Fracture Mechanics of Concrete and Concrete Structures -
High Performance, Fiber Reinforced Concrete, Special Loadings and Structural Applications- B. H. Oh, et al. (eds)
 ISBN 978-89-5708-182-2

Shear strength and deformation capacity of dampers with SHCC

H. Suwada
Building Research Institute, Ibaraki, Japan

H. Fukuyama
Building Research Institute, Ibaraki, Japan

ABSTRACT: Strain Hardening Cementituous Composite (SHCC) shows Pseudo Strain Hardening behavior (PSH behavior) under tensile stress. The purpose of this study is to verify the influencing factors on shear strength and deformation capacity of dampers using SHCC. In this study, the structural tests using SHCC dampers are conducted to obtain the basic data on shear behavior. The test variables are shear reinforcement ratio, depth to width ratio of cross sectional area, width span ratio, presence of flexural yielding, and the influence of hysteresis cyclic loading. On that basis, the shear resistance properties of dampers using SHCC are examined based on the results of experiments. The test results offer the following conclusions. When the shear failure occurs without flexural yielding, the value of shear strength is the same as that of RC member using SHCC tensile stress instead of shear reinforcement. When it occurs with flexural yielding, the value of deformation capacity is larger than RC members with the same condition. In case of cyclic loading, the larger difference between two values of each can be observed.

1 INTRODUCTION

High Performance Fiber Reinforced Cementitious Composite (SHCC) [1)~5)]exhibits Pseudo Strain Hardening Behavior (PSH behavior, hereafter) by Multiple Crack under tensile stress. These days, there has been an increase of research[6)] in order to use this newly developed material into structural members. Aiming mainly the damage control of Reinforced Concrete Structures (RC structures, hereafter), authors have been engaged in the development of a new damper. The damper should have the higher shear stress over 5N/mm^2 than the conventional RC columns, have more enhanced deformation capacity (drift angle at 10%), and bear an axial force (Figure 1)[7)~9)]. In order to apply members like this into structures, the evaluation method on the shear strength and deformation capacity in addition to rigidity and bending strength of the member is needed. Therefore, one of the most important issues is to clarify how SHCC's characteristics influence on shear strength and deformation capacity of structural members.

Nagai et al.[10)] performed bending-shear tests of beams using SHCC. They proposed the shear strength evaluation which increased the tensile stress of SHCC by using Design Guidelines for earthquake resistant reinforced concrete buildings based on ultimate strength concept (hereafter the guideline on ultimate strength concept)[13)]. Kasahara et al.[11)] performed bending –shear tests of beams and columns using SHCC. They added the tensile stress of SHCC into the force of a pair of shear reinforcements and assumed the cross sectional area would increase compare to the shear reinforcement. As a result, they proposed shear strength evaluation using guideline on ultimate strength concept.

Shimizu et al. [12)] performed bending-shear test of beams using SHCC. They proposed shear strength evaluation which added the same value of shear stress as uniaxial tensile strength into guideline on ultimate strength concept, assuming that the shear stress on the cracking surface plays a dominant role in the stress of SHCC against acting shear force.

Compare to the conventional RC structural members, however, many factors which could influence the shear strength and deformation capacity of SHCC members still remain to be investigated. Additionally, the evaluation method has not yet standardized. Therefore, in order to establish the standard method for evaluation, it is essential to collect the experimental data on broader facts.

Based on the above background, in this study, the experiments will be implemented to investigate the various factors which influence the shear strength and deformation capacity on dampers under bending shear force, and to collect the basic data.

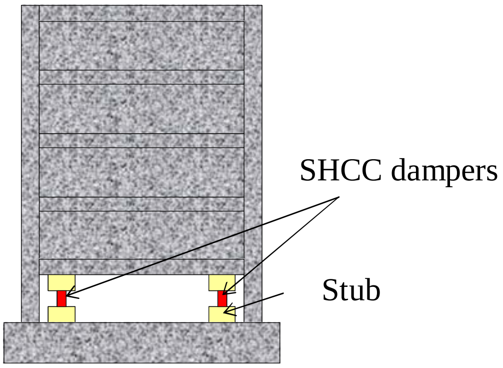


Figure 1. Application of SHCC dampers.

