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IDEA OF HYBRID COLUMN WITH ENERGY ABSORPTION ELEMENT

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SUMMARY

RC structure doesn't absorb energy before yielding, but once it yields and absorbs a large amount of energy, it causes a large residual deformation. One idea to control the response is an introduction of base isolation system or vibration control devices. Another idea is to give energy absorption ability to some building elements, and to combine it with another structural element. For example, RC column with wing walls has a big chance of shear failure because of its geometrical proportion. If the wing walls fail earlier and the column survives the damage, the wing walls will work similarly to a vibration control device. To realize this hybrid column, the wing walls should be made of a material that has low cracking strength and high toughness after cracking. It is difficult to increase toughness only by mixing chopped fiber with normal concrete. If the tensile strength of concrete is lowered by using super lightweight aggregate and the bond strength of fiber is not much reduced, it may be possible to increase the toughness.

This paper will describe the pilot test to verify an idea of the hybrid column, and the development of super ductile mortar for wing walls.

CONCEPT OF HYBRID COLUMN

Shear force-displacement relations of RC bare column, RC column with wing walls and hybrid column with super ductile wing walls are schematically shown in Fig. 1. The filled circles in the figure indicate the maximum response at the event of an earthquake. The rigidity of RC column with wing walls is high, and the induced shear force becomes large. Then, it has a big chance to fail in shear and collapse. On the other hand, the stiffness of RC bare column is low in comparison with RC column with wing walls. It will fail in flexural mode and exhibit a ductile behavior. However, it may take a flexural damage and eventually cause a large residual deformation. The hybrid column proposed in this study consists of a high strength column and wing walls made of super ductile concrete. The concrete of wing walls has low tensile strength and the shear cracks on the wing walls will be generated earlier at the small drift angle because of geometrical proportion. Furthermore, the concrete of wing walls shows a strain hardening after cracking, and the multiple cracks are generated before longitudinal bars in column section reach the yield strain. The low strength steel bars crossing the cracks on the wing walls yield and absorb the energy.

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If the wing walls made of super ductile concrete works as a vibration control device and the response will be limited within the yield displacement of the column, the column can survive a heavy damage and a reparable structure can be realized.

This study focuses on the development of super ductile concrete that can be applicable to wing walls and the experimental verification of the idea of hybrid column with super ductile wing walls. This idea will be applicable to spandrel walls, too, that shortens the deflectable length of the column.

