DUCTILE ENGINEERED CEMENTITIOUS COMPOSITE ELEMENTS FOR SEISMIC STRUCTURAL APPLICATION

Hiroshi FUKUYAMA[1], Yukihiro SATO[2], Victor C LI[3], Yasuhiro MATSUZAKI[4] And Hirozo MIHASHI[5]

SUMMARY

A collaborative effort between US and Japanese researchers has focused on the development of high-performance elements for seismic structural applications based on a new materials technology as an Engineered Cementitious Composite (ECC) designed using micromechanical principles. ECC exhibits strain-hardening with strain capacity in excess of 1% in tension and multiple cracking properties. The excellent identical properties of ECC make it especially suitable for critical elements in seismic applications where high performance is required. Applications of ECC to energy absorption devices and damage tolerant structural elements are considered to meet the performance requirements of structures under the performance based engineering. These new structural elements with ECC are expected to reduce the seismic response and damage of structures. Objective of this research is to investigate the upgrading effects on structural performance of ECC reinforced elements. The ECC employed in this research is Polyvinyl Alcohol (PVA) fiber reinforced mortar. A tension-compression reversed cyclic test of ECC material and a structural test with six beam elements were conducted. This paper summarizes the basic mechanical properties of PVA-ECC and structural performance of the PVA-ECC reinforced beams. The micromechanics concepts, which support the development of ECC, are also briefly presented. Results of the beam test indicate that brittle failures as shear failure and bond splitting failure observed in the RC beams can be prevented by using PVA-ECC in place of the concrete. As a result, the beams with PVA-ECC indicate excellent ductile manner. The shear crack widths up to 5 % rad. in deflection angle in the beams with PVA-ECC were less than 0.3 mm, which is the maximum limit from the view of durability. Through this test, it can be clarified that ECC has much feasibility to upgrade the structural performance and damage tolerance of structural elements.

INTRODUCTION

One of the lessons from the Japanese current destructive earthquakes including the 1995 Hyogoken-Nanbu Earthquake (Kobe Earthquake) is that most new buildings designed according to the current seismic codes showed fairly good performance with the view of preventing severe damage and/or collapse for life safety. However, the problem was that the seismic performance of buildings was widely ranged from the level of collapse preventing to function keeping, which have not been identified by the current seismic codes. It is, therefore, strongly needed to develop the more rational seismic design codes based upon the performance-based design concept. The performance on seismic resistance of buildings including structural safety and functional soundness during and/or after earthquake, and reparability after earthquake may be explicitly explained. The Japanese Building Standard Low is now under revising to be performance-based regulations. Since the low is a minimum requirement, a new evaluation and statement system of building performance beyond the code requirement is also under developing. Then it is a high priority issue to develop the new structural technologies to meet the high level of structural performance requirement.

[1] *Snr Researcher, IISEE, Building Research Inst, Ministry of Construction, Tsukuba, Japan Email: fukuyama@kenken.go.jp*
[2] *Research Engineer, Technical Research Institute, Fujita Corporation, Atsugi, Japan, Email: ysato@fujita.co.jp*
[3] *Professor, ACE-MRL, Dept of Civil and Env Eng, The University of Michigan, MI, U.S.A., Email: vcli@engin.umich.edu*
[4] *Professor, Dept of Architecture, Faculty of Eng, Science Univ of Tokyo, Tokyo, Japan Email: ymatsu@rs.kagu.sut.ac.jp*
[5] *Professor, Dept of Architecture, Faculty of Eng, Tohoku Univ, Sendai, Japan Email: mihashi@timos.str.archi.tohoku.ac.jp*

A collaborative effort between US and Japanese researchers has focused on the development of high-performance elements for seismic structural applications, based on a new materials technology. The new materials technology involves an Engineered Cementitious Composite (ECC) designed using micromechanical principles [Li, 1993]. ECC exhibits excellent ductile properties and damage tolerance, which are strain-hardening with strain capacity of 1.5% to 7% in tension and multiple cracking properties [Li, 1993, Fukuyama et al., 1999]. The ultra ductile behavior of ECC, combined with its flexible processing requirements, isotropic properties and moderate fiber volume fraction, which is typically less than 2% depending on fiber type and characteristics of interface and matrix, make it especially suitable for critical elements in seismic applications where high-performance are required. Applications of ECC to energy absorption devices and damage tolerant structural elements are considered to meet the performance requirements of structures under the performance based engineering. These new structural elements with ECC are expected to reduce the seismic response and damage of structures.

