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Nonlinear model of reinforced concrete frames retrofitted by in-filled HPFRCC walls

Chang-Geun Cho†

Hanwha Research Institute of Technology, Hanwha E&C, Korea

Gee-Joo Ha

Department of Architectural Engineering, Kyungil University, Korea

Yun-Yong Kim‡

Department of Civil Engineering, Chungnam National University, Korea

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Abstract. A number of studies have suggested that the use of high ductile and high shear materials, such as Engineered Cementitious Composites (ECC) and High Performance Fiber Reinforced Cementitious Composites (HPFRCC), significantly enhances the shear capacity of structural elements, even with/without shear reinforcements. The present study emphasizes the development of a nonlinear model of shear behaviour of a HPFRCC panel for application to the seismic retrofit of reinforced concrete buildings. To model the shear behaviour of HPFRCC panels, the original Modified Compression Field Theory (MCFT) for conventional reinforced concrete panels has been newly revised for reinforced HPFRCC panels, and is referred to here as the HPFRCC-MCFT model. A series of experiments was conducted to assess the shear behaviour of HPFRCC panels subjected to pure shear, and the proposed shear model has been verified through an experiment involving panel elements under pure shear. The proposed shear model of a HPFRCC panel has been applied to the prediction of seismic retrofitted reinforced concrete buildings with in-filled HPFRCC panels. In retrofitted structures, the in-filled HPFRCC element is regarded as a shear spring element of a low-rise shear wall ignoring the flexural response, and reinforced concrete elements for beam or beam-column member are modelled by a finite plastic hinge zone model. An experimental study of reinforced concrete frames with in-filled HPFRCC panels was also carried out and the analysis model was verified with correlation studies of experimental results.

Keywords: HPFRCC panel; in-plane shear; MCFT; seismic retrofit.

1. Introduction

The present study is primarily concerned with modeling of the shear behavior of High

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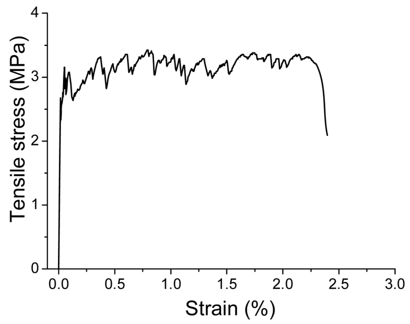
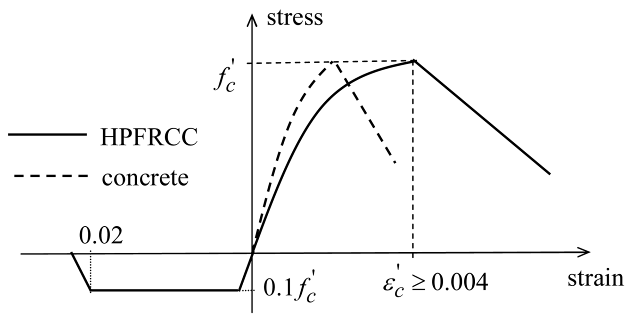
† E-mail: chocg70@hanwha.co.kr
‡ Professor, Corresponding author, E-mail: yunkim@cnu.ac.kr



(a) Tensile stress-strain behavior of HPFRCC



(b) Stress-strain curve of concrete and HPFRCC

Fig. 1 Stress-strain characteristic of HPFRCC

Performance Fiber Reinforced Cementitious Composites (HPFRCC) materials on the bases of their unique characteristics, from a material level to a element level, especially for HPFRCC panels experiencing in-plane shear. The development of HPFRCC was primarily motivated by demands to improve the quasi-brittle tensile behavior, which is typical for normal concrete and mortar. HPFRCCs can be considered as a special family of fiber reinforced concrete that exhibits pseudo strain-hardening behavior under uniaxial tension. By increasing tensile loads, as shown in Fig. 1, HPFRCCs generally show multiple fine cracks of reduced width, without strain localization. Unlike normal concrete, HPFRCC can sustain tensile stresses corresponding with high strains (Kim *et al.* 2004, Li 1992, 1993).

This high performance characteristic of HPFRCC can improve the in-plane shear behavior of HPFRCC panels to compare with normal concrete. A number of studies have suggested that the use of HPFRCC significantly enhances the shear capacity of structural elements, even with/without shear reinforcements. The high performance characteristic of HPFRCC panels could effectively enhance the structural performance of reinforced concrete frames with in-filled HPFRCC panels under lateral loads (Nagai *et al.* 2002). Mikame *et al.* (1998) and Hakuto *et al.* (2001) were shown through the experiments of HPFRCC walls that the tensile properties of HPFRCC in the HPFRCC walls affected the shear strength of the HPFRCC walls.