2 EXPERIMENT

2.1 *Test Specimens*

The lists of test specimens classified by experimental parameters are shown in Table 1 and the bar arrangements of all the specimens are shown in Figure 2. The total number of specimens is 17. The specimens from series I to series IV are planned to investigate the effects of shear-span ratio (*M/DQ*), cross section (*b/D*), shear reinforcement ratio (p_w), and axial force, by focusing on the shear ultimate strength. Those from series V and VI are planned to investigate the effects of shear failure after flexural yielding, and cyclic loading hysteresis. No.2 specimen is planned as a standard specimen for those from series I to series IV which are aimed to be the type of shear failure prior to flexural yielding. No. 11,12,15,16 and 17 specimens are planned to compare to SHCC specimens and examine the shear resistant mechanism. In this case, the SHCC tensile resistance is converted into shear reinforcement $p_w\sigma_{wy}$ (p_w: shear reinforcement ratio, σ_{wy}: yielding stress of shear reinforcement) and is added as shear reinforcement for RC test specimen. As a calculation process, three methods proposed by Nagai, et al. 10), Kasahara et al. 11), and Shimizu et al 12) were employed, respectively. To obtain the shear ultimate strength of the SHCC specimen (p_w=0.28%), σ_{wy} was substituted into 392.3N/mm^2 (4000kg/cm^2) , compressive strength of SHCC was substituted into

Table 1. Test specimens.

Series I (*M/QD*)

Specimen	*L* (mm)	*M/QD*	*b/D*	p_w (%)	*n*	Axial reinforcement	Loading type	Material
No.1	300	0.5	0.75(225/300)	0.28(D6@100)	0	6-D13 (SD785)	Monotonic	SHCC
No.2	400	1.0	0.75(150/200)	0.28(D6@150)				
No.3	600	1.5						

Series II (*b/D*)

Specimen	*L* (mm)	*M/QD*	*b/D*	p_w (%)	*n*	Axial reinforcement	Loading type	Material
No.4	600	1.0	0.5(150/300)	0.28(D6@150)	0	6-D13 (SD785)	Monotonic	SHCC
No.2	400		0.75(150/200)					
No.5	300		1.0(150/150)					

Siries III (p_w)

Specimen	*L* (mm)	*M/QD*	*b/D*	p_w (%)	*n*	Axial reinforcement	Loading type	Material
No.6	400	1.0	0.75(150/200)	0.00	0	6-D13 (SD785)	Monotonic	SHCC
No.2				0.28(D6@150)				
No.7				0.43(D6@100)				
No.17				0.64(D6@67)				Concrete

Siries IV (*n*)

Specimen	*L* (mm)	*M/QD*	*b/D*	p_w (%)	*n*	Axial reinforcement	Loading type	Material
No.2	400	1.0	0.75(150/200)	0.28(D6@150)	0	6-D13 (SD785)	Monotonic	SHCC
No.8					0.4			

Siries V (Yield stress of axial reinforcement)

Specimen	*L* (mm)	*M/QD*	*b/D*	p_w (%)	*n*	Axial reinforcement	Loading type	Material
No.9	400	1.0	0.75(150/200)	0.28(D6@150)	0	6-D13 (SD295)	Monotonic	SHCC
No.10	600	1.5						
No.11	400	1.0		0.64(D6@67)				Concrete
No.12	600	1.5						

Siries VI (Loading type)

Specimen	*L* (mm)	*M/QD*	*b/D*	p_w (%)	*n*	Axial reinforcement	Loading type	Material
No.13	400	1.0	0.75(150/200)	0.28(D6@150)	0	6-D13 (SD295)	Cyclic	SHCC
No.14	600	1.5						
No.15	400	1.0		0.64(D6@67)				Concrete
No.16	600	1.5						

L : Length
M/QD : Shear span ratio
b/D : Depth thickness ratio
p_w : Shear reinforcement ratio
n : Axial force ratio