Objective of this research is to investigate the upgrading effects on structural performance of building elements by using ECC. The ECC employed in this research is Polyvinyl Alcohol (PVA) fiber reinforced mortar designed using micromechanical concepts. A tension-compression reversed cyclic test of material and a structural test with six beam elements were conducted. This paper summarizes the basic mechanical properties of PVA-ECC and the structural performance of PVA-ECC reinforced beam elements with the view of application to seismic resistant structures. The micromechanics concepts, which support the development of ECC, are also briefly presented.

MICROMECHANICS CONCEPT FOR ECC

The development of ECC is based on the micromechanics of fiber bridging and matrix crack extension. The theoretical foundation was first described by Li [Li, 1993]. As a result of the micromechanics analysis, it was shown that pseudo strain-hardening under tensile loading can be accomplished with short randomly oriented fiber reinforcement of a cementitious matrix, at moderate dosage no more than 2% by volume. Various fiber types can be utilized as long as the fiber volume fraction V_f satisfies:

$$V_f > V_f^{crit} \equiv \frac{12 J_c}{g \tau \left(L_f / d_f\right) \delta_o} \quad (1)$$

where, $\delta_0 = \tau L_f^2 / [E_f d_f \{1 + (V_f E_f)/(V_m E_m)\}]$ is the crack opening corresponding to the maximum bridging stress, d_f is fiber diameter, E_f and E_m are Young's Moduli of fiber and matrix, respectively, g is snubbing factor, L_f is fiber length, τ is friction between fiber and matrix, V_f and V_m are the volume fraction of fiber and matrix, respectively, V_f^{crit} is the critical fiber volume fraction, and J_c is matrix toughness. Supplementary conditions are described by Li and Leung [Li and Leung, 1992]. The critical fiber volume fraction V_f^{crit} is therefore dependent on fiber, matrix, and fiber/matrix interaction properties. Fiber properties include fiber length L_f, diameter d_f, and modulus E_f. The fiber/matrix interaction properties include friction τ and a snubbing factor g [Li et al., 1990]. The matrix properties include matrix modulus E_m and matrix toughness J_c.

It should be noted that Eq. (1) is applicable only to the case when fiber rupture does not occur, and that the fiber/matrix interface is governed only be simple friction with no chemical bond. Extension of Eq. (1) to composite with these properties have been considered by Kanda and Li [Kanda and Li, 1997]. The reformulation of (1) leads to V_f^{crit} which depends on fiber strength and chemical bond strength, in addition to those already mentioned above.

Equation (1) prescribes the recipe for formulating a ECC material systematically. It guides the composite design by specifying the necessary combinations of fiber, matrix and fiber/matrix interaction properties. Most current FRCs would have these micromechanical parameter combinations which lead to high V_f^{crit}. This means that unless the fiber volume fraction is high, (say e.g. > V_f^{crit} = 10%), psudo strain hardening cannot be achieved. The power of Eq. (1) is to allow systematic tailoring of the micromechanical properties in order to achieve a low to moderate V_f^{crit}.

TENSION-COMPRESSION CYCLIC TEST OF PVA-ECC

A tension-compression reversed cyclic test with PVA-ECC cylindrical specimen, which shape is 100 mm in diameter and 200 mm in height, was conducted to observe the uniaxial mechanical properties. The properties of

PVA fiber used and the mix proportions of PVA-ECC are shown in Table 1 and Table 2, respectively. The mix proportion of PVA-ECC was designed using micromechanical concepts. The fiber volume fraction of PVA-ECC was 1.5 %.