The present study focuses on the development of a nonlinear model of shear behaviour of HPFRCC panel elements for application to the seismic retrofit of reinforced concrete buildings. In order to model the shear behaviour of HPFRCC panels, the original Modified Compression Field Theory (MCFT) for conventional reinforced concrete panels, proposed by Vecchio *et al.* (1986) and Montoya *et al.* (2001), has been newly revised for reinforced HPFRCC panels. The proposed shear model of HPFRCC panels has been applied in the prediction of seismic retrofitted reinforced concrete buildings with in-filled HPFRCC panels. A series of experiments on reinforced concrete frames with in-filled HPFRCC walls was carried out and the analysis model was verified with correlation studies using experimental results.

2. Proposed HPFRCC-MCFT model

To compare with normal concrete, the material characteristics of HPFRCC, as shown in Fig. 1, retain a low elastic modulus in compression and a high ductility of tensile strain of about 2% in tension caused by multiple fine cracks (Kim *et al.* 2004, Li 1993). In the past few decades, studies on shear behavior of reinforced concrete panels have been reported. A representative work from this period is the Modified Compression-Field Theory (MCFT) proposed by Vecchio *et al.* (1986). The present study focuses on developing a model of the in-plane shear prediction of reinforced HPFRCC panels, referred to as the HPFRCC-MCFT model, based on revision of the original MCFT model. In the original MCFT model, cracked concrete was treated as a new material with its own stress-strain characteristics, and equilibrium, compatibility, and a constitutive law were formulated in terms of average stresses and average strains. The current model has been newly developed to focus on the following three important characteristics of cracked HPFRCC panel elements: the compressive strength reduction effect of HPFRCC panels varying with the lateral tensile strain of a cracked element, high ductile performance characteristic of HPFRCC in tensile strain after cracking, and transmission of shear stresses across a cracked HPFRCC surface under compressive stress. These three characteristics of cracked HPFRCC are dealt with in this chapter as main points in modeling the in-plane shear behavior of reinforced HPFRCC concrete panel elements.

2.1 Compatibility conditions

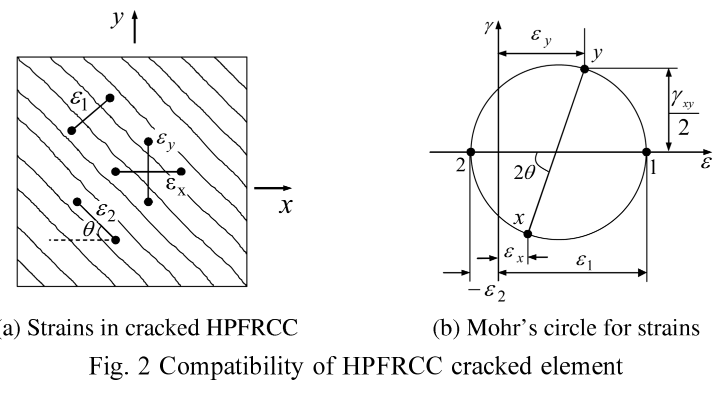
Assuming that the reinforcement is anchored to the concrete, compatibility requires that any deformation experienced by the concrete should be matched by an identical deformation of the reinforcement. From the three strain components ε_x, ε_y, and γ_{xy} in the x-y plane, as shown in Fig. 2, the strain in the principal axes of strains can be found. The shear strain related to x-y axes can be derived from the geometry of plane stress as

$$\gamma_{xy} = \frac{2(\varepsilon_x - \varepsilon_2)}{\tan\theta} \tag{1}$$

where ε_1 is the principal tensile strain, ε_2 is the principal compressive strain, and θ is the angle of principal strains to the x-axis.

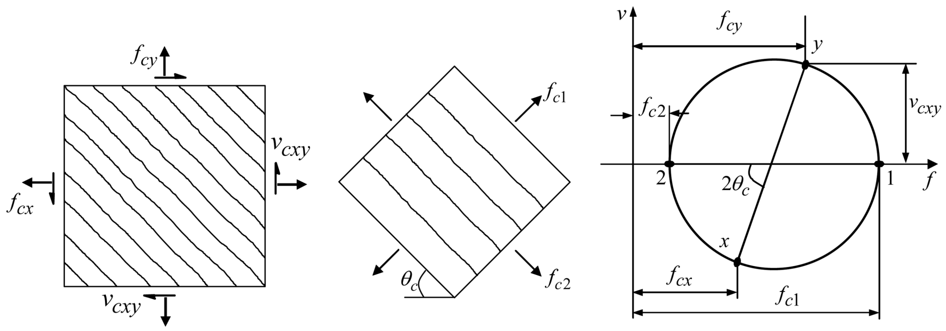
2.2 Equilibrium

Similar to reinforced concrete elements, the forces applied to a reinforced HPFRCC element are resisted by stresses in the HPFRCC and stresses in the reinforcement. From the equilibrium



