Shear Behavior of UHPFRC Web Retrofitted Single – layered RC Squat Wall

You-sun Yi, Sung-gul Hong, and Young mi Park

***Abstract*—**This study suggested to use UHPFRC which has higher structural performance than normal strength concrete for section enlargement retrofitting to enhance single – layered RC squat wall. Since there exists few researches related to this topic, this study planned experimental program to verify retrofitting effect of this method. Moreover, this study proposed an analytical algorithm for deriving shear retrofitting effect of it by deriving shear stress – shear strain curve of the retrofitted wall. The validity of the proposed method can be confirmed by the test results and assumed models. By using the proposed method, it is able to determine failure mode of the retrofitted wall, and find out that ratio of thickness of the RC squat wall and that of the UHPFRC section can affect failure mode of the retrofitted wall.

***Keywords*—**Single – layered squat wall, Shear retrofitting effect, Section enlargement, UHPFRC

I. INTRODUCTION

WALL structures built before 1980's in South Korea used single – layered RC squat wall. Therefore, they could not satisfy recent seismic provision. Korea used single-layered RC shear wall. Since they could not satisfy recent seismic provision, several retrofit strategies are needed to improve its seismic performance. One of the most general retrofitting method is section enlargement method, casting new RC section to retrofitting target. It's economical and practical advantages make it able to apply at lots of workplaces. However, the existing section enlargement with normal strength concrete is actually ineffective method in architectural view point, because vertical and transverse reinforcements have to be arranged in the enlarged section to improve the squat wall's shear capacity. Therefore, the thickness of the enlarged section becomes too thick, and space waste problem can be occurred. To resolve this problem, a new material comes to the fore; the ultra-high performance fiber reinforced concrete (UHPFRC). Its high performance material properties can reduce the thickness of the retrofitting section, and expected that the fibers mixed in the UHPFRC can play a role of the reinforcements. However, since there exists almost no researches related to the pure shear retrofitting effect of UHPFRC web retrofitted RC squat wall[1], this study planned experimental program and analytical study to confirm it.

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II. EXPERIMENTAL PROGRAM

A. Material & reinforcement detail of retrofitting target

Since this study focused on the single – layered RC squat wall used for shear wall type low-rise building built in 1980's, material properties and reinforcement detail of the single – layered squat wall are based on structural drawing of existing shear wall type low – rise building built in 1980's in Republic of Korea. The compressive strength of concrete used for the single – layered squat wall is 21Mpa, and SS400 is used for reinforcement of the single – layered squat wall. Therefore, this study designed test specimens with concrete strength of 24Mpa and same type of reinforcement. Moreover, vertical and transverse reinforcement ratios of the specimens are also determined from structural drawing of the existing building. One of the single – layered squat wall from the structural drawing has 0.33% vertical reinforcement ratio and 0.47% transverse reinforcement ratio with HD10 reinforcement. Therefore, the same ratios are applied to the wall panels of the specimen. Aspect ratio of the squat all is one to induce shear failure of the wall panel.

Although the specimens were planned to be 1/2 scaled at the first time, there exists some limitations. Since there was no deformed reinforcement has smaller diameter than HD10 and smaller thickness of the squat wall makes it harder to secure cover thickness of dowel bars placed between the squat wall and retrofitting column component to behave monolithically, the specimens used geometric value of the original structural drawing only for diameter of vertical, transverse reinforcements, and thickness of the squat wall.

B. Material properties & detail of retrofitting UHPFRC section

Since performance of the UHPFRC is different depending on its mixture proportions, there are several types of the UHPFRC under investigation depending on the mixture proportions of the UHPFRC around the globe. This study used Sung-hoon Kang, and Sung-gul Hong's mixture proportions[2] for the UHPFRC web retrofitting as shown in Table I. It's expected compressive strength is 150Mpa, and flexural strength is 60Mpa according to previous studies.

TABLE I
MIXTURE PROPORTIONS OF UHPFRC

	Cement	Silica fume	Sand	Filler	Super plasticizer	Water	Steel fiber (vol. %)
Mixture proportion	1	0.23	1.1	0.39	0.02	0.19 ~0.25	2.0 ± 0.5

The thickness of the retrofitting UHPFRC section is 40mm for constructability and retrofitting efficiency. To evaluate net retrofitting effect of the web UHPFRC retrofitting to the squat wall, there does not exist any tensile member like wire mesh or reinforcement in the retrofitting section. The width of the UHPFRC retrofitting section is same as that of retrofitting target's web; however, the height of the UHPFRC retrofitting section is 200mm larger than that of retrofitting target's web. This is the reason to prevent rocking failure of the UHPFRC retrofitting section by inserting it into the foundations of the retrofitting target.