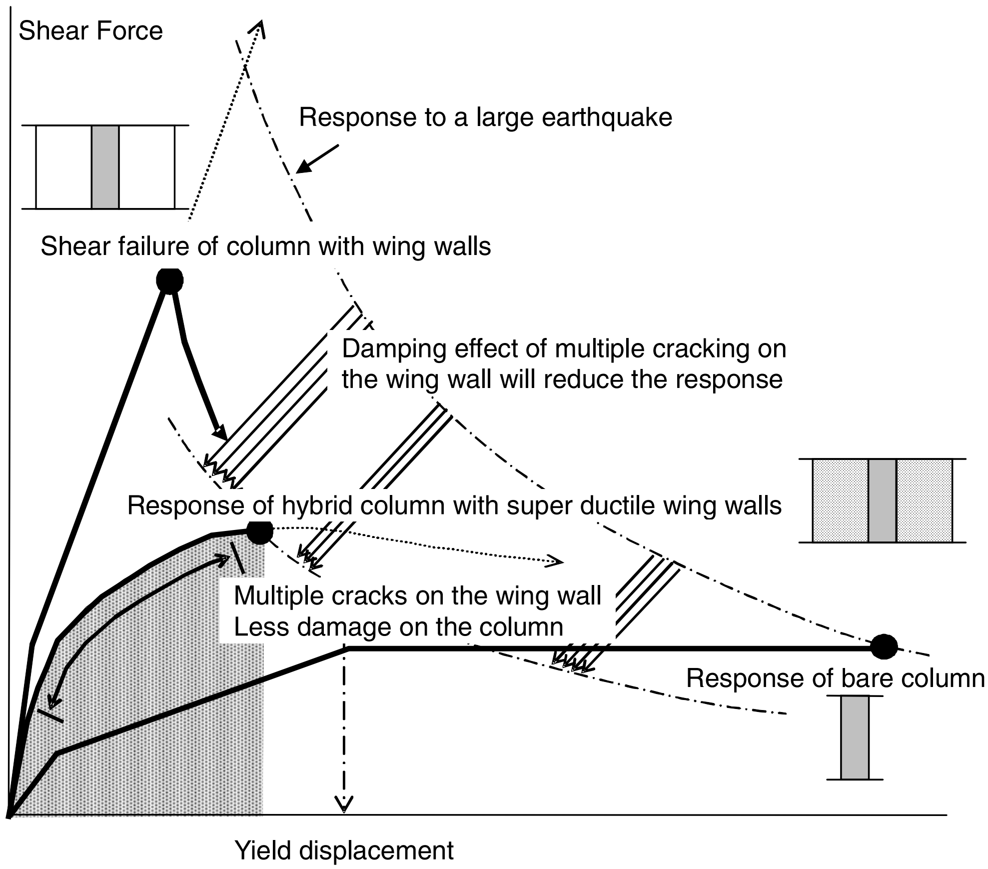

Fig. 1 Design concept

DESIRABLE MATERIALS FOR WING WALL

A possible material for the wing walls is fiber reinforced concrete (FRC). FRC has been studied for various purposes. For example, Shima[1] and Kuratani [2] investigated structural members controlling damage by FRC. Hatta[3] and Fujiwara [4] also conducted test to clarify structural performance of devices absorbing energy by FRC. However, it is difficult to increase toughness and cause multiple cracks only by mixing chopped fiber with normal concrete. If the tensile strength of matrix is small in comparison with that of fiber, the fiber can transfer the tensile force across the cracks and can generate the multiple cracks. Kobayashi [5] tested the beams with super lightweight concrete and found that the cracking strength was much reduced, but the bond strength with steel bar was not much reduced. To obtain a low tensile strength concrete, the use of super lightweight aggregate was discussed in this study, and to obtain the toughness after cracking, the mixing of polyvinyl alcohol (PVA) fiber with super lightweight concrete was discussed.

PVA Fiber Reinforced Lightweight Mortar

Mechanical properties of fiber and mixture proportions of PVA fiber reinforced lightweight mortars are shown in Table 1 and Table 2. PVA fiber is shown in Photo. 1. The super lightweight aggregate is shown in Photo. 2, that was made from the glass waste. A common factor for mixture proportions in Table 2 is water cement ratio (W/C) of 60%. To reduce the amount of cement and obtain the low strength, 5% or 7% of cement was replaced by the concrete demolition powder. Three different size of glass waste aggregates were combined and used for mixing mortal. The smallest size (S) is less than 1.2mm, the medium size (M) is 1.2 to 2.5mm and the large size (L) is 2.5 to 5.0mm. The primary variables are the proportion of particle size (S:M:L) and the fiber volume fraction. In cases of G6-60P7F1.0W20 and G6-60P7F1.6W20 listed in Table 2, the glass waste aggregates were pre-wetted to better workability.