(a) Strains in cracked HPFRCC (b) Mohr's circle for strains

Fig. 2 Compatibility of HPFRCC cracked element



(a) HPFRCC stresses (b) Principal stresses (c) Mohr's circle for stresses

Fig. 3 Stresses of HPFRCC cracked element

conditions and Mohr's circle for the HPFRCC stresses shown in Fig. 3, the following relationships are yielded

$$f_{cx} = f_{c1} - v_{cxy}/\tan\theta_c \tag{2}$$

$$f_{cy} = f_{c1} - v_{cxy} \cdot \tan\theta_c \tag{3}$$

$$f_{c2} = f_{c1} - v_{cxy}(\tan\theta_c + 1/\tan\theta_c) \tag{4}$$

where f_{cx} and f_{cy} are the stress in HPFRCC, respectively, in the x- and y-directions, v_{cxy} is the shear stress on HPFRCC relative to the x, y axes, and θ_c is the angle of principal stresses in HPFRCC to the x-axis. If the stresses f_{cx}, f_{cy}, and v_{cxy} are known, the stress conditions in the HPFRCC can be fully defined.

2.3 Constitutive law of cracked HPFRCC with reinforcement

Constitutive laws are required to link average stresses to average strains for both reinforcement and HPFRCC. Unlike normal concrete, HPFRCC show multiple fine cracks of reduced width without strain localization and can sustain tensile stresses corresponding with high strains of about 2% in tension. The high ductile characteristics of HPFRCC are going to manifest somewhat different from those of normal concrete, such as in the compressive behavior of panels under tensile force of HPFRCC, in the compressive behavior of cracked HPFRCC, in the high-ductile tensile behavior of HPFRCC after cracking, and in the transmitting shear stresses across cracks by aggregate interlocking.

2.3.1 Steel reinforcements

In steel reinforcements, it is assumed that the axial stress depends only on the axial strain in the reinforcement and that the average shear stress on the plane normal to the reinforcement resisted by the reinforcement is zero. For the relationship of axial stress and axial strain, the trilinear uniaxial stress-strain curve shown in Fig. 4 has been adopted.

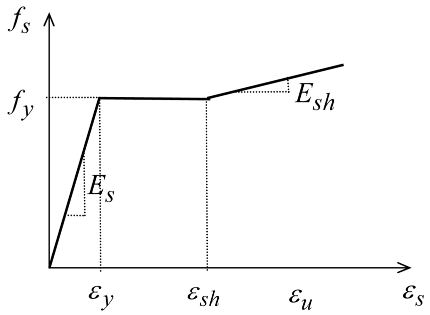


Fig. 4 Stress-strain curve of reinforcement

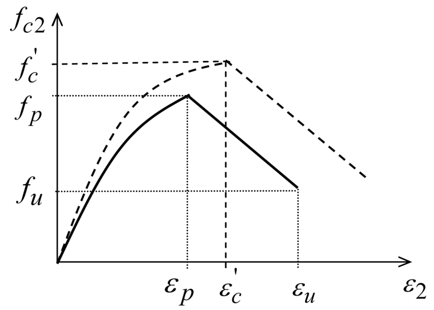


Fig. 5 Stress-strain curve of cracked HPFRCC in compression

2.3.2 Compressive strength reduction effect of HPFRCC

In normal concrete, the effect of tensile strains is to reduce the compressive strength in the direction parallel to the cracks (Vecchio *et al.* 1986, Vecchio 1992). In the case of HPFRCC, however, the reduction of compressive strength with the effect of tensile strains may be somewhat different from that of normal concrete due to the high performance characteristics of HPFRCC. The stress-strain curve of cracked HPFRCC in compression can be plotted as in Fig. 5, where f_p is the reduced compressive strength of HPFRCC. A series of experiments on compressive properties of HPFRCC was conducted by Fukuyama *et al.* (2003) with three kinds of HPFRCC, and the experimental results on the reduction factor of compressive strength related to tensile strain are shown in Fig. 6. From the experimental works, the reduction factor of compressive strength of HPFRCC has been newly proposed as

$$\beta_{HP} = \frac{1.0}{0.68 + 0.45 \cdot \left(\frac{\varepsilon_1}{\varepsilon_c'} + 0.13\right)^{0.36}} \tag{5}$$

where ε_1 is the principal tensile strain.