C. *Result of material property test*

The compressive strength and the yield strength of the reinforcements used for the specimens derived from the result of the material property tests. The test results are tabulated in Table II.

TABLE II
STRENGTH OF CONCRETE AND REINFORCEMENT

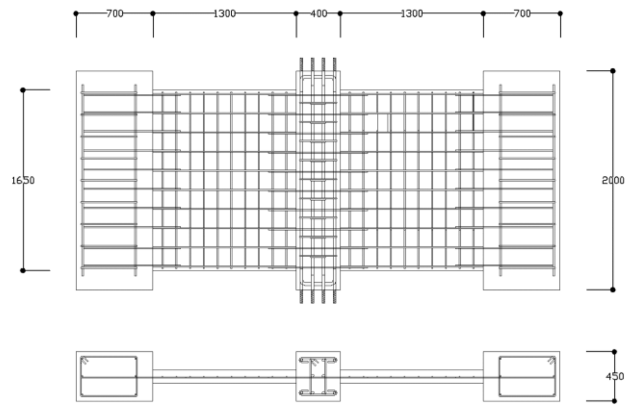
	Concrete	UHPFRC		Reinforcement
	(f_{ck})	Compressive (f_{ck}^{UHPC})	Flexural tensile	(f_y)
Nominal strength	24 MPa	150 MPa	60 MPa	400 MPa
Actual strength (Average value)	30 MPa	100 MPa	29.5 MPa	488 MPa

As shown in Table II, the compressive strength and the flexural tensile strength of the UHPFRC are lower than the expected strength. The reason of this distinction is supposed that moisture in the air was penetrated into binding materials; concrete, sand, silica fume, and filler. This study did not deal with this problem.

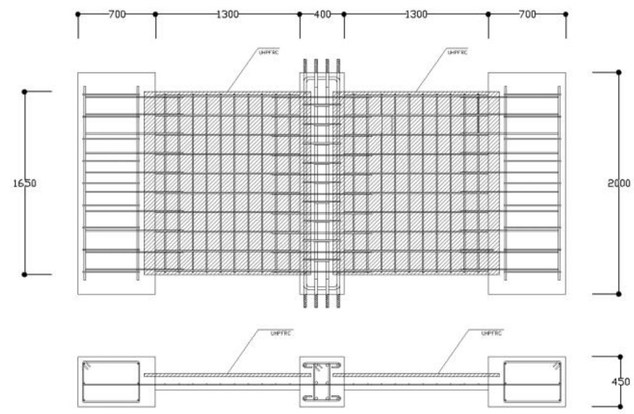
D. *Specification of test specimens*

To evaluate shear retrofit effect of the UHPFRC web retrofitting method, this study planned two types of specimens; one is non retrofitted single – layered squat wall(WN), another one is UHPFRC web retrofitted single – layered squat wall (WR).

The test specimens consist of three boundary elements, and two wall panel elements. Vladmir Cervenka and Kurt H. Gerstle had used this type of specimen to evaluate inelastic behavior of RC wall panel[3], and they showed that this type of specimen can be used for test of squat wall by concentrating all cracks in the wall panels. The boundary elements located at the both ends of the specimen are used to make fixed boundary condition, and the boundary element located at the center of the specimen used for loading point. Every boundary elements of the specimen has relatively large size to concentrate all cracks into the wall panels. The details of the specimens are shown in Figure 1.



a) Specification of WN



b) Specification of WR

Fig. 1 Specification of specimens

E. *Test set-up*

To evaluate the UHPFRC web retrofit effect against to the seismic load, this study planned to apply cyclic loading to the specimens. In addition, several LVDTs were installed to measure force – directional and shear deformation. The test set-up and location of each LVDT are shown in Figure 2.