Table 1 Mechanical properties of fiber

Type of fiber	Tensile strength (N/mm^2)	Diameter (mm)	Length (mm)	Modulus of elasticity (N/mm^2)	Elongation (%)
PVA	910	0.2	12	29000	7

Table 2 Mixture proportions of PVA fiber reinforced lightweight mortars

Type of mortal	W/C (%)	Cement (kg/m^3)	Water (kg/m^3)	Fine Agg.* (kg/m^3)	S:M:L**	P*** (kg/m^3) (Weight %)	Fiber**** (Volume %)
G5-60-P5F1.6	60	602.9	361.8	300.5	5:3:2	30.1(5%)	1.6
G6-60-P5F1.6	60	607.9	364.7	302.9	6:3:1	30.4(5%)	1.6
G7-60-P5F1.6	60	610.4	366.2	304.2	7:2:1	30.5(5%)	1.6
G6-60P7F1.0W20	60	611.6	367.0	304.8	6:3:1	42.8(7%)	1.0
G6-60P7F1.6W20	60	607.9	364.7	302.9	6:3:1	42.6(7%)	1.6

* Super lightweight glass aggregate
** S: Particle size is less than 1.2mm M: 1.2 to 2.5mm L: 2.5 to 5mm.
*** Demolition powder of concrete
**** Polyvinyl alcohol fiber

Photo. 1 PVA fiber

Photo. 2 Lightweight glass aggregate (Type : L)

Four Points Loading Test

Four points bending tests were conducted to investigate the material property. The dimension of the test specimen is 50×150×530mm as shown in Fig. 2. The relations between the applied load and the deflection at the center are shown in Fig. 3. A typical cracking pattern on the bottom of the specimen is shown in Photo. 3.

The expected strain hardening after cracking and the multiple cracks were observed in all the specimens. Regardless the proportion of particle sizes (S:M:L) and the amount of fiber volume fraction, the first bending crack occurred at almost same stress level. On the influence of the proportion of particle sizes, the maximum bending strength and the highest toughness were achieved in G6-60-P5F1.6 that had the proportion of particle size S:M:L=6:3:1. When the fiber volume fraction is 1.6%, G5-60-P5F1.6 with the proportion of particle size S:M:L=5:3:2 showed the poorest behavior. When the fiber volume fraction was larger, the maximum bending strength and the toughness were higher. As mentioned above, the test revealed that the material performance was affected by the proportion of particle size and the fiber volume fraction.