Fig. 1 shows the loading set up of the tension-compression reversed cyclic test. Since the basic data of material properties under reversed cyclic loading is necessary to discuss about the seismic structural application, a new testing method was developed for reversed cyclic loading test of the composite material. In this method, mechanical chuck is used to grip both ends of the cylindrical specimen for tensile loading. This chuck has a mechanism that gripping force is increased in proportion to the tensile loading force. Continuous tension and compression loading are available, since both plane surfaces of the specimen are attached to the steel plates of the loading machine. Uniaxial glass fiber sheets were wrapped with resin so as to line fibers vertically in Fig. 1 at the top and bottom of the specimen to reinforce the gripping zone and to control the initiation of cracks into the 100 mm of displacement measuring length. Since the size of this cylindrical specimen of PVA-ECC is the same as that of concrete pieces used for compression test, the compressive properties observed in this test can be treated as standard compressive test results.

From the observed stress-strain relationships as shown in Fig. 2, the PVA-ECC employed in this research exhibited multiple cracking and strain-hardening with strain capacity of around 1.5 % in tension. After this capacity point, stress is gradually decreased with increase of strain due to the rupture of PVA fiber. However, the

Table 1: Properties of PVA fiber

Diameter	Length	Elastic modulus	Tensile strength	Specific gravity
40.8 micron	*15.0 mm*	*43.9 GPa*	*1850 MPa*	*1.30*

Table 2: Material mix proportions in weight fractions

Materials	Cement (C)	Silica fume (SF)	Super-plasticiser (SP)	Water (W)	Coarse aggregate (CA)	Sand (FA)
(ratio)		SF/C	SP/C	W/(C+SF)	CA/(C+SF)	FA/(C+SF)
PVA-ECC	*1.00*	*0.25*	*0.03*	*0.45*	---	*0.40*
Concrete	*1.00*	---	*0.01*	*0.46*	*2.63*	*2.12*

brittle behavior in compression after maximum strength, and the slip behavior near the horizontal axis when the loading was changed from tension to compression were observed.

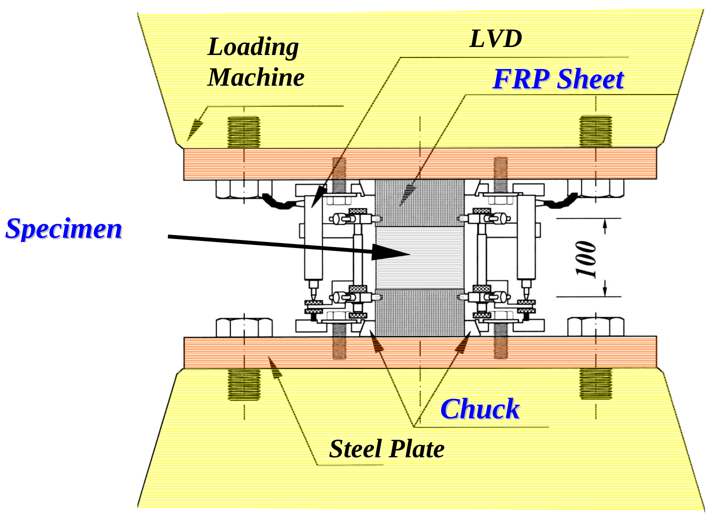
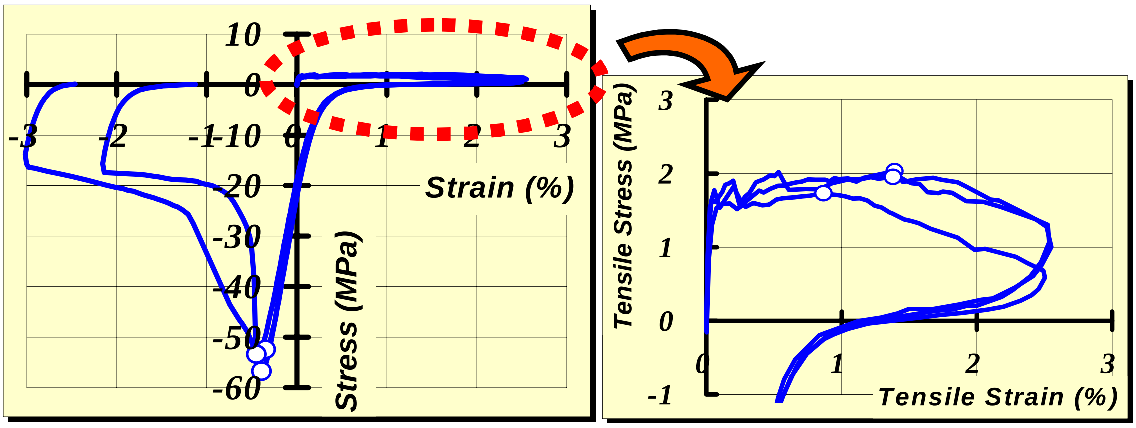