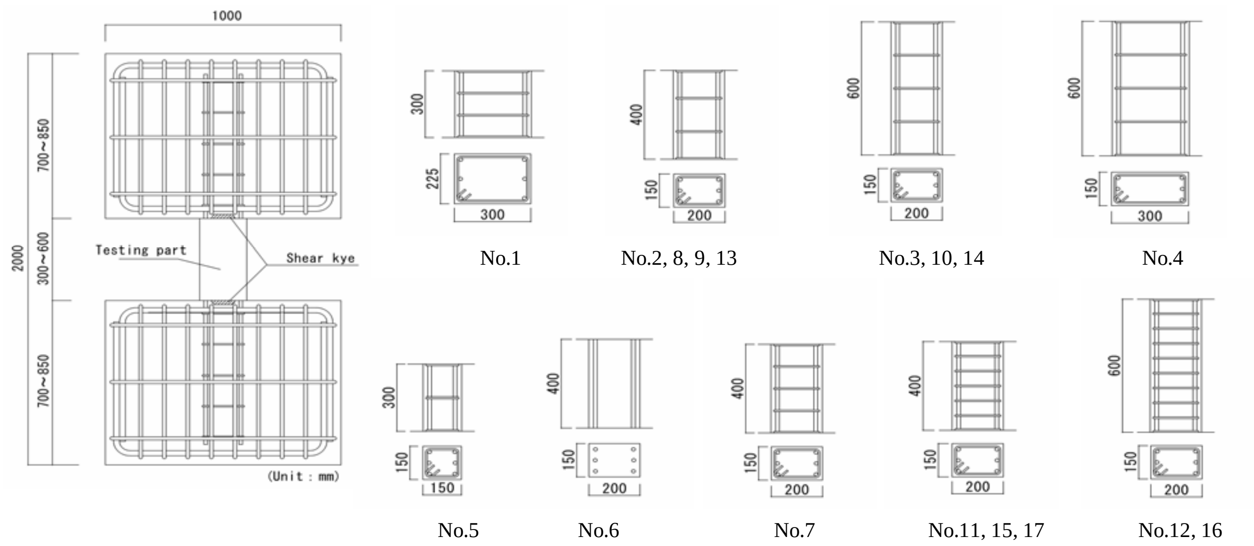


Figure 2. Configuration and bar arrangement of specimens.

Table 2. List of calculated values.

	Control specimen (p_w=0.28%)	Nagai's Eq [10]	Kasahara's Eq [11]	Shimizu's Eq [12]	Average	Value obteined by Ref. [13] (p_w=0.64%)
Shear strength	No.2 (*M/QD* =1.0)	132	168	158	153	153
	No.10 (*M/QD* =1.5)	113	159	138	137	141

Table 3. Mixture proportions of SHCC.

Fibers	L_f mm	d_f μmm	E_f GPa	σ_u MPa	V_f vol.%	*W/B*	*S/B*	Silica fume /B
Polyethylene	6	12	88～123	2600	0.75	0.45	0.45	0.15
Steel cord	32	405	200	2700	0.75			

L_f : Fiber length E_f : Fiber elastic modulus V_f : Fiber volume fraction
d_f : Fiber diameter σ_u : Nominal fiber strength

Table 4. Material properties.

Cementitious material			
	E_c (N/mm^2)	σ_B (N/mm^2)	ε_B (%)
Concrete	3.61? 0^4	78.5	0.306
SHCC	1.47? 0^4	64.9	0.520
Reinforcement			
	E_s (N/mm^2)	σ_{wy} (N/mm^2)	ε_{wy} (%)
D13(SD785)	2.03? 0^5	858※	0.624※
D13(SD295)	1.90? 0^5	360	0.193
D6(SD295)	1.83? 0^5	422	0.244

E_c , E_s : Young's modulus σ_{wy} : Yield stress
σ_B : Compresive strength ε_{wy} : Yield strain
ε_B : Strain at compresive strength ※: 0.2% offset

68.6N/mm^2 (700kg/cm^2) and tensile strength was substituted into 1.96N/mm^2 (20kg/cm^2) . In order to have the equivalence of the average of calculated values and the value obtained by guideline on ultimate strength concept, shear reinforcement ratio of RC specimens was determined. The list of calculated values is shown in Table 2. The tested area of specimen were made of precast concrete, and after prescribed care period, loading stubs were arranged and concrete was cast. The shear cotters were provided on the boarder between tested area and loading stubs in order to transmit shear force.

The used materials for SHCC are shown in Table 3. The results of the material tests are shown in Table 4. SHCC used in this study is hybrid type. The volume fraction of polyethylene fiber and steel code is 0.75 %, respectively. In this study, the different type of fiber are used from those tested by Nagai, Kasahara and Shimizu et al, however, there is not a big difference when to evaluate the resistant mechanism of material which shows PSH behavior under tensile stress.

2.2 *Test Methods*

The outline of the loading apparatus for anti-symmetrical moment condition is shown in Figure 3. In Series VI focusing on cyclic loading, deformation angle R is used as control parameter, the test procedure is follows; R=±1/400rad. is loaded one time, R=±1/100, ±1/67, ±1/50, ±1/33, ±1/25 are loaded twice, respectively. Relative deformation between top and bottom loading stubs is measured with a high sensitive displacement measure (measuring length 100mm) through aluminum measuring jig. The strain on the critical section of main bar and the

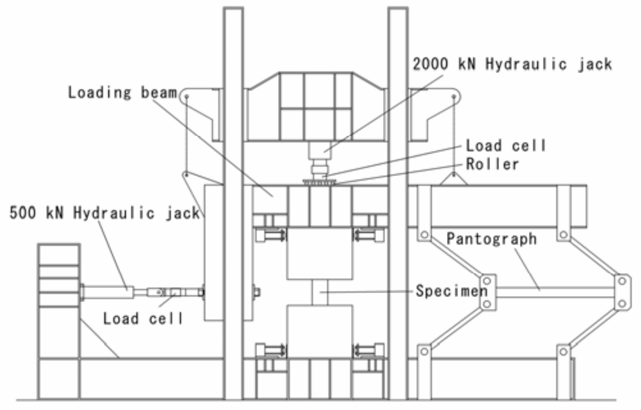


Figure 3. Loading setup.

strain of shear reinforcement are measured with a strain gage.