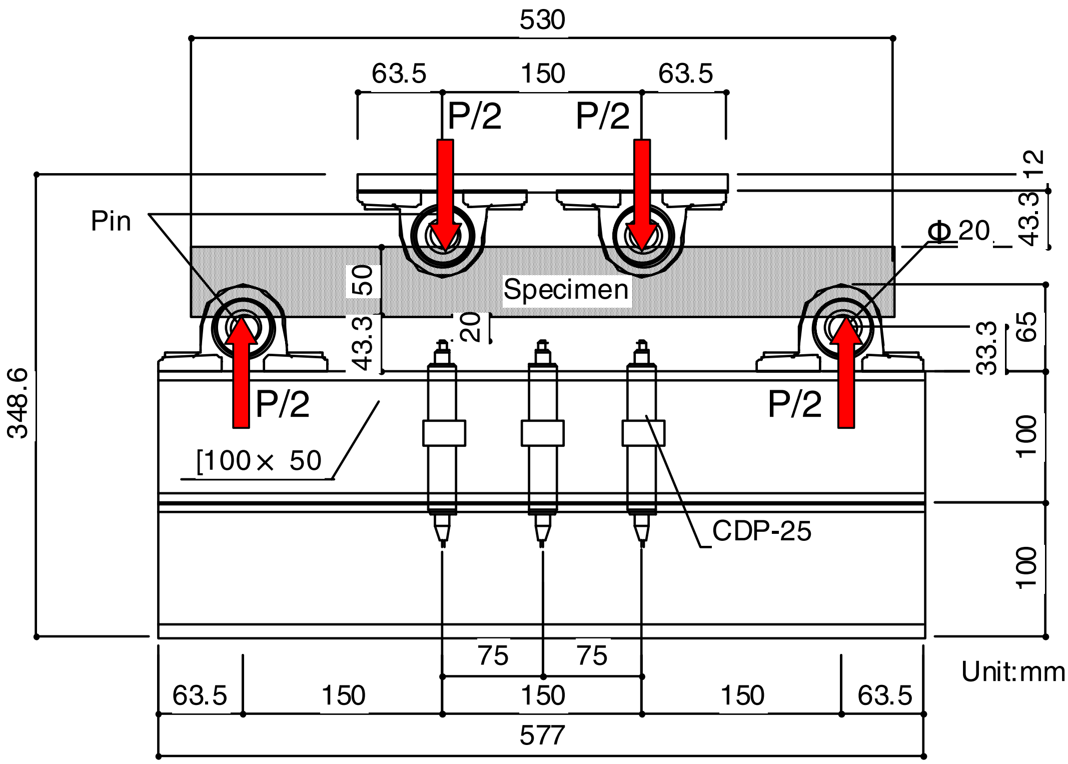

Fig. 2 Four points bending test setup and dimensions

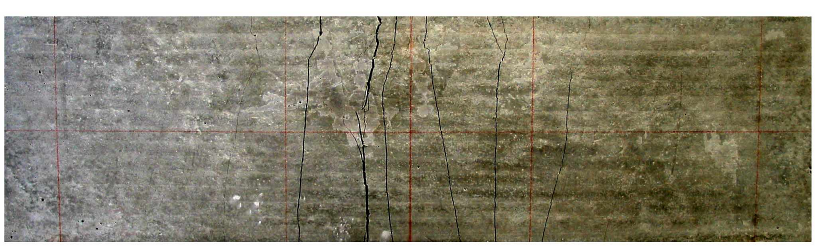

Photo. 3 An example of a typical cracking pattern on the bottom for the specimen

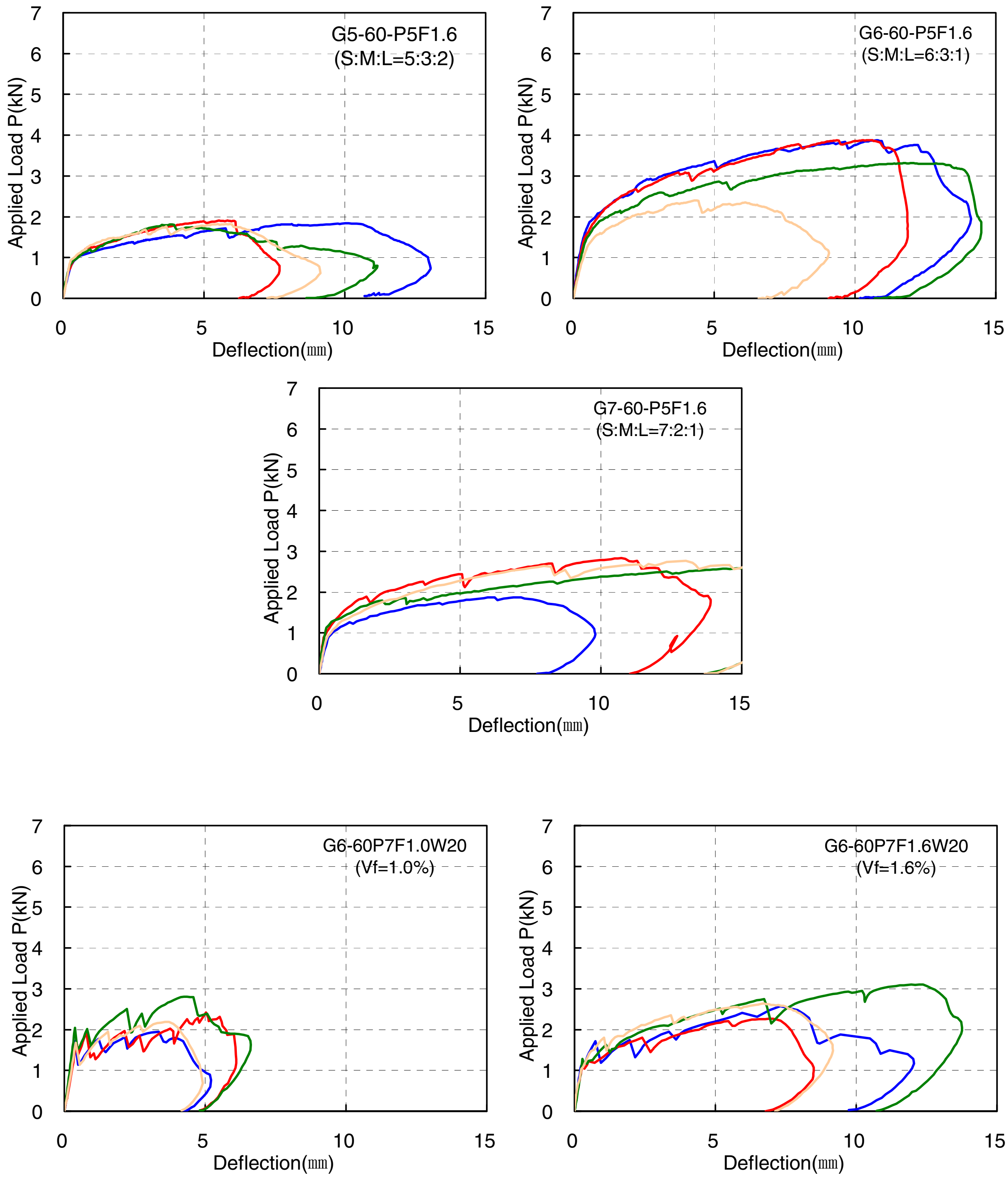

Fig. 3 The relations between the applied load and the deflection at the center
for lightweight mortals reinforced with PVA fiber

VERIFICATION OF THE IDEA OF HYBRID COLUMN

Outline of Experiment

Two specimens in Table 3 were tested to verify the idea of hybrid column proposed in this study. The cross section size of columns ($B \times D$) is 100mm in width x100mm in depth. The shear span to depth ratio of the bare column (a/D) is 2.0. Ten main bars of D6 were arranged in the column. The transverse reinforcement of 4φ was placed at the interval of 30mm as shown in Fig. 4. The shear reinforcement ratio (p_w) of the columns is 1.67%. It simulates a high strength concrete column with high strength steel bars.

One specimen is RC bare column and the other one is a hybrid column with wing walls made of super ductile mortal described in the previous section. The shear keys were made at the interface between the wing walls and the column and beams as shown in Fig. 5. The length of the wing wall is two times of column depth (200mm), and the thickness is 30mm. The shear reinforcement ratio of the wing wall (p_{sh}) is 0.38%. The wing walls were designed so that they would fail in shear, but the shear cracks would not pass through the column and eventually the hybrid column with wing wall would fail in flexural mode.

Table 3 Summary of specimens

Specimen	Column		Wing wall	
	p_w(%)	Type of Concrete	P_{sh}(%)	Type of Concrete
RC bare column	1.67	Normal concrete		
Hybrid column with wing walls		Normal concrete	0.36	PVA fiber reinforced lightweight mortal