Figure 1: Loading set up



(a) Whole data **(b) Focus on tensile loading**

Figure2: Stress-Strain relationship

BEAM TEST

Specimens and Loading Setup

The Ohno-type cyclic loading test with six beam elements was conducted. Main objective of the test is to investigate the upgrading effects on structural performance of energy dissipation and damage tolerance of the PVA-ECC reinforced beams. Configuration and bar arrangements of the specimens are shown in Fig. 2. The cross section in clear span of the beams is 200 mm in width, 270 mm in depth and its length is 1,080 mm, which is 1/2 to 1/3 scaled model. Table 3 shows the outline of the specimens. Variables in the test are type of cement material, longitudinal bar arrangement, stirrup arrangement, and yield strength of longitudinal steel bar.

The RC control beam No.1 was designed to fail by shear. Beam No.2 is the same as beam No.1 except utilizing PVA-ECC in place of the concrete. Therefore, the upgrading performance in shear by using PVA-ECC can be discussed by the comparison of capacities between beams No.1 and No.2. Beam No.3 is the same as beam No.2 except yield strength of the longitudinal steel, which was around twice of that of beam No.2. Since the aim of beam No.3 is to investigate the shear capacity of PVA-ECC beam, the high yield strength steel is necessary to prevent flexural yielding. Beam No.4 is the same as beam No.2 without stirrups. Then PVA-ECC is the unique material for shear resistance after shear cracking in beam No.4. Beam No.5 is a RC beam designed to fail by bond splitting. Four D16 bars, which means deformed steel bar with 16 mm in diameter, are arranged for both the top and bottom longitudinal reinforcements. Beam No.6 is the same as beam No.5 except utilizing PVA-ECC instead of the concrete. Then the upgrading effect on bond splitting by PVA-ECC can be discussed by the comparison between beams No.5 and No.6.