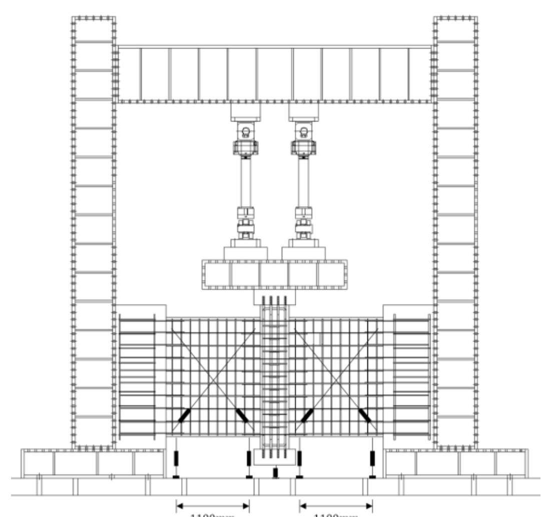


Fig. 2 Test set-up

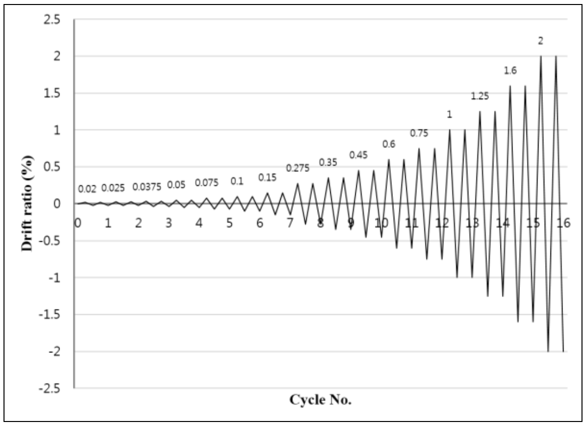


Fig. 3 Lateral loading protocol set-up

The cyclic loading test was performed by displacement – controlled loading abided by manual of test method for precast concrete structural wall[4]. The load profile of the cyclic loading is shown in Figure 3.

III. Test Result

A. *Test result of WN*

The total cyclic response of WN is shown in Figure 4. The failure of WN was accompanied with yielding of the transverse reinforcements in the both wall panels of the specimen. The failure mode of WN was governed by diagonal tension failure of the only one wall panel in WN. The crack pattern of WN after the test was finished is shown in Figure 5.

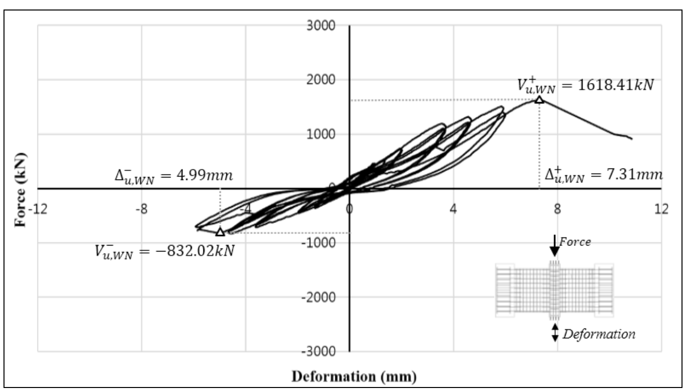


Fig. 4 Total cyclic response of WN

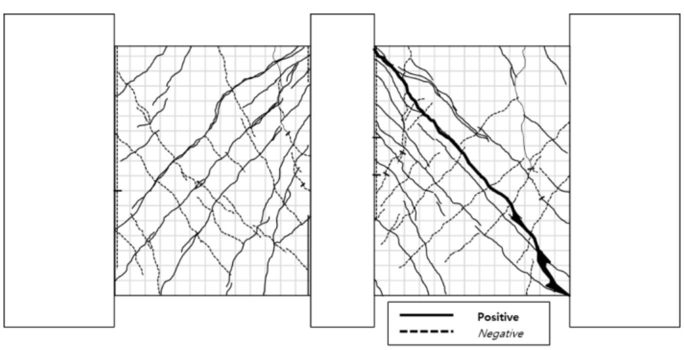


Fig. 5 Crack pattern of WN (0.56% drift ratio)

Since the transverse strains measured through the cyclic loading showed that both left and right wall panel contributed almost same portion to the behavior of the specimen. Therefore, it is reasonable to consider that the cyclic behavior of the one wall panel is same as that of the specimen with half strength. However, there exists some gap between the positive directional strength and the negative directional strength of the specimen. The reason of this imbalance phenomenon is supposed that there occurred some gap between the both boundary elements and the foundation frame when the negative directional load was applied to the specimen.

B. *Test result of WR*

Since there occurred some unexpected problems during the test, WR could not reach its ultimate state. The strength and the deformation in the negative direction could not be measured after the 9th cycle (0.35% drift ratio), because some through reinforcements arranged at the middle boundary element of the specimen were fractured due to high tensile force applied to the specimen.. In addition, there occurred distortion of the middle boundary element during the first cycle of the 12nd cycle (0.75% drift ratio), and the test was re-conducted after readjusting the distorted middle boundary element from the 12nd cycle. However, there did not occurred any specific damage in the specimen after that time, and the specimen could not reach its ultimate state due to interface failure between the squat wall and the UHPFRC panel at the modified 14th cycle (1.25% drift ratio) as shown in Figure 6.

The total cyclic response of WR until the interface failure was occurred is shown in Figure 7. In addition, cracking of the UHPFRC panel did not occurred before the 12nd cycle, though lots of cracks were occurred in the normal strength concrete wall panel at that time. The crack pattern of WR after the test was finished is shown in Figure 8.