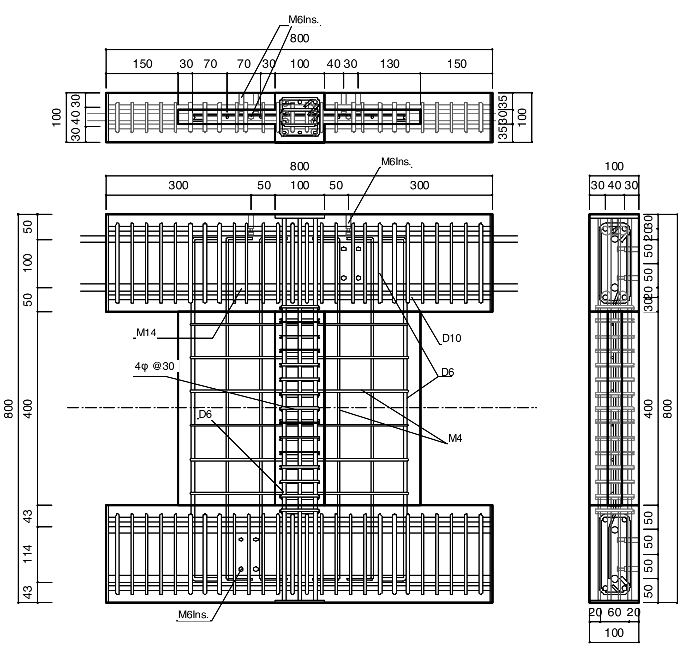

Fig. 4 Details of hybrid column with wing wall

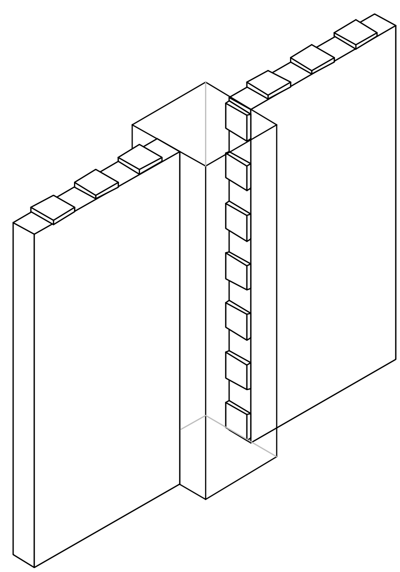

Fig. 5 Arrangement of cotter

The mechanical properties of concrete and steel bars are listed in Table 4 and Table 5. The mixture proportion of PVA fiber reinforced lightweight mortal, G6-60P7F1.6W20, in Table 2 was adopted for the wing walls because it showed the most desirable performance.

Table 4 Mechanical properties of concrete

Concrete		
Normal Concrete	Compressive Strength (N/mm^2)	44.0
	Splitting Tensile Strength (N/mm^2)	3.09
	Young's Modulus (N/mm^2)	2.64×10^4
	Strain at Compressive Strength (μ)	3045
PVA Fiber Reinforced Lightweight Mortar	Compressive Strength (N/mm^2)	23.3
	Splitting Tensile Strength (N/mm^2)	1.86
	Young's Modulus (N/mm^2)	0.760×10^4
	Strain at Compressive Strength (μ)	3726

Table 5 Mechanical properties of steel bars

Steel Bar			
Type of Steel Bar	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Young's Modulus (N/mm^2)
M4*	467	515	2.10×10^5
4ϕ	265	365	1.83×10^5
D6	353	544	1.86×10^5

* Screw bar was used as a replacement of deformed bar to ensure the bond resistance.

The loading apparatus is illustrated in Fig. 6. The reversed cyclic loads were given gradually increasing the drift angle so that the clear span has a reversed symmetrical moment distribution. The horizontal load and the relative displacement between the upper and the lower stubs were measured with load cell and linear variable displacement transducers (LVDTs), respectively.