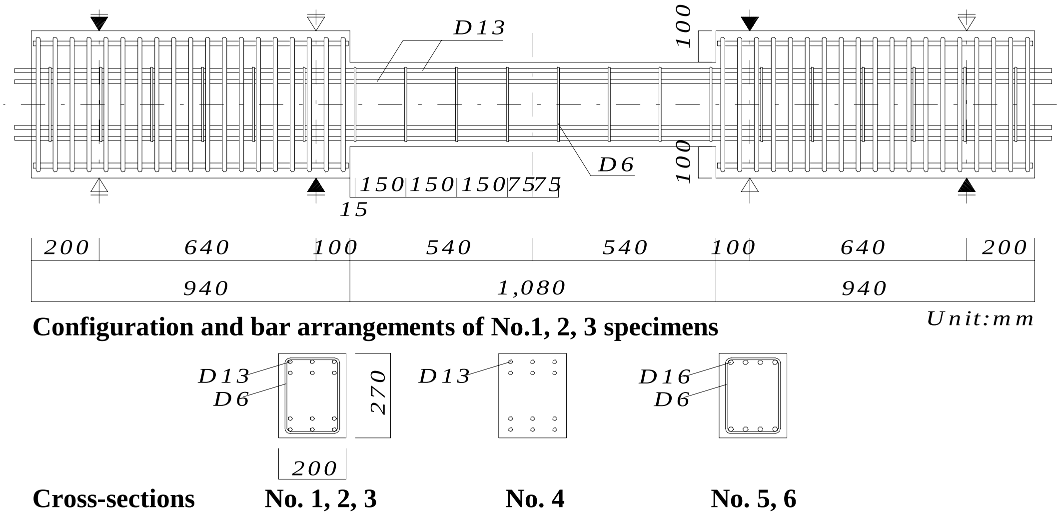


Figure2: Configuration and bar arrangements of specimens

Table 3: Outline of beam specimens

Specimen No.		1	2	3	4	5	6
Dimension (width x depth)		*200 x 270 (mm)*					
Cement Composites	Type	*Concrete*	*PVA-ECC (V_f=1.5%)*			*Concrete*	*PVA-ECC (V_f=1.5%)*
	Compressive Strength (MPa)	*34.9*	*50.5*			*34.9*	*50.5*
Tensile Reinforcement (Total Cross Section Area)		*6-D13 (13mm in deameter) (7.62 cm^2)*				*4-D16 (16mm in deameter) (7.96 cm^2)*	
Yield Strength (MPa)		*393*		*760*	*393*	*396*	
Stirrups		*2-D6 (6mm in deameter)*			*non*	*2-D6 (6mm in deameter)*	
Spacing (mm)		*150*				*75*	
Yield Strength (MPa)		*272*				*272*	