Similar to the case of WN, since the transverse strains measured through the cyclic loading showed that the both left and right wall panel contributed almost same portion to the behavior of the specimen. Therefore, it is also reasonable to the cyclic behavior of the one wall panel is same as that of the specimen with half strength.

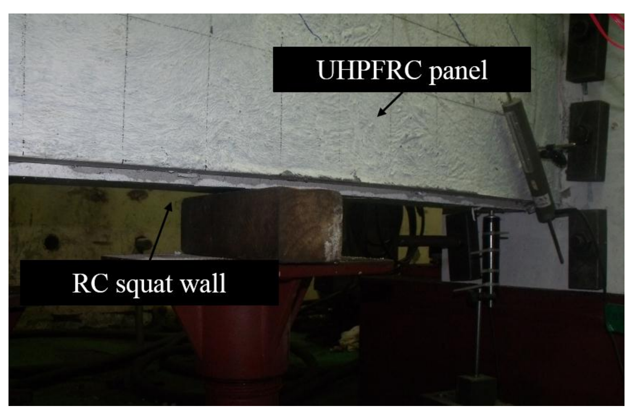


Fig. 6 Interface failure of WR (Modified 14th cycle)

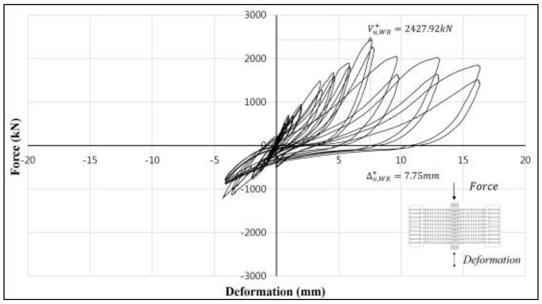
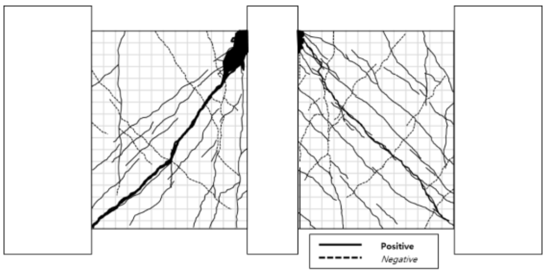
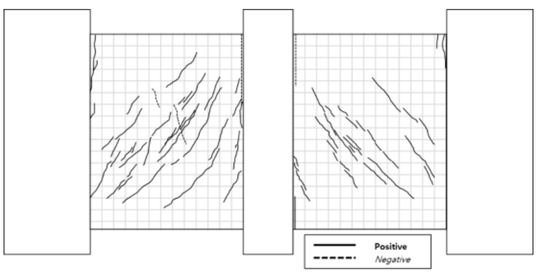


Fig. 7 Total cyclic response of WR

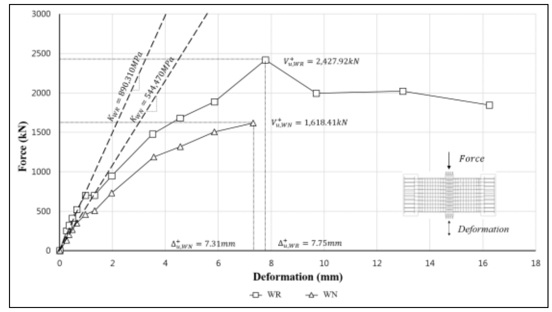


a) Specification of WN

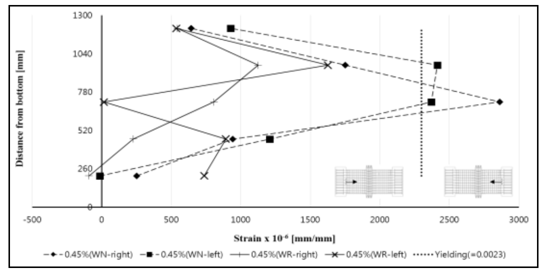


b) Crack pattern of UHPFRC panel

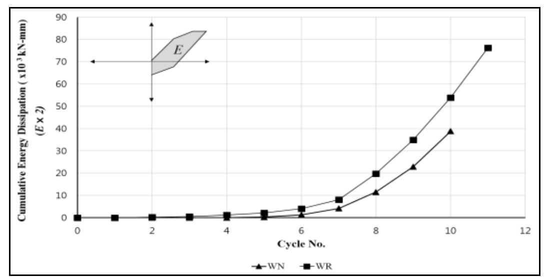
Fig. 8 Crack pattern of WR (1.25% drift ratio)