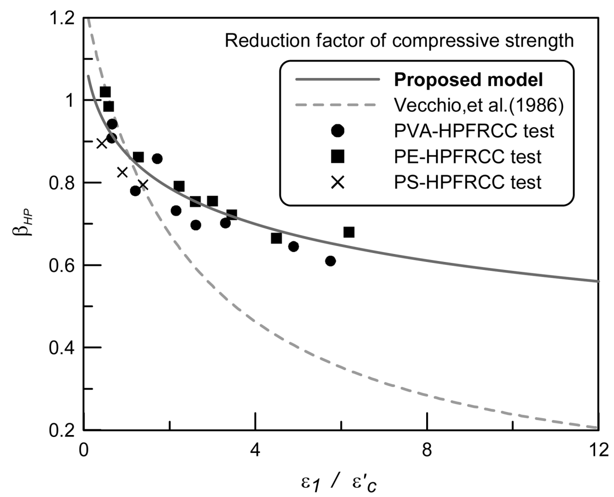


Fig. 6 Reduction factor of compressive strength of HPFRCC

The proposed reduction factor has been plotted in Fig. 6, comparing both experimental results of HPFRCC and the predicted curve proposed by Vecchio *et al.* (1986) for normal concrete. As shown in the figure, the effect of compressive strength reduction in accordance with the increase of tensile strain in HPFRCC was less than that in concrete.

Therefore, the principal compressive stress and the principal tensile strain relationship of HPFRCC can be modeled as a parabolic curve as follows

$$f_{c2} = \beta_{HP} \cdot f_c' \cdot \left[2\left(\frac{\varepsilon_2}{\varepsilon_c'}\right) - \left(\frac{\varepsilon_2}{\varepsilon_c'}\right)^2 \right] \tag{6}$$

Note that as ε_c' is a negative quantity and usually −0.002 for normal concrete. However, in the current model, ε_c' is adopted as −0.004 for HPFRCC.

2.3.3 Tensile behavior of HPFRCC

As shown in Fig. 7, HPFRCC was developed mainly to improve the quasi-brittle tensile behavior of normal concrete and mortar (Kim *et al.* 2004, Li 1992, 1993). By increasing tensile loads, unlike normal concrete, HPFRCC can sustain tensile stresses corresponding with high strains. This is because HPFRCC generally shows multiple fine cracks of reduced width, without strain localization.

In order to model the tensile behavior of HPFRCC, as shown in Fig. 7(b), it was considered that after cracking, the tensile stress was kept constant until reaching the ultimate tensile strain, and after the ultimate tensile strain, the tensile stress was released to zero. The ultimate tensile strain was about 2% for HPFRCC. Therefore, the relationship between the principal tensile stress and strain in the HPFRCC was suggested as

For $\varepsilon_1 \leq \varepsilon_{cr}$

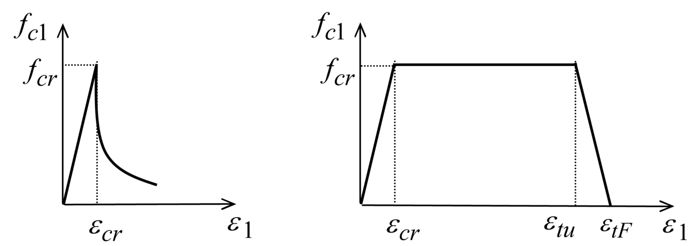
$$f_{c1} = E_c \cdot \varepsilon_1 \tag{7}$$

For $\varepsilon_{cr} < \varepsilon_1 \leq \varepsilon_{tu}$

$$f_{c1} = f_{cr} \tag{8}$$

For $\varepsilon_{tu} < \varepsilon_1 \leq \varepsilon_{tF}$

$$f_{c1} = f_{cr} - \frac{f_{cr}}{\varepsilon_{tF} - \varepsilon_{tu}}(\varepsilon_2 - \varepsilon_{tu}) \tag{9}$$



(a) Concrete in tension (b) HPFRCC in tension

Fig. 7 Tensile stress and strain curves of concrete and HPFRCC

2.3.4 Shear transmission across cracked HPFRCC surface

For the vast majority of concrete, cracking will occur along the interface between the cement paste and the aggregate particles. The resulting rough cracks can transfer shear by aggregate interlock. The shear transfer mechanisms on a cracked concrete surface have been experimentally studied by a number of investigators (Walranven 1980). Based on the experiments and the analytical model proposed by Vecchio *et al.* (1986), the following relationship on the shear across the crack was updated for cracked HPFRCC panel elements as follows

$$v_{ci} = a_{c1} \cdot v_{ci\max} + a_{c2} \cdot f_{ci} + a_{c3} \cdot \frac{f_{ci}^2}{v_{ci\max}} \tag{10}$$

