CYCLIC RESPONSE OF DAMAGED MEMBERS REPAIRED BY DIFFERENT TYPES OF SHCCS

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Abstract: Capability of a rapid jacketing technique for damaged RC column using Ultra High Performance-Strain Hardening Cementitous Composites (UHP-SHCC), was confirmed. UHP-SHCC has tensile strength more than 8MPa and tensile strain capacity more than 1%. Cyclic loading tests for the wall specimens (cross section: 500x1200mm) were conducted. Two kinds of repair materials were adopted; one was ordinary SHCC and the other was UHP-SHCC. Each repair material has similar material ductility (tensile strain hardening) but different tensile strength. The test results showed that the developed technique using UHP-SHCC can be applied to large size of specimens. And not only material ductility but also tensile strength affects recovery of repaired specimens (ultimate strength and energy dissipation).

1 INTRODUCTION

For concrete structures damaged due to earthquake, development of rapid repair/ retrofitting methods [1, 2] is a very important issue and required in terms of business continuity plan (BCP). There are a wide variety of methods such as jacketing with steel plate, continuous fibers and RC. These methods, however, involve many construction processes such as manufacture of parts and grouting of epoxy in the case of steel jacketing technique, formwork, arrangement of steel reinforcement and casting of concrete in the case of RC jacketing technique. These construction processes give longer downtime of service on the infrastructure.

Ultra High Performance-Strain Hardening Cementitious Composites (UHP-SHCC) [3], which is one of the fiber reinforced composites, has high strength in both compression and tension, high strain capacity in tension with pseudo strain hardening behavior. And spraying technique with UHP-SHCC [4] has been also developed to reduce a construction process for repair applications.

This paper introduces the developed rapid jacketing technique using UHP-SHCC for damaged RC wall subjected to seismic loading. The RC wall specimen repaired by UHP-SHCC was tested, and load carrying capacity and ductility were evaluated comparing to the specimen repaired by ordinary Strain Hardening Cementitious Composites (SHCC).

2 CONCEPTUAL IDEA ON RAPID JACKETING TECHNIQUE AND ITS ADVANTAGES

Figure 1 illustrates the conceptual idea on rapid jacketing technique by using UHP-SHCC. UHP-SHCC is sprayed to a damaged part without any additional reinforcement. Both the novel material properties (i.e. high strength and high strain capacity) and spraying technique enable to develop the rapid jacketing, and followings are remarkable features of the developed technique including its advantages.

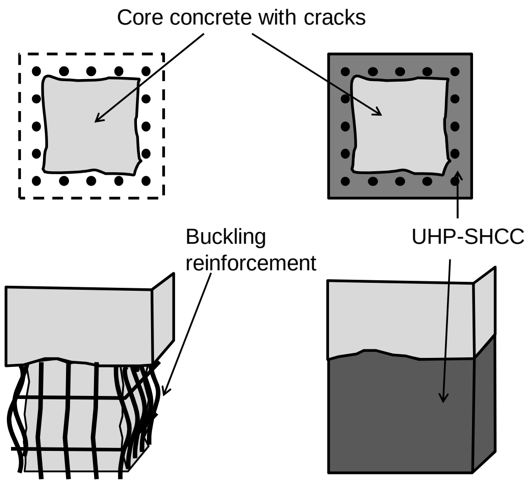
· The target of this technique is a damaged structure that has buckling of longitudinal reinforcement with spalling of cover concrete.

· The target of recovery level such as load carrying capacity and ductility after the jacketing is as well as that before the repair.

· Cross sectional shape after the recovery is the same as that before damage. It means that the damaged concrete corresponding to cover concrete is replaced by the repair material (UHP-SHCC). It allows to apply the other strengthening (e.g. steel plate jacketing) later.

· No additional reinforcement is utilized in the jacketing.

· No formwork is required because of spraying technique.



(a) damaged column (b) repaired column

Figure 1: Construction procedure of developed technique.

3 OUTLINE OF EXPERIMENTAL PROGRAM

In this study, a cyclic loading was carried out in order to induce initial damage for wall specimen (namely initial loading). After that, repair works were applied by using two kinds of repair materials; one was ordinary SHCC, and the other was UHP-SHCC. Both repair materials can be sprayed to the damaged part due to the first loading. After the curing of the repaired specimens (SHCC: 10 days, UHP-SHCC: 5 days), a cyclic loading was conducted again (second loading). Figure 2 shows the experimental procedure in this study.