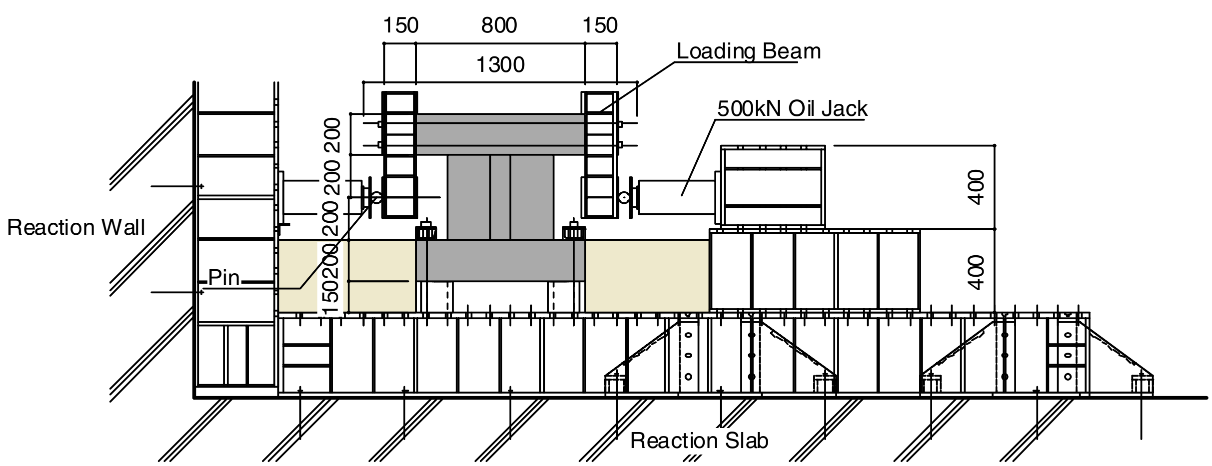

Fig. 6 Loading apparatus.

Experimental Results

Cracks at the drift angle of 0.8/100 radian are shown in Photo. 4. Bending and shear cracks of RC bare column concentrated in the plastic hinge zone. Bending cracks at column top and bottom opened widely.

On the other hand, shear cracks on the wing walls initiated at very small drift angle and a large number of cracks were generated before the drift angle reached 0.8/100 radian. Only a few cracks were generated on the column, but the crack width did not expanded as shown in Photo. 4. The hybrid column was finally loaded until the drift angle of 3.3/100 radian. The shear force gradually decreased due to the crash of concrete on the wing walls. The number of cracks on the column increased, but it was much less than that in RC bare column.

RC bare column

Hybrid column with wing walls

Photo. 4 Cracks at the drift angle of 0.8/100 radian

Shear Force vs. Displacement Relationships

Relationships between shear force and horizontal displacement are shown in Fig. 7. RC bare column showed typical flexural restoring force characteristics, but its flexural capacity is small and the amount of energy absorption is not much before yielding. Then, the response displacement must become large and cause a large residual displacement after the event.

As for the hybrid column with super ductile wing walls, both the rigidity and the flexural capacity gained a lot due to the contribution of wing walls. The longitudinal bars in the column were supposed to have yielded at the drift angle of 0.8/100 that was same as the yield displacement of the bare column. After yielding, the column did not fail in shear and kept the shear force at yielding till the drift angle of 2/100. The diagonal strut on the wing wall gradually crashed and the bearing force decreased. The hysteretic loop showed a spindle shape even after yielding, though the wing walls had so many shear cracks.

It can be concluded that the energy absorption ability of the hybrid column with wing walls is much superior to that of the bare column because the capacity gained a lot without deterioration of restoring force characteristics.