where

$$v_{ci\max} = \frac{\alpha_{Sh}\sqrt{-f'_{ci}}}{0.31 + 24w/(a+16)} \tag{11}$$

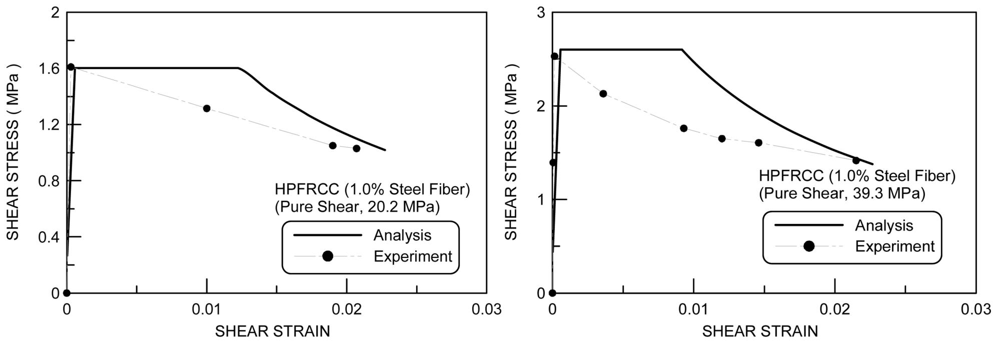
Here, a is the maximum aggregate size in millimeters and the stresses are in MPa, the crack width w should be the average crack width over the crack surface, α_{c1}, α_{c2}, α_{c3} are the parameters of shear transmission on cracked surface, and α_{Sh} is a parameter of maximum shear strength of HPFRCC panel elements.

2.3.5 Solution of in-plane shear behavior of reinforced HPFRCC elements

By applying currently developed material models for HPFRCC elements into the original modified compression field theory (Vecchio *et al.* 1986), an analytical solution has been introduced that is capable of predicting the shear stress-strain response of reinforced HPFRCC elements subjected to in-plane shear and normal stresses; the predictive model is called HPFRCC-MCFT. The solution technique adopted in the HPFRCC-MCFT model corresponds with that of the original modified compression field theory (Vecchio *et al.* 1986).

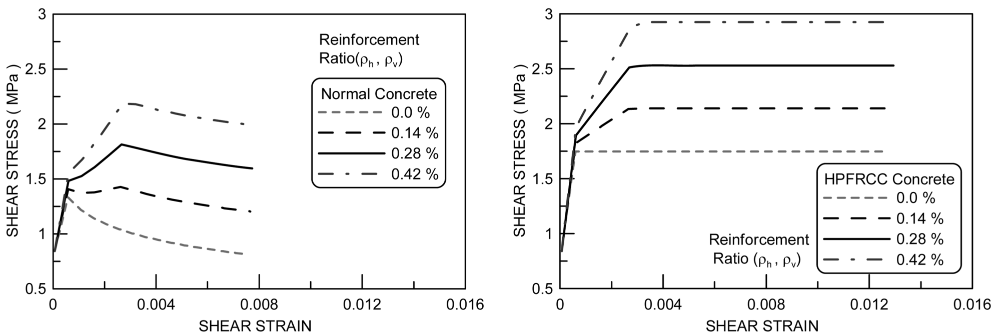
3. In-plane shear prediction of hpfrcc elements

In this chapter, the proposed MCFT model for prediction of in-plane shear behaviour of HPFRCC elements has been verified with experimental results of HPFRCC elements under pure shear test. The experimental program, conducted and developed by Hisabe *et al.* (2005), involves a simple pure shear test for a cement-based membrane element for small-scaled panels. In the pure shear test of HPFRCC elements, the test specimen was made as a square membrane element with dimensions of 206×206×100 mm with the corners cut off. Therefore, the effective plane area subjected to shear stress was 170×170 mm. In mix proportions for the test specimens, HPFRCC was manufactured by mixing 1.0% steel fiber per volume to concrete, and steel bars were not reinforced. From experimental results, two specimens of HPFRCC panels were analyzed. For specimen N01, cast with a water-cement ratio of 60%, the uniaxial compressive strength became 20.2 MPa, and for specimen N02, cast with a water-cement ratio of 45%, the uniaxial compressive strength became 39.3 MPa. From experimental studies (Kim *et al.* 2007, Walranven 1980), α_{Sh} was taken as 1.15, and α_{c1}, α_{c2}, and α_{c3} were taken as 0.18, 1.64, and −0.82, respectively. Experimental and predicted shear stress-strain relationships for two specimens are presented in Fig. 8. Until the maximum shear strength, the proposed model well predicted not only the pure shear stress-strain relationship of each



(a) Specimen A (20.2 MPa) (b) Specimen B (39.3 MPa)

Fig. 8 Pure shear predictions of HPFRCC panels



(a) Reinforced concrete panels (b) Reinforced HPFRCC panels

Fig. 9 Predicted pure shear behaviors of concrete and HPFRCC

specimen but also the maximum shear strength of the specimen. However, there was somewhat difference between analytical behavior and the experimental one in the region of post-peak behavior. In the current model, the tensile strain capacity of HPFRCC element was considered 2% and this value was common in HPFRCC materials reinforced by 1.5~2.0% volume fraction of PVA fibers. Since the specimens in the pure shear test were made by HPFRCC with 1.0% volume fraction of steel fibers, there was somewhat difference between the predicted post-peak behavior and the experimental one.