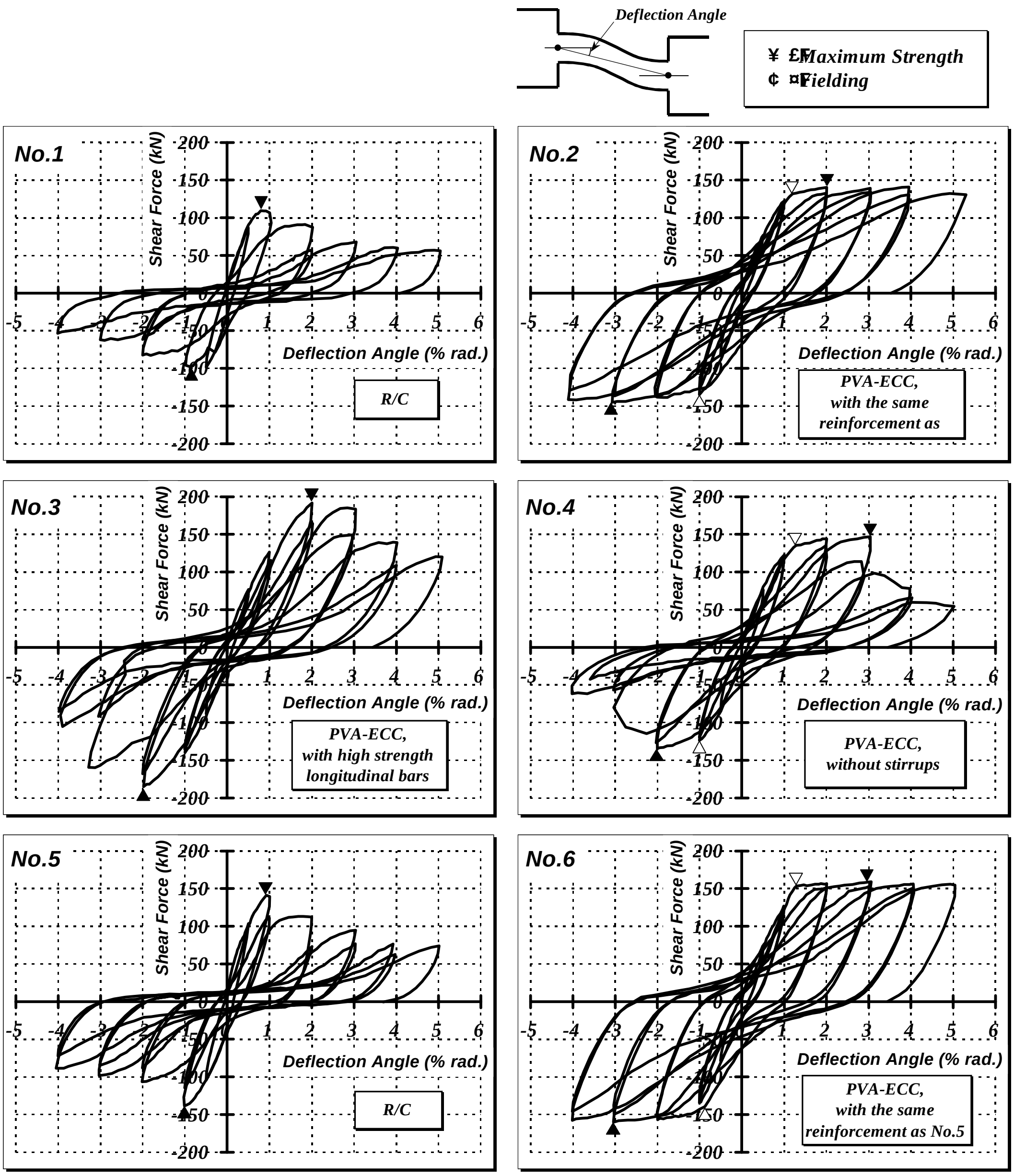


Figure3: Shear force - deflection angle relationships

The compressive strength of PVA-ECC was 50.5 MPa, though that of concrete was 34.9 MPa. The PVA-ECC used in this test is the same as that used in the tension-compression cyclic test. Cyclic loading was performed under control of maximum deflection angles, which were 0.5, 1.0, 2.0, 3.0, 4.0 and 5.0 % radian. Basically two times of cyclic loading was done for each target deflection angles. Load, deflection, strain of steel bar and crack width were measured.

Results and Discussions

Shear force and deflection angle relationships of each specimen are shown in Fig. 3. Damaging processes and failure patterns of each beam are as follows.

In the control RC beam No.1, flexural crack and shear diagonal crack initiated firstly at 14.8 kN and 58.2 kN in shear force, respectively. Yielding of stirrup was observed at 72.5 kN. After initiation of some flexural and shear cracks, shear failure was occurred at 110 kN in shear force, which was the capacity of beam No.1. Under the loading after the capacity point, the resistance shear force in the envelope curve of shear force - deflection angle relationship decreased gradually with increase of defection angle.

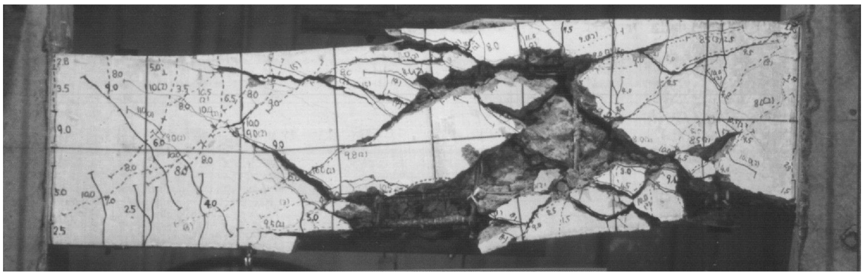
In the PVA-ECC beam No.2 with the same steel bar arrangement as that of beam No.1, flexural crack and shear crack initiated at 19.6 kN and 54.2 kN, which are similar to the observation in beam No.1. However, cracking progress was much different between beams No.1 and No.2. A large number of fine flexural and shear cracks were observed in beam No.2 compared with beam No.1. Yield of stirrup was occurred firstly at 123 kN, which was much larger than that of beam No.1. This indicates that the PVA-ECC worked as shear resistance material effectively. Flexural yielding of the beam was observed at 127 kN without shear failure observed in beam No.1. Excellent ductile manner was shown after yielding of the beam with increase of shear cracking. Any brittle failures were not observed up to end of the test. From these results, it can be said that the good ductile performance with large amount of energy dissipation could be achieved with preventing shear failure by using PVA-ECC in place of concrete.

Similar damage process with beam No.2 was observed in the PVA-ECC beams No.3 and No.4. Since the high strength steel was used for longitudinal reinforcement, flexural yielding of beam No.3 was not observed. It was failed by shear at 191 kN, which was 74 % larger than the shear capacity of beam No.1. Flexural yielding and ductile manner were observed in beam No.4, PVA-ECC beam without steel stirrups, up to 2 % rad. of deflection angle. However, shear failure after yielding of the beam was occurred at around 2 % rad. of deflection angle caused by the rupture of PVA fibers. This indicates that PVA-ECC worked as the reinforcement for not only shear but also confinement of concrete expansion after yielding of the beam. The results of beam No.4 suggest that superior ductility of ECC is necessary to achieve the large energy absorption properties of structural elements. In the another control RC beam No.5 showed similar damage progress with the observation in beam No.1. However, bond-splitting crack was initiated at 135 kN and bond splitting failure was occurred at 141 kN in shear force. After this failure occurred, the shear force decreased gradually with increase of defection angle like beam No.1.