a) Backbone curve of WN & WR



b) Restrained strain of transverse reinforcement at 0.45% drift ratio



c) Dissipated energy of WN & WR

Fig. 9 Comparison results

C. Retrofitting effect of UHPFRC web retrofitting

Since the specimens were subjected to the cyclic loading, it is convenient to verify retrofitting effect of UHPFRC web retrofitting by using positive directional backbone curves of them as shown in Figure 9. Although WR could not reach its ultimate state, it is able to confirm that about 60% of initial stiffness and about 50% of ultimate strength are enhanced by 40mm thickness UHPFRC web retrofitting without any reinforcement in the retrofitting section. Moreover, the UHPFRC panel restraints the strain increment of the transverse reinforcements. This fact can be confirmed by the strain distribution of the both specimens at the 10th cycle when the transverse reinforcement of WN yielded as shown in Figure 9. The transverse reinforcement of WR did not yielded at that time. Nevertheless, the comparison result of dissipated energy derived from the area of the positive directional cycles between WN and WR shows conflicting this fact. The dissipated energy of WR is always larger than that of WN at every load cycles as shown in Figure 9. This contradiction can be explained by energy dissipation contribution of the UHPFRC panel. Therefore, it is able to delay yielding of the transverse reinforcement, and increase the dissipated energy than the single – layered squat wall by the UHPFRC panel at the same load cycle.

IV. Proposed Method To Evaluate Behavior Of UHPFRC Web Retrofitted Single-Layered Squat Wall

A. Revised softened membrane model (SMM)

There were lots of shear theories had been studied by lots of researchers. Hsu and Zhu proposed the softened membrane model (SMM) considering Hsu/Zhu ratios defined as poisson ratios of cracked RC element to predict shear behavior of it[5]. The SMM makes it possible to compute every strains and stresses applied to the RC 2-D element in l – t and 1 – 2 coordinate for 2 – directional biaxial compressive strain, ε_2. The 1 – 2 coordinate can be determined by the applied principal stresses direction, and the l – t coordinate is same as direction of the arranged vertical and transverse reinforcements in the RC element. This study revised the SMM to analyze the UHPFRC web retrofitted single – layered RC squat wall based on some assumptions. First, the RC squat wall and the UHPFRC panel behaved with same strain values, ε_1, ε_2, and γ_{12} at the same time. Second, the UHPFRC panel and the RC squat wall have same strut angle, α_1 of the applied principal stress in the 1 – 2 coordinate. Third, since the softening behavior of the UHPFRC has not be studied before, this study assumed that existing softening coefficient ζ for the normal strength concrete also can be used for strength of the UHPFRC. By these assumptions, this study revised the SMM, and proposed flow chart for it as shown in Figure 10. Each step of the flow chart can be summarized in this study step by step.

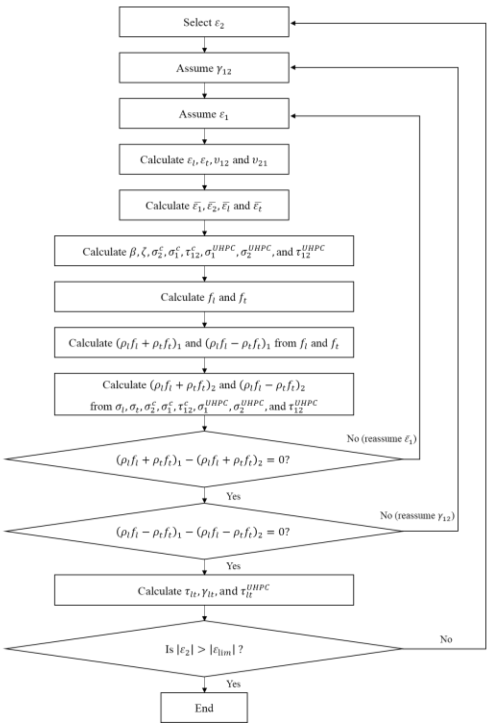


Fig. 10 Flow chart of solution procedure for revised SMM

- Calculate ε_l, ε_t, υ_{12} and υ_{21}

Before beginning the flow chart, it is recommended to establish stress equilibrium equations and strain compatibility equations of the RC element and the UHPFRC element. Since the RC element is consist of the concrete and reinforcements assumed as smeared steel for the revised SMM, the Mohr stress circle of the RC element subjected to the external stress can be divided into that of the concrete element and that of the smeared steel. Based on this Mohr stress circle, it is able to derive Mohr strain circle of the RC element that is same with that of the UHPFRC element. According to that, the stress equilibrium equations strain compatibility equations can be derived as below equations.