An analytical comparative study of pure shear behaviors between normal concrete panel elements and HPFRCC panel elements was conducted, as shown in Fig. 9, with varying horizontal and vertical reinforcement ratios. It was assumed in the analytical study that the uniaxial compressive strength was 20.2 MPa for both normal concrete and HPFRCC elements, and the material characteristics of the HPFRCC element were the same as those of specimen N01. Moreover, in the analysis of reinforced concrete panel elements, the original MCFT model for reinforced concrete was applied (Vecchio *et al.* 1986). As shown in the predicted results, to compare with reinforced concrete panels, reinforced HPFRCC panels showed more improved in-plane shear strength and post peak shear behavior. This is attributed to the high performance characteristic of HPFRCC lending an advantage in improving the in-plane shear strength and shear performance of HPFRCC panel elements, compared with normal concrete panel elements.

4. Reinforced concrete frames retrofitted by infilled hpfrcc walls

The high ductile characteristic of HPFRCC materials in tension can bring improvement to the seismic performance of conventional reinforced concrete structures. In the current study, reinforced concrete frame systems with and without retrofitting by in-filled HPFRCC walls were tested and the retrofitted systems were also analyzed.

For the analysis of reinforced concrete frame structures, generally, a nonlinear beam-column finite element is prefer than a nonlinear solid finite element (Cho *et al.* 2002). The analysis model for the retrofitted reinforced concrete frame systems is summarized in Fig. 10. In the developed analysis model, the inelastic finite element tangent stiffness for reinforced concrete beam-column elements was derived using the finite inelastic hinge zone model (Roufaiel *et al.* 1987, Cho *et al.* 2004), and the inelastic section moment-curvature relationship was computed using the fiber cross-sectional approach (Mander 1984). The reinforced HPFRCC wall element was modeled as a nonlinear shear link element and the flexural response of the wall was ignored since the wall is sufficiently low-rising. For the nonlinear shear link element, the nonlinear primary curve for the shear response of