2.3 *Test results*

Horizontal force-drift angle relationship (*Q* - *R* relationship hereinafter) of all the specimens are shown in Figure 4, and the final failure mode are in shown in Photograph 1, respectively.

(1) Series I (Shear-span-ratio used as a test parameter)

In the tests of series I, No.1 specimen (*M/QD*=0.5) didn't attain the failure because of the overcapacity of the loading system. No.3 specimen (*M/QD*=1.5) experienced the shear failure after the flexural yielding when a part of the main bar on tension side yielded before the ultimate strength, which was not the shear failure expected by the failure mode. No.2 specimen (*M/QD*=1.0) which was the standard specimen showed the expected shear failure mode along with the strength reduction before the yield of the main bar on the tension side. The main factors of the strength reduction of No. 2 and 3 specimens were the crack localization and the crack extension.

(2) Series II (Cross section properties used as a test parameter)

In the test of series II, No.4 specimen (*b/D*=0.5) experienced the shear failure after the flexural yielding when a part of the main bar on tension side yielded before the ultimate strength, which was not the shear failure expected by the failure mode. No.5 specimen (*b/D*=1.0) showed the expected shear failure mode with the decrease of strength before the yielding of a main bar on the tension side. The main factors of the strength reduction of No.4 and 5 specimens were the crack localization and the crack extension.

(3) Series III (Shear reinforcement ratio used as a test parameter)

In the test of series III, No. 6 specimen (p_w=0%), No. 2 specimen (p_w=0.28%) and No.17 (RC) specimen (p_w=0.64%) showed the expected shear failure mode with the strength reduction before main bars on the tension side yielded. On the other hand, in No.7 specimen (p_w=0.43%), the strain of the main bar on the tension side at the ultimate strength was almost the same as the yield strain obtained from the material test. No. 17 specimen was reinforced in order to compare with No. 2 specimen reinforced with SHCC tensile resistance. In this case, the ultimate strength of No. 17 specimen was almost the same as that of No.2 specimen. The main factors of the strength reduction of all the specimens in Series III test were the crack localization and the crack extension.

(4) Series IV (Presence or absence of axial force used as a test parameter)

In the test of series IV, compare to No. 2 specimen without axial force, No. 8 specimen with axial force showed the remarkable increase of rigidity and the ultimate strength. The strength of No. 8 specimen, however, drastically decreased after the ultimate strength. At the ultimate strength of No. 8 specimen, main bar on the tension side didn't yield and showed the expected failure mode. The main factors of the strength reduction of No.8 specimen were the crack localization and the crack extension as well as those of No. 2 specimen's.