a) Stress equilibrium equations (RC element)

$$\sigma_l = \sigma_1^c \cos^2\alpha_1 + \sigma_2^c \sin^2\alpha_1 - \tau_{12}^c 2\sin\alpha_1\cos\alpha_1 + \rho_l f_l \quad (1a)$$

$$\sigma_t = \sigma_1^c \sin^2\alpha_1 + \sigma_2^c \cos^2\alpha_1 + \tau_{12}^c 2\sin\alpha_1\cos\alpha_1 + \rho_t f_t \quad (1b)$$

$$\tau_{lt} = (\sigma_1^c - \sigma_2^c)\sin\alpha_1\cos\alpha_1 + \tau_{12}^c(\cos^2\alpha_1 - \sin^2\alpha_1) \quad (1c)$$

b) Stress equilibrium equations (UHPFRC element)

$$\sigma_l^{UHPC} = \sigma_1^{UHPC}\cos^2\alpha_1 + \sigma_2^{UHPC}\sin^2\alpha_1 - \tau_{12}^{UHPC} 2\sin\alpha_1\cos\alpha_1 \quad (2a)$$

$$\sigma_t^{UHPC} = \sigma_1^{UHPC}\sin^2\alpha_1 + \sigma_2^{UHPC}\cos^2\alpha_1 + \tau_{12}^{UHPC} 2\sin\alpha_1\cos\alpha_1 \quad (2b)$$

$$\tau_{lt}^{UHPC} = (\sigma_1^{UHPC} - \sigma_2^{UHPC})\sin\alpha_1\cos\alpha_1 + \tau_{12}^{UHPC}(\cos^2\alpha_1 - \sin^2\alpha_1) \quad (2c)$$

c) Strain compatibility equations

$$\varepsilon_l = \varepsilon_1\cos^2\alpha_1 + \varepsilon_2\sin^2\alpha_1 - \frac{\gamma_{12}}{2} 2\sin\alpha_1\cos\alpha_1 \quad (3a)$$

$$\varepsilon_t = \varepsilon_1\sin^2\alpha_1 + \varepsilon_2\cos^2\alpha_1 + \frac{\gamma_{12}}{2} 2\sin\alpha_1\cos\alpha_1 \quad (3b)$$

$$\frac{\gamma_{lt}}{2} = (\varepsilon_1 - \varepsilon_2)\sin\alpha_1\cos\alpha_1 + \frac{\gamma_{12}}{2}(\cos^2\alpha_1 - \sin^2\alpha_1) \quad (3c)$$

Where ε_l, ε_t, σ_l and σ_t are biaxial strains and uniaxial stresses in *l – t* coordinate, and ε_1, ε_2, σ_1 and σ_2 are biaxial strains and uniaxial stresses in *1 – 2* coordinate. γ_{lt}, γ_{12}, τ_{lt} and τ_{12} are shear strain in *l – t* coordinate and *1 – 2* coordinate, respectively. Moreover, Hsu/Zhu ratios, υ_{12} and υ_{21} can be derived by the strain in the reinforcement that reaches yield strain ε_y first, ε_{sf} (ε_l or ε_t).

In the case of $\varepsilon_{sf} \le \varepsilon_y$;

$$\upsilon_{12} = 0.2 + 850\varepsilon_{sf} \quad (4a)$$

In the case of $\varepsilon_{sf} > \varepsilon_y$;

$$\upsilon_{12} = 1.9 \quad (4b)$$

$$\upsilon_{21} = 0 \text{ after cracking, } \upsilon_{21} = 0.2 \text{ before cracking} \quad (4c)$$

- Calculate $\bar{\varepsilon}_1$, $\bar{\varepsilon}_2$, $\bar{\varepsilon}_l$, and $\bar{\varepsilon}_t$

Based on the first selected and assumed strains, ε_1, ε_2, and γ_{12}, it is able to compute uniaxial strains in *1 – 2* coordinate, $\bar{\varepsilon}_1$ and $\bar{\varepsilon}_2$ by using the determined Hsu/Zhu ratios, υ_{12} and υ_{21}.

$$\bar{\varepsilon}_1 = \frac{1}{1-\upsilon_{12}\upsilon_{21}}\varepsilon_1 + \frac{\upsilon_{21}}{1-\upsilon_{12}\upsilon_{21}}\varepsilon_2 \quad (5a)$$

$$\bar{\varepsilon}_2 = \frac{\upsilon_{21}}{1-\upsilon_{12}\upsilon_{21}}\varepsilon_1 + \frac{1}{1-\upsilon_{12}\upsilon_{21}}\varepsilon_2 \quad (5b)$$