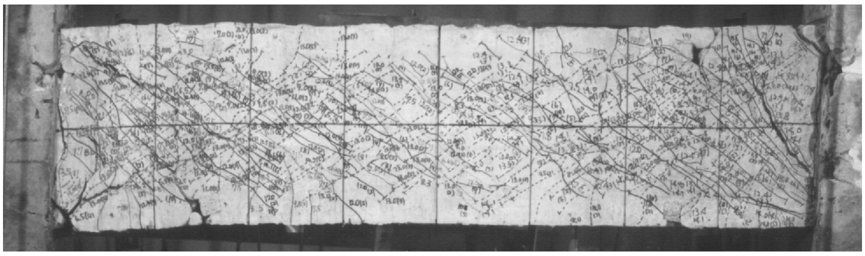
In the PVA-ECC beam No.6 with the same steel bar arrangement as that of beam No.5, neither bond splitting failure nor bond-splitting cracks were observed. This indicates that PVA-ECC worked effectively as the reinforcement for bond splitting.

The damage patterns at the final of the test are shown in Fig. 4. Severe damage can be seen in the RC beam No.1, which failed by shear. In this damage level, the concrete should be demolished and re-placed in the restoration work for reuse of this element. On the other hands, the damage of beam No.2 is much lighter in comparison to that of beam No.1, though many fine cracks are observed. Similar tendency can be seen in the comparison between beams No.5 and No.6. When the bond splitting failure occurred, restoration work is not easy as in the case of shear failure.

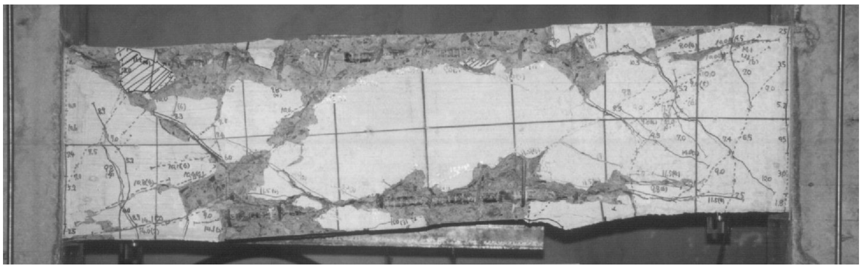
Unique result on shear crack width was obtained by this test. Fig. 4 shows largest shear crack width and deflection angle relationships observed in beams No.1, 2, 3 and 4. The largest shear crack widths of each PVA-ECC beam before 2 % rad. of deflection angle were less than 0.3 mm, which is the maximum limit for durability. Especially, those of beams No.2 and No.3 were less than 0.3 mm up to 5 % rad. of deflection angle, which the test terminated.



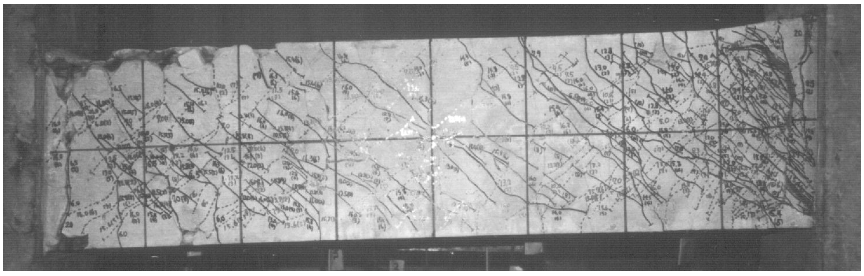
Beam No.1 (RC beam)



Beam No.2 (PVA-ECC beam)



Beam No.5 (RC beam)



Beam No.6 (PVA-ECC beam)