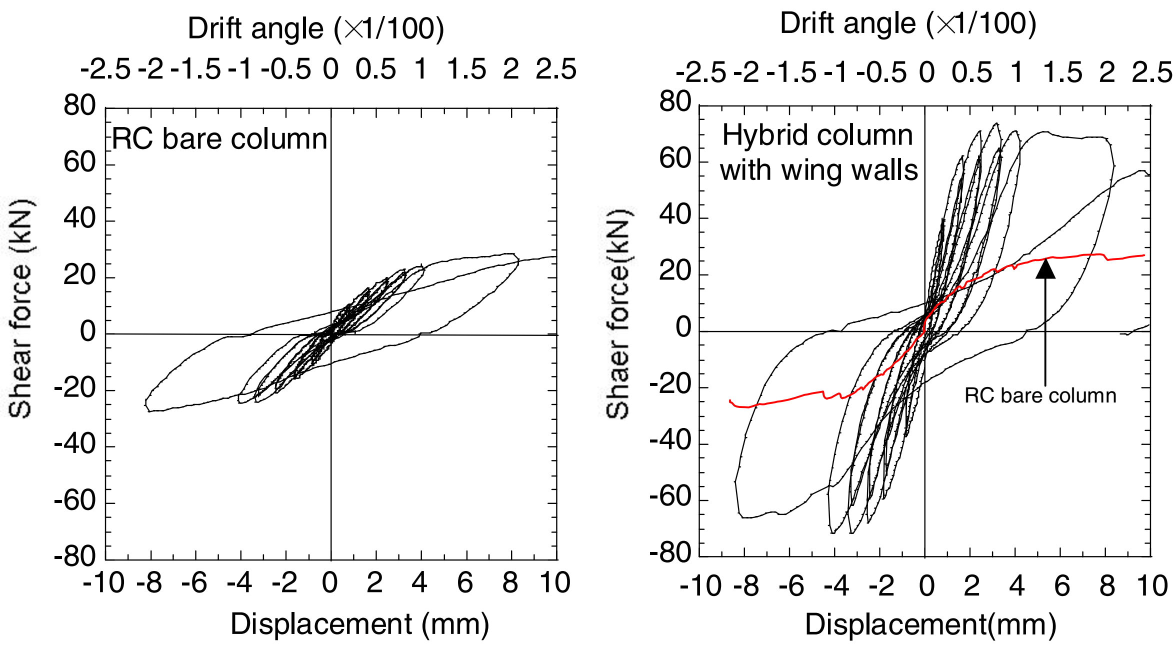

Fig. 7 Relationships between shear force and horizontal displacement

CONCLUSIONS

1. A super lightweight mortal reinforced with fiber is a very possible material for the wing walls of the proposed hybrid column in this study. In order to obtain the toughness after cracking, the optimal fiber fraction and an ideal aggregate size distribution might exist.
2. A scaled RC column with wing walls made of fiber reinforced super lightweight mortal was tested and it was found that the hybrid column proposed in this study could be realized.
3. Design criteria for the hybrid column must be developed in the next phase so that the expected performance of the hybrid column can be guaranteed, and the effect of response control must be verified by the dynamic response analysis.

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REFERENCES

1. Shima D., Kuratani Y., Fukuyama H., Nakano K., Matsuzaki Y. “Study on Ductile Cement Composites for Structural Elements. Part 6 Structural Performance of Beams using Ductile Engineered Cementitious Composites (Outline and Results of Experiment)” Summaries of Technical Papers of AIJ Annual Meeting, C-2, 1999: 645-646
2. Kuratani Y., Shima D., Fukuyama H., Nakano K., Matsuzaki Y. “Study on Ductile Cement Composites for Structural Elements. Part 7 Structural Performance of Beams using Ductile Engineered Cementitious Composites (Investigation of Experimental Results)” Summaries of Technical Papers of AIJ Annual Meeting, C-2, 1999: 647-648
3. Hatta N., Fujiwara T., Iso M., Fukuyama H., Nakano K., Matsuzaki Y. “Experimental Study on Structural Performance of Device using PVA-HPFRCC (Part 1 Outline of Result of Experiment)” Summaries of Technical Papers of AIJ Annual Meeting, C-2, 2001: 515-516
4. Fujiwara T., Hatta N., Iso M., Fukuyama H., Nakano K., Matsuzaki Y. “Experimental Study on Structural Performance of Device using PVA-HPFRCC (Part 2 Investigation of Experimental Results)” Summaries of Technical Papers of AIJ Annual Meeting, C-2, 2001: 517-518
5. Kobayashi K., Matsuzaki Y., Fukuyama H., Hakuto S. “ Performance Evaluation of RC Elements with Ultra Lightweight Concrete.” Proceedings of 6th ASCCS Conference, Los Angels, USA, 2, 2000: 977-984