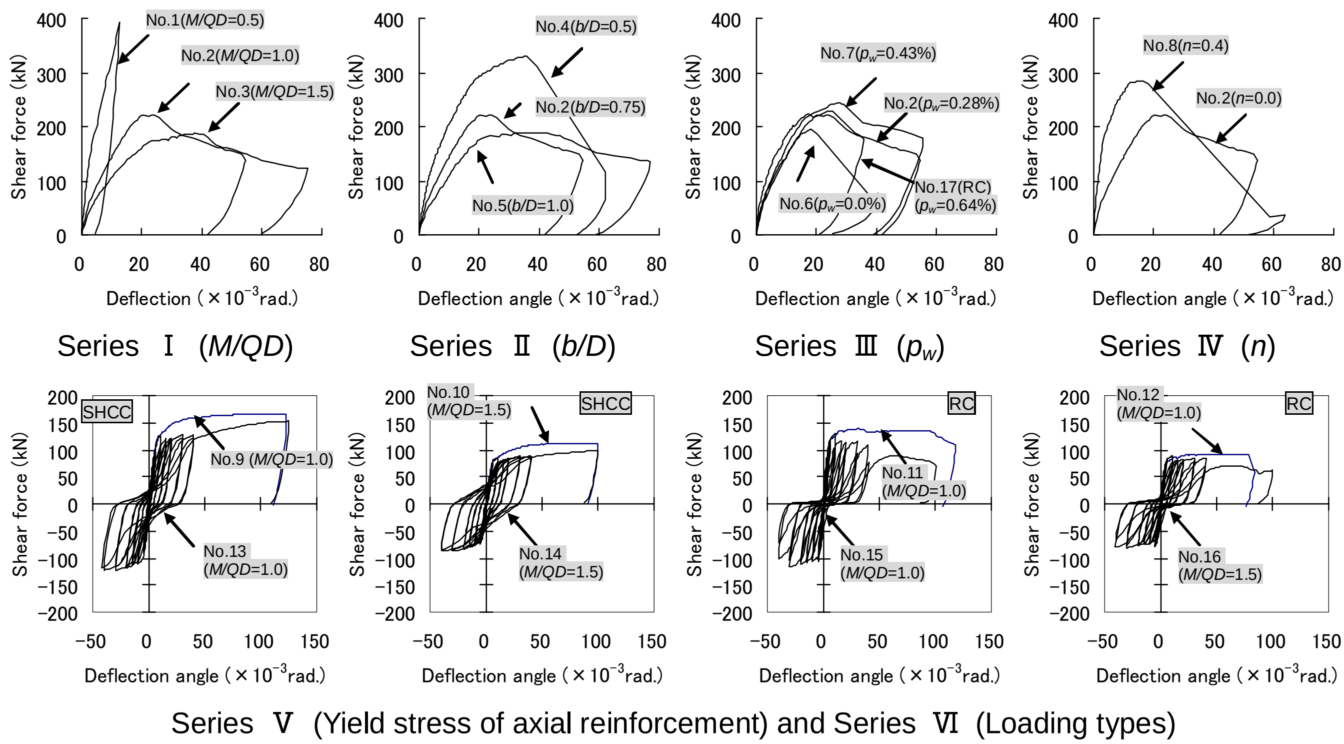
(5) Series V (Deformation capacity after the flexural yielding focused)

In series V, the specimens (*M/QD*=1.0 and *M/QD*=1.5) were picked up, and the performance between SHCC specimens and RC specimens were compared. Among all the specimens, RC specimens (No. 11 and No.12) were reinforced more than SHCC specimens (No. 9 and No.10), because the effect of the tensile resistance of SHCC was considered as the effect of the shear reinforcement.

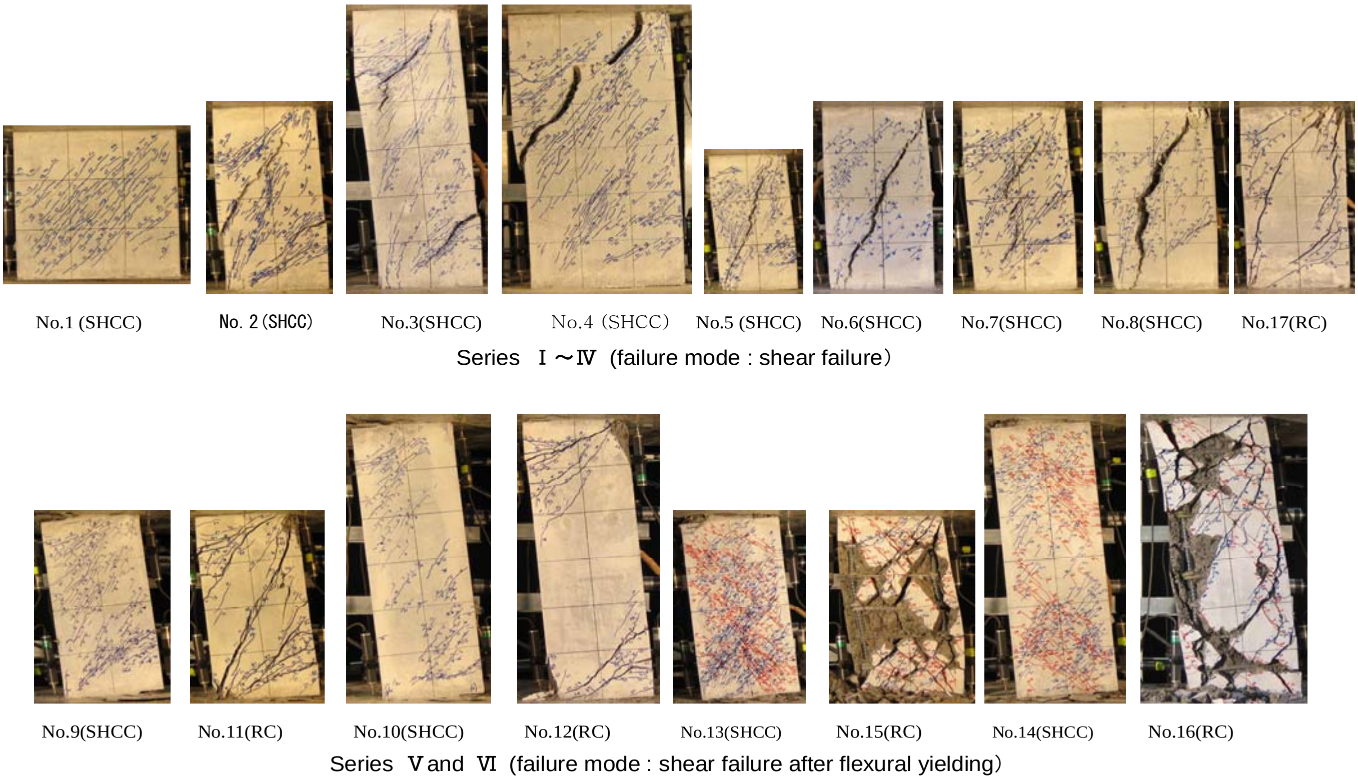
No. 9 specimen (*M/QD*=1.0) didn't show the strength reduction until the end of the loading(*R*=1/8rad.). On the other hand, No. 11 specimen (*M/QD*=1.0) showed the strength reduction due to the shear failure (the crack extension) at *R*=1/11rad. No.10 specimen (*M/QD*=1.5) didn't show the strength reduction until the end of the loading (*R*=1/10rad.). No. 12 specimen (*M/QD*=1.5) showed the strength reduction due to the shear failure (the crack extension) at *R*=1/13rad. Photo 1 shows that SHCC specimens (No. 9 and No. 10) showed the excellent reduction effects including the multiple cracking at the major deformation, compare to RC specimens (No. 11 and No.12).