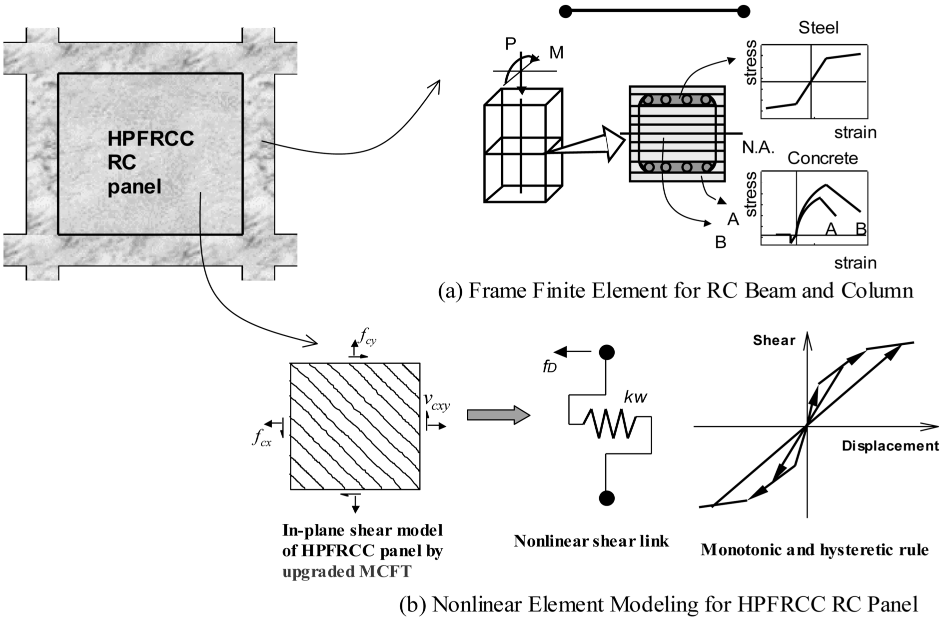


Fig. 10 Nonlinear model of RC frame retrofitted by HPFRCC walls

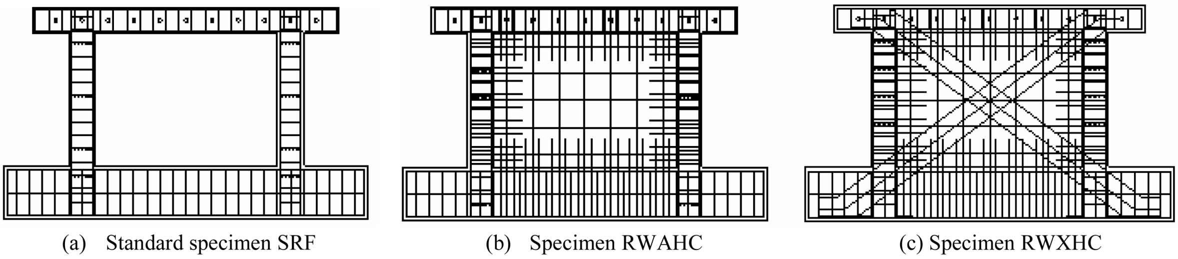


Fig. 11 Test specimens

Table 1 Comparison of analytical and experimental results

Specimen name	Size (m)	f_c' (MPa)	RC wrame + infilled HPFRCC wall						Design parameters
			Beam		Column		HPFRCC wall		
			0.2 m×0.2 m		0.2 m×0.2 m		1.4 m×1.0 m		
			Main bar	Stirrup	Main bar	Stirrup	Hori. Reinf.	Vert. Reinf.	
SRW RWAHC RWXHC	2.8 × 1.6	21	6-D10	Φ6 @100	8-D10	Φ6 @100	Φ6-@200	Φ6-@200	·ACI Building Code ·HPFRCC wall ·HPFRCC wall + X-type wars

Table 2 Characteristics of reinforcement

Bar type	Area (A) (cm^2)	Yield stress (MPa)	Tensile strength (MPa)	Young modulus (MPa)	ε_{max} (%)
HD 10	0.71	400	526	2.05×10^5	22.1
φ 6.0	0.28	280	457	2.3×10^5	32.1

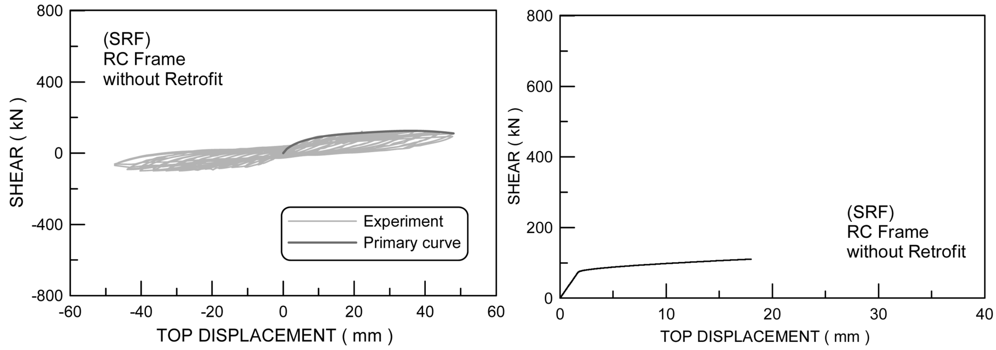
Table 3 Characteristics of PVA fiber

Diameter (m)	Length (mm)	Nominal strength (MPa)	Elongation (%)	Oiling agent content (%)	Young's modulus (GPa)
39	12	1620	6	0.8	38.9

the reinforced HPFRCC wall was computed from the developed HPFRCC-MCFT model.

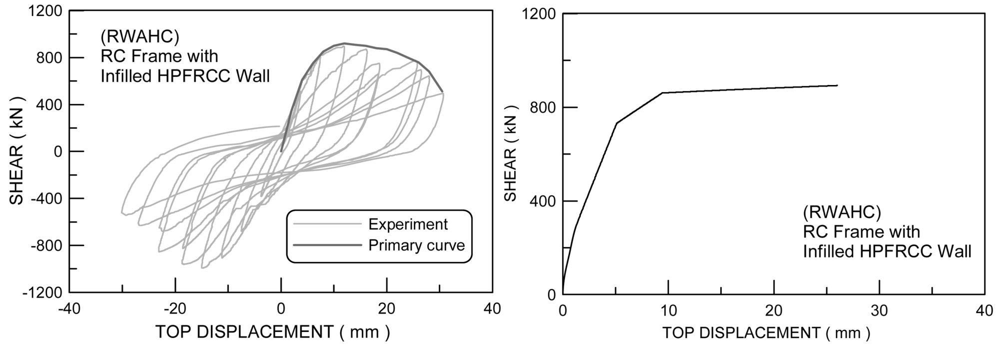
In the experimental program for evaluating retrofitted reinforced concrete frame systems, three specimens of portal frames with and without retrofitting by in-filled HPFRCC walls were constructed as 1/3 small-scaled models, as shown in Fig. 11. The standard specimen, SRF, was not retrofitted as a conventional reinforced concrete frame structure, and specimens RWAHC and RWXHC were retrofitted by in-filled reinforced HPFRCC walls. In the case of specimen RWXHC, the horizontal and vertical reinforcement ratios in the wall were the same as those of specimen RWAHC, but X-typed inclined reinforcements were additionally designed in the HPFRCC wall. Detailed of the properties and reinforcement of each specimen are summarized in Table 1 and the characteristics of the reinforcements are presented in Table 2. In order to cast in-filled reinforced HPFRCC walls, HPFRCC was made using PVA-fiber at 2.0% per volume and its material characteristics are listed in Table 3. From a cylinder test, the uniaxial compressive strength of HPFRCC was determined to be 26.5 MPa. In order to lend sufficient strength and stiffness to the retrofitted systems, anchor bolts were installed at 20 cm spacing between the frame system and the HPFRCC wall. For each specimen, a constant axial load of 125 kN was applied to each column and a lateral load was applied to the top story of the frame as a displacement-controlled reversed cyclic load. The test specimens were also analyzed under a monotonic lateral load using the currently developed program for the nonlinear analysis of retrofitted reinforced concrete frame structures.

