Conclusions from the PRESSS Five-Storey Precast Concrete Test-Building. *PCI Journal*, **44(6)**, 42-67.
[4] Englekirk, R., E. (2002), Design-Construction of the Paramount – A 39-story Precast Prestressed Concrete Apartment Building. *PCI Journal*, **47(4)**, 56-71.
[5] Niwa, Y., Watanabe, F., Nishiyama, M. and Muguruma, H. (1993), Energy Dissipating Precast-Prestressed Beam-Column Connection. *Summaries of technical papers of Annual Meeting Architectural Institute of Japan.* **Structures II**, 535-536. (in Japanese)
[6] Okada, M., Hamahara, M., Suetsugu, H., Motooka, J. (1990). Elasto-Plastic Hysteretic Behavior of Prestressed Concrete Beams. *Journal of Structural and Construction Engineering*, **410,** 63-69. (in Japanese)
[7] Architectural Institute of Japan. (1987). *Standard for Structural Design and Construction of Prestressed Concrete Structures*. (in Japanese)
[8] The Building Center of Japan. (2005). *Commentary on technical standards and calculation example of seismic design method based on energy balance*, 109. (in Japanese)