(6) Series VI (Cyclic loading hysteresis focused)

In Series VI, the specimens with the same configuration as that of Series V were made. The comparison test between specimens under cyclic loading and those under the uniaxial monotonic loading was complemented. And the comparison test between



Figur 4. Shear force (Q)- deflection angle (R) relationships.



Photograph 1. Final failure mode.

SHCC and RC of cyclic hysteresis behaviors was also carried out.

In comparison test of loading methods, with either *M/QD*, SHCC specimens didn't show the strength reduction neither under the cyclic loading (No. 13 and No.14) nor under the uniaxial monotonic loading (No. 9 and No. 10) until the same level of the deformation angle. On the other hand, RC specimens (No. 15 and No.16) under the cyclic loading showed the strength reduction at the smaller deformation angle than the specimens (No. 11 and No. 12) under the uniaxial monotonic loading.

In the comparison of hysteresis behaviors between SHCC specimens and RC specimens, with either *M/QD*, RC specimens showed the remarkable slip behavior around where the loading was 0, and

SHCC specimens showed the excellent hysteresis loop. According to Photo 1, SHCC specimens (No. 13 and No.14) can control the localization and extension of cracks, and the separation of covering concrete, whereas RC specimens (No.11 and No. 12) cannot. The damage reduction effect due to SHCC can be more remarkably observed when specimens are under the cyclic loading than when under the uniaxial monotonic loading.

3 INVESTIGATION

Nagai et al. conducted the bending shear test of beams using SHCC. Based on the test results, it is assumed that SHCC tension stress resists the shear cracks which are the main factor for the strength reduction in the orthogonal direction. The shear strength evaluation method that employs in order to increases the tension stress of SHCC is proposed.

$$V_{su} = b \cdot j\left(p_w \sigma_{wy} + \sigma_t\right)\cot\phi + \tan\theta(1-\beta)bD\nu\sigma_B / 2 \quad (1)$$

$$\beta = \frac{(1+\cot^2\phi)(p_w\sigma_{wy}+\sigma_t)}{\nu\sigma_B} \quad (2)$$

$$\tan\theta = \sqrt{(L/D)^2+1} - L/D \quad (3)$$

$$\cot\phi = 1 \quad (4)$$

$$\nu = 0.7 - \sigma_B/2000 \quad (5)$$

where, $\left(p_w\sigma_{wy}+\sigma_t\right) \leq \nu\sigma_B/2$

Kasahara et al. conducted the bending shear test of beams and columns using SHCC. Based on the test results, it is assumed that cross sectional area increases in size compare to the conventional shear reinforcement by adding the SHCC tension stress into the stress of a pair of shear reinforcements. The shear strength evaluation method using the guideline on ultimate strength concept is proposed.

$$T_s = a_w\sigma_{wy} + bx\sigma_t \quad (6)$$

$$a_w' = T_s/\sigma_{wy} \quad (7)$$

where,
a_w : cross sectional area of a pair of shear reinforcements,
b : member width,
x : spacing of shear reinforcements
σ_{wy} : yielding strength of shear reinforcements
σ_t : tension stress of SHCC
a_w' : cross sectional area of shear reinforcement with SHCC tension stress added.