From experimental and analytical predictions for each specimen, the lateral load and displacement relationships of the specimens are shown in Figs. 12, 13, and 14, respectively. As can be seen from the experimental results in the figures, the proposed retrofit technique can enhance the lateral load-



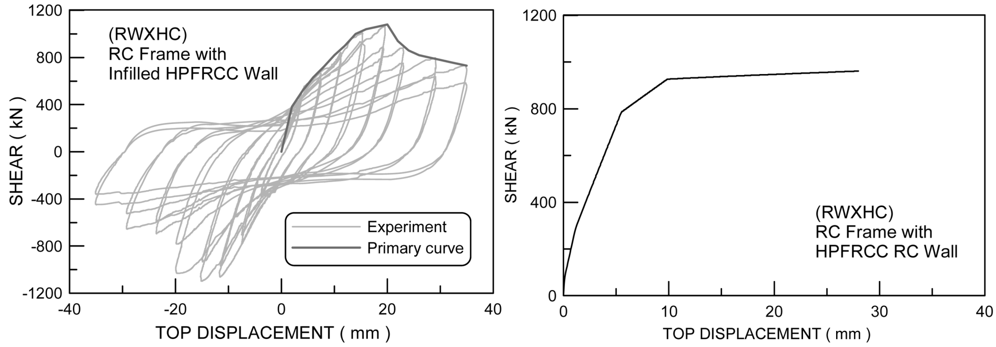
(a) Experiment (b) Analysis

Fig. 12 Lateral load and displacement (SRF)



(a) Experiment (b) Analysis

Fig. 13 Lateral load and displacement (RWAHC)



(a) Experiment (b) Analysis

Fig. 14 Lateral load and displacement (RWXHC)

carrying capacity and energy dissipation capacity of conventional reinforced concrete frame structures. From a comparison of two specimens, RWAHC and RWXHC, additional X-typed inclined reinforcements applied in the design of the HPFRCC wall provides increased strengthening and performance enhancement of the retrofitted systems. The predicted load-displacement curves of all specimens under a monotonic load matched well with the primary curves of the specimens

Tabe 4 Comparison of analytical and experimental results

Specimens	Predicted shear strength	Predicted displacement at failure	Experiment shear strength	Experimental max. displacement
SRF	110.6 kN	18.0 mm	128.8 kN	40.4 mm
RWAHC	893.0 kN	26.1 mm	994.2 kN	29.6 mm
RWXHC	961.5 kN	28.3 mm	1096.6 kN	33.3 mm

obtained from experiments under a cyclic load. In the current analysis of frame systems under a monotonic load, the program was stopped if one of columns was reached the crush of concrete and it was judged that the frame system reached to failure. As shown in Table 4, the predicted maximum load-carrying capacity and lateral displacement at failure of each specimen agreed well with the experimental results.

5. Conclusions

In the current study, the HPFRCC-MCFT model, a nonlinear model for predicting the in-plane shear behaviours of reinforced HPFRCC panel elements has been developed. The model newly considers the following important characteristics of cracked HPFRCC materials: the compressive strength reduction effect of HPFRCC panels varying with the lateral tensile strain of the cracked element, the high ductile performance characteristic of HPFRCC in tensile strain after cracking; and the transmission of shear stresses across a cracked HPFRCC surface under compressive stress. The proposed in-plane shear model of HPFRCC panel elements predicted well the experimental results of HPFRCC panel elements under pure shear. In addition, the proposed shear model has been extended to develop a nonlinear model of reinforced concrete frame systems retrofitted by in-filled HPFRCC walls. Correlation studies between the experimental and analytical results of retrofitted systems revealed that the current retrofit technique can enhance the lateral load-carrying capacity and energy dissipation capacity of conventional reinforced concrete frame systems, and the analysis model provides good agreement with the experimental results of retrofitted systems.

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