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Then, it is able to compute uniaxial strain of *l-t* coordinate, $\overline{\varepsilon_l}$ and $\overline{\varepsilon_t}$ using strain compatibility equations;

$$\overline{\varepsilon}_l = \overline{\varepsilon}_1 \cos^2 \alpha_1 + \overline{\varepsilon}_2 \sin^2 \alpha_1 - \frac{\gamma_{12}}{2} 2 \sin \alpha_1 \cos \alpha_1 \quad (6a)$$

$$\overline{\varepsilon}_t = \overline{\varepsilon}_1 \sin^2 \alpha_1 + \overline{\varepsilon}_2 \cos^2 \alpha_1 + \frac{\gamma_{12}}{2} 2 \sin \alpha_1 \cos \alpha_1 \quad (6b)$$

- Calculate β, ζ, σ_1^c, and σ_2^c

The deviation angle, β is the difference between the angle α_1 of the applied principal stresses in the *1 – 2* coordinate and the angle α_r of the principal concrete stresses in the *r – d* coordinate. It also can be derived from the below equation

$$\beta = \frac{1}{2} \tan^{-1} \left[\frac{\gamma_{12}}{(\varepsilon_1 - \varepsilon_2)} \right] \quad (7)$$

Since the strains of the concrete element and reinforcements, $\overline{\varepsilon}_1$, $\overline{\varepsilon}_2$ are determined in the previous equations, stresses applied to the concrete element can be computed by using constitutive relationship of the concrete element.

- Constitutive relationship of concrete and UHPFRC element

The constitutive relationships of the concrete compressive stress σ_2^c and the uniaxial compressive strain $\overline{\varepsilon}_2$ and the tensile stress σ_1^c and the uniaxial compressive strain $\overline{\varepsilon}_1$ are shown in Figure 11. Moreover, the constitutive relationships of the UHPFRC compressive stress σ_2^{UHPC} and the uniaxial compressive strain $\overline{\varepsilon}_2$ and the tensile stress σ_1^{UHPC} and the uniaxial compressive strain $\overline{\varepsilon}_1$ are also shown in Figure 11. The constitutive relationships of the UHPFRC are assumed to be same as that of the K-UHPC provision[6]. In addition, the smeared tensile stress–strain relationship of reinforcement embedded in concrete is determined bilinear model considering strain hardening.

Since uniaxial strains of the concrete and the UHPFRC in the direction of the applied principal stresses and that of the reinforcement in the vertical and transverse direction are derived from the former process, it is able to compute all the stresses in the concrete, UHPFRC, and reinforcement by using these constitutive relationships.

In addition, smeared stress–strain relationships of the concrete and UHPFRC in shear can be obtained as below equations based on the Mohr circle for stresses and strains of the RC element and UHPFRC element, and assuming that the direction of the principal stress of concrete coincides with the principal strain.

$$\tau_{12}^c = \frac{\sigma_1^c - \sigma_2^c}{2} \tan 2\beta \quad (8a)$$

$$\tau_{12}^{UHPC} = \frac{\sigma_1^{UHPC} - \sigma_2^{UHPC}}{2} \tan 2\beta \quad (8b)$$

$$\gamma_{12} = (\varepsilon_1 - \varepsilon_2) \tan 2\beta \quad (9)$$

Since uniaxial strains of the concrete and the UHPFRC in the direction of the applied principal stresses and that of the reinforcement in the vertical and transverse direction are derived from the former process, it is able to compute all the stresses in the concrete, UHPFRC, and reinforcement by using these constitutive relationships.

- Convergence criteria

Since the retrofitted member is subjected to the pure shear in this study, force equilibrium considering the stresses of the RC squat wall and the UHPFRC panel (Equation (1a) ~ (1b), and Equation (2a) ~ (2b)) and the thickness of them also has to be included.

$$\sigma_l t_w + \sigma_l^{UHPC} t_{UHPC} = 0 \quad (10a)$$

$$\sigma_t t_w + \sigma_t^{UHPC} t_{UHPC} = 0 \quad (10b)$$

Based on these equations, it is able to define revised convergence criteria of the revised SMM considering the stresses and the thickness of the UHPFRC panel by summing up and subtracting the Equation (10a) and the Equation (10b) as below;

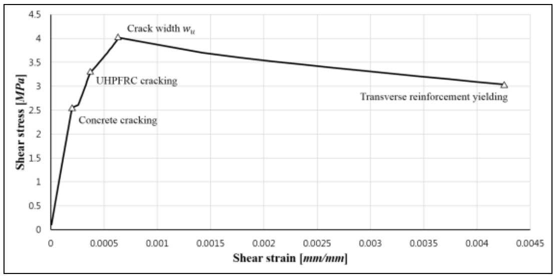
In the case of pure shear;

$$(\rho_l f_l + \rho_t f_t)_2 = (\sigma_1^c + \sigma_2^c) - \frac{t_{UHPC}}{t_w} (\sigma_1^{UHPC} + \sigma_2^{UHPC}) \quad (11a)$$