Shimizu et al. conducted the bending shear test of beams using SHCC. Based on the test results, it is assumed that the shear stress on the cracking surface plays a dominant role in the stress of SHCC against acting shear force. The shear strength evaluation method which added the same value of shear stress as uniaxial tensile strength is proposed using guideline on ultimate strength concept.

$$V_{su} = bj_t\left(p_w\sigma_{wy}\cdot\cot\phi + \sigma_t\right) + \tan\theta(1-\beta)bD\nu\sigma_B/2 \quad (8)$$

$$\tan\theta = \sqrt{(L/D)^2+1} - L/D \quad (9)$$

$$\beta = \frac{\left(1+\cot^2\phi\right)\left(p_w\sigma_{wy}+\sigma_t/\cot\phi\right)}{\nu\sigma_B} \leq 1 \quad (10)$$

$$\cot\phi = \min\{2, j_t/(D\tan\theta)\} \quad (11)$$

$$\nu = 3.68\sigma_B^{-0.333} \quad \text{(The unit of } \sigma_B \text{ is kgf/cm}^2\text{)} \quad (12)$$

where,
b: member width,
j_t: center to center distance of main bars,
p_w: shear reinforcement ratio,
σ_{wy}: yielding strength of shear reinforcements,
σ_t: tension stress of SHCC,
D: member depth,
ν: effective coefficient of compressive strength,
σ_B: compressive strength,
L: member length.

The relationships of proposed methods and the test results mentioned in the previous chapter are shown in Figure 5. According to this, all the proposed formulas can lead to estimation on the safe side. It needs more consideration for accuracy improvement. These proposed methods don't consider the compatibility condition of strain because they are based on the lower-bound theorem of the theory of plasticity. Therefore, the fluctuation of the ultimate tensile strain cannot be considered. It also needs more consideration on this point. It is important for the future projects to obtain more research examples on the evaluation method for the deformation capacity after the flexural yielding.

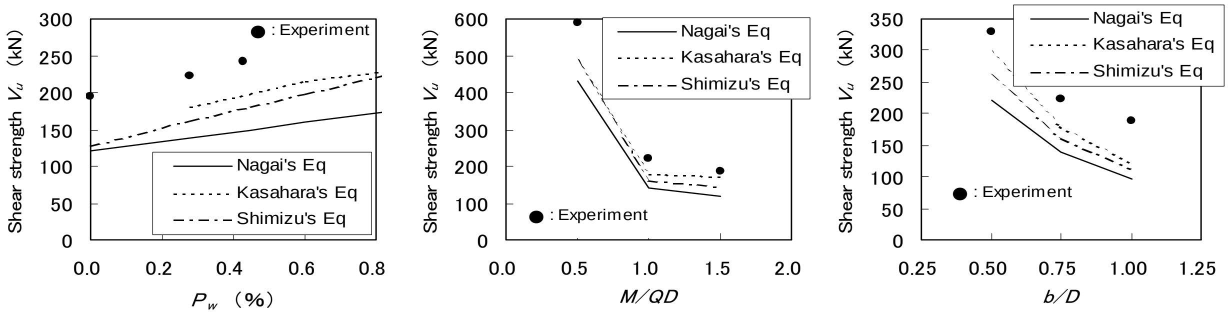


Figure 5. Relationships of proposed methods and test results.

4 CONCLUSION

Bending shear tests were conducted to verify the main factors on the shear strength and the deformation capacity of dampers with SHCC. Shear span ratio, cross sectional properties, shear reinforcement ratio, presence or absence of axial force, shear failure after the flexural yielding and cyclic loading hysteresis were focused on. The following conclusions were obtained,

1) SHCC specimens and RC specimens were compared. In the tests, the effect of the reinforcement of RC specimens was considered to be the effect of the tensile resistance of SHCC. When the specimens experienced the shear failure before the flexural yielding, both SHCC and RC specimens showed almost the same level of the ultimate strength. On the other hand, when the specimens experienced the shear failure after the flexural yielding, SHCC specimens showed the larger deformation capacity.
2) In the test of the specimens which experienced the shear failure after the flexural yielding under cyclic loading, SHCC specimens showed the same level of the ultimate strength as the ones under uniaxial monotonic loading. On the other hand, RC specimens showed the decreased deformation capacity compare to the one under uniaxial monotonic loading. The hysteresis loop of SHCC specimens was more excellent than the one of RC.
3) In the test of the specimens which experienced the shear failure after the flexural yielding, SHCC specimens showed the better damage reduction effects at the major deformation than RC specimens. The effects include the multiple cracking, and the control of the crack localization and the separation of covering concrete. The effect worked more remarkably under cyclic loading than under uniaxial monotonic loading.