Figure 4: Damage properties after testing

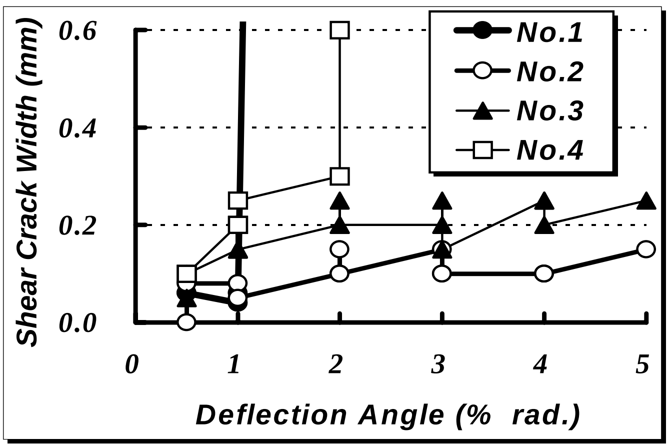


Figure 5: Change of shear crack widths

CONCLUSIONS

ECC, which exhibits excellent properties in ductility and damage tolerance, was developed for applying to the seismic resistant structural elements. The ECC employed in this research is the PVA fiber reinforced mortar designed using micromechanical concepts.

A tension-compression reversed cyclic test with cylindrical specimen was conducted to observe the uniaxial mechanical properties of PVA-ECC. From this test, PVA-ECC with 1.5 % of fiber volume fraction exhibits strain-hardening with strain capacity of around 1.5 % in tension.

To demonstrate the potential of ECC in structural performance of elements, a cyclic loading test of six beam elements was conducted to investigate the upgrading effects on structural performance of beams with PVA-ECC. The test results indicate that the brittle failures as shear failure and bond splitting failure observed in the RC beams can be prevented by using PVA-ECC in place of the concrete. As a result, the beams with PVA-ECC indicate excellent ductile manner. This means that PVA-ECC worked as the reinforcement for not only shear and bond splitting but also confinement of concrete expansion after yielding of beams. The maximum shear crack widths up to 5 % rad. in deflection angle of some PVA-ECC beams were less than 0.3 mm, which is the maximum limit value for durability. Through this test, it can be clarified that PVA-ECC has much feasibility to upgrade the structural performance and damage tolerance of structural elements.

Continued research will maintain the materials-structure interaction approach, and the academic / industry / government collaborative stance. Additional work will focus on filling in knowledge gaps in material properties and design, as well as on element and system response under seismic loads. The long range output from the collaborative research between US and Japan will include design methods for ECC materials; analytical model and technique for FEM to evaluate the structural performance of element with ECC; and design guideline for structural system with ECC elements.

REFERENCES

Fukuyama, H., Matsuzaki, Y., Nakano, K. and Sato, Y. (1999), "Structural Performance of Beam Elements with PVA-ECC", *Proceedings of High Performance Fiber Reinforced Cement Composites 3 (HPFRCC 3),* Ed. H.W. Reinhardt and A. Naaman, RILEM Publications S.A.R.L., PRO 6, pp 531-541.

Kanda, T., Li, V.C. (1997), "Effect of Apparent Fiber Strength and Fiber-Matrix Interface Properties on Crack Bridging in Cementitious Composites", *ASCE Journal of Engineering Mechanics*, Vol. 123, No. 10, ASCE.

Li, V.C., Wang, Y. and Backer, S. (1990), "Effect of Inclining Angle, Bundling, and Surface Treatment on Synthetic Fiber Pull-Out from a Cement Matrix", *Journal of Composites*, Vol. 21, No. 2, pp 132-140.

Li, V.C. and Leung, C.K.Y. (1992), "Steady-State and Multiple Cracking of Short Random Fiber Composites", *Journal of Engineering Mechanics*, Vol. 118, No. 11, ASCE, pp 2246-2264.

Li, V.C. (1993), "From Micromechanics to Structural Engineering – The Design of Cementitious Composites for Civil Engineering Applications", *Structural Engineering and Earthquake engineering*, Vol. 10, No.2, Japan Society of Civil Engineers, pp 37-48