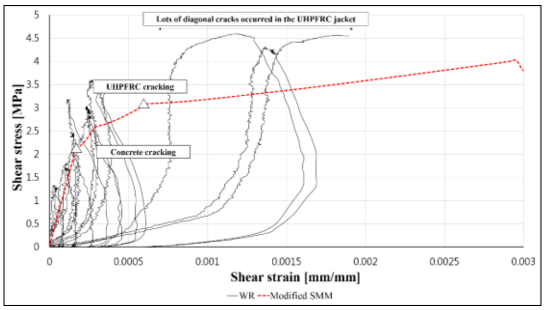
$$(\rho_l f_l - \rho_t f_t)_2 = -(\sigma_1^c - \sigma_2^c) \cos 2\alpha_1 + 2\tau_{12}^c \sin 2\alpha_1 - \frac{t_{UHPC}}{t_w} \left[(\sigma_1^{UHPC} - \sigma_2^{UHPC}) \cos 2\alpha_1 + 2\tau_{12}^{UHPC} \sin 2\alpha_1 \right] \quad (11b)$$

B. Failure mode of UHPFRC web retrofitted RC squat wall determined from revised SMM

Therefore, it is able to follow the flow chart of the revised SMM considering the UHPFRC panel behaved with the same strain conditions of the RC squat wall. The failure mode of the web UHPFRC retrofitted RC squat wall also can be verified. The shear stress–shear strain curve of the UHPFRC web retrofitted RC squat wall plotted from the modified SMM as shown in Figure 11**Error! Reference source not found.**.



a) Analytical result of the web UHPFRC retrofitted RC squat wall



a) Comparison result of WR & revised SMM

Fig. 11 Validity of the revised SMM

According to the analytical result of the revised SMM, the failure mode of the UHPFRC web retrofitted RC squat wall can be arranged with some specific events. After the normal strength concrete cracking is occurred, stiffness does not decreased so much different from the case of the non-retrofitted RC squat wall. When the UHPFRC panel is cracked, bridging action is started by fibers. The maximum shear stress is appeared when the crack width of the UHPFRC panel reaches w_u when the maximum tensile stress of the UHPFRC is occurred. Beyond the maximum shear stress, linearly descending branch is formed by fibers of the UHPFRC panel. Finally, yielding of the transverse reinforcement causes diagonal tension failure. The comparison result between the test result of WR and the analytical result is also shown in Figure 11. The shear strain of WR is measured from its diagonally installed LVDTs until the 12nd cyclic loading; the distortion of the middle boundary element was occurred. The analytical maximum shear stress of the UHPFRC web retrofitted squat wall is about 70% of that of the test result, similar to the case of WN. Although the test result crack widening of the UHPFRC could not follow that of the RC wall due to lack of the interface shear, and the ultimate failure of the test could not be determined, there are some evidences that can support the validity of the analytical result. First, the overall appearance of the test result is similar to that of the analytical result. Second, the restraint of the strain of the transverse reinforcement at the earlier cycles shows that the RC squat wall and the UHPFRC panel behaved with the same strains. Third, occurrence of the lots of diagonal cracks at the test (11st ~ 12nd cycle) within the region from the point of the UHPFRC cracking to the point of the UHPFRC crack width reaches w_u. Therefore, it's able to conclude the validity of the proposed method, a certain extent.

V. Conclusions

The UHPFRC web retrofitted single-layered squat wall was analyzed in experimental and analytical way in this study. Although the test result was not good enough to prove the retrofitting effect of the UHPFRC web retrofitting method, it is able to determine the failure mode of the retrofitted squat wall by modified SMM proposed in this study. The conclusions of this chapter are also summarized below.

- Compared to the non-retrofitted specimen, the retrofitting UHPFRC panel restraints strain increment of the transverse reinforcements. This fact can be confirmed by the comparison results of the strain distribution between the specimens; WN and WR
- The dissipated energy of WR is always larger than that of WN at every load cycles. Based on this fact, it is able to confirm the energy dissipation contribution of the retrofitting UHPFRC panel.
- Since WR could not reach its ultimate state, the softened membrane model (SMM), reliable model for analyzing 2-D RC membrane element was revised in this study to consider the retrofitting effect of the UHPFRC panel with considering the thickness ratio t_{UHPC}/t_w. Based on the similarities found between the both experimental and analytical results, it is confirmed that the revised SMM can predict the UHPFRC web retrofitted squat wall conservatively.

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