All the proposed formulas can lead to estimation on the safe side. It needs more consideration for accuracy improvement. These proposed methods don't consider the compatibility condition of strain because they are based on the lower-bound theorem of the theory of plasticity. Therefore, the fluctuation of the ultimate tensile strain cannot be considered. It also needs more consideration on this point. It is important for the future projects to obtain more research examples on the evaluation method for the deformation capacity after the flexural yielding.

5 ACKNOWLEDGEMENTS

This study was conducted as the part of the research project "Cooperative research committee on the manufacturing system of SHCC and members, and the design method of damage control elements; Chair: Mihashi, K. Professor of Tohoku university. Authors thank all the committee members for their technical advice.

REFERENCES

Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Ultimate Strength Concept, 1990. Architectural Institute of Japan.

Fukuyama, H. & Kuramoto, H. 2001. Smart Concrete -High Performance Fiber Reinforced Cementitious Composites-, *Concrete Journal,* Japan Concrete Institute, Vol.39, No.1, pp.104-109. (in Japanese)

Fukuyama, H. & Suwada, H. 2003. Experimental Response of HPFRCC Dampers for Structural Control. *Journal of Advanced Concrete Technology,* Vol.1, No.3, pp.317-326.

Iwabuchi, K. Fukuyama, H. Suwada, H. & Yoshimura, M. 2005. Substructure Pseudo Dynamic Test of Existing RC Buildings with Soft Story Incorporating Response Control Element, *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, No.596, pp.79-86. (in Japanese)

Japan Concrete Institute. 2004. Final report of Task Committee on Performance Evaluation and Structural Application of Ductile Fiber Reinforced Cement Composites. (in Japanese)

Kanda, T. & Li, V. C. 1999. New Micromechanics Design Theory for Pseudo strain Hardening Cementitious Composite, *Journal of Engineering Mechanics,* ASCE, Vol.125, No.4, pp.373-381.

Kasahara, M. Matsuzaki, Y. & Nakano, K. 2002. Experimental Study on the Structural Performance of Columns and Beams using Ductile Engineered Cementitious Composite. *Journal of Structural and Construction Engineering*, Architectural Institute of Japan, No 553, pp.89-95. (in Japanese)

Li, V. C. 1993. From Micromechanics to Structural Engineering, The Design of Cementitious Composites for Civil Engineering Applications. *J. Struct. Mech. Earthquake Eng.,* Japan Society of Civil Engineering, Vol.10, No.2, pp.37-48.

Naaman, A. E. & Reinhardt, H. W. 1995. Characterization of high performance fiber reinforced cement composites-HPFRCC. *Proceedings of the Second International RILEM Workshop on High Performance Fiber Reinforced Cement Composites (HPFRCC2)*, edited by A.E. Naaman, H.W. Reinhardt, RILEM Proceedings 31, E & FN SPON, pp.1-24.

Nagai, S. Takaine, Y. Kanda, T. & Maruta, M. 2001. Shear and Flexural Performance of Reinforced Beam using High Performance Fiber Reinforced Cement Composite -Part 2 Considerations of the Test Result-, *Summaries of Technical Papers of Annual Meeting*, Architectural Institute of Japan. (in Japanese)

Shimuzu, K. Kanakubo, T. Kanda, T. & Nagai, S. 2004. Evaluation of Ultimate Shear Strength for PVA-ECC Beam. *Proceedings of Japan Concrete Institute*, Japan Concrete Institute, Vol.27, No.2, pp.1537-1542, 2004

Suwada, H. & Fukuyama, H. 2006. Experimental Study on Influencing Factors on Pseudo Strain Hardening Behavior of High Performance Fiber Reinforced Cementitious Composite, *Journal of Structural and Construction Engineering,* Architectural Institute of Japan, No. 605, pp.1-8. (in Japanese)

Suwada, H. Fukuyama, H. Mukai, T. & Nomura, S. 2005. Test on high performance seismic resistance elements with high strength, stiffness, ductility. *Proceedings of Japan Concrete Institute*, Japan Concrete Institute, Vol.27, No.2, pp.1087-1092. (in Japanese)