Initial loading
Repair (ordinary SHCC or UHP-SHCC)
Curing (ordinary SHCC: 10days, UHP-SHCC: 5days)
Second loading

Figure 2: Experimental procedure.

Shape of wall specimens and reinforcement arrangement in the specimens are shown in Fig. 3. Cross sectional size of the specimen was 1200 x 500 mm^2, and height of it was 1600 mm. As listed in Table 1, compressive strength at the age of 30 days (corresponding to the age of initial loading) was 23.1MPa. Twenty eight longitudinal reinforcements (D16, SD345, fy=391 MPa) were used, and hoop reinforcement (D13, SD345, fy=365 MPa) were also arranged at intervals of 100 mm, as tabulated in Table 2. Reinforcement ratio of longitudinal reinforcement was about 1.2%. Two specimens were prepared in this study.

A cyclic loading was adopted to the wall specimens in both initial loading and second one. Axial load to induce nominal axial stress of 1 MPa was adopted. The loading was terminated, when the load was decreased up to yielding load after the peak.

4 INITIAL LOADING

Figure 4 shows the relationship between load and displacement of the specimen under initial loading. Note that specimen No.1 and specimen No.2 mean the specimens repaired by SHCC and UHP-SHCC, respectively. Yielding of longitudinal reinforcement in both specimens was occurred at load of 380 kN and displacement of 7.4 mm (δy). The peak load of the specimen No.1 was 418 kN at the

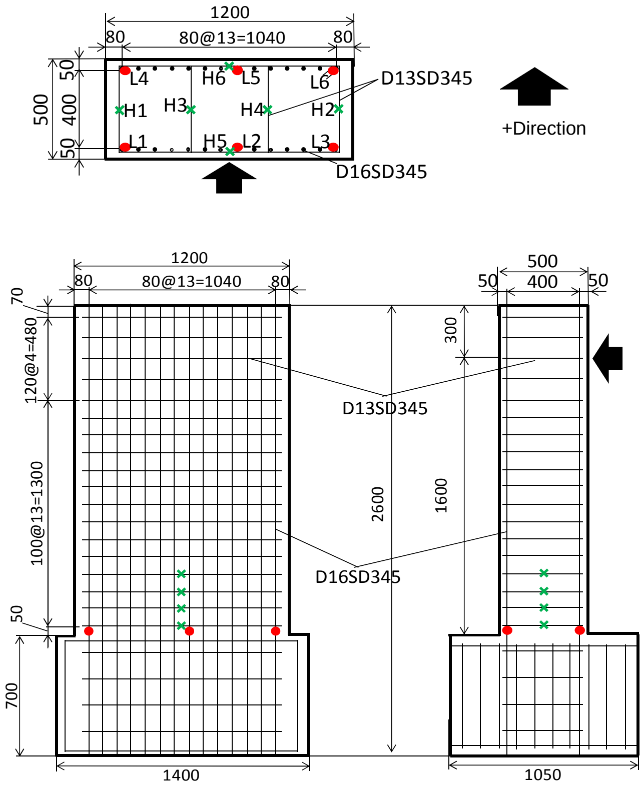


Figure 3: Specimen and reinforcement arrangement.

Table 1: Material properties of concrete (30 days).

Comp. strength (MPa)	Young's modulus (GPa)
23.1	26.2

Table 2: Material properties of reinforcement.

Longitudinal (D16)	Hoop (D13)
Yeild strength (MPa)	Yeild strength (MPa)
391	365

displacement of 37.0 mm (5 δy). The response of specimen No.2 was almost the same with that of specimen No.1. The initial loading was terminated at the displacement of 10 δy (380 kN). Eventually, both specimens exhibited similar load-displacement response, as shown in Fig. 4.

Flexural cracks occurred and propagated at hinge part (height: about 500 mm) of the wall specimens mainly. Then spalling of cover concrete was observed. Finally, buckling of longitudinal reinforcement was observed after spalling of cover concrete, as shown in Fig. 5. In addition, fracture of core concrete was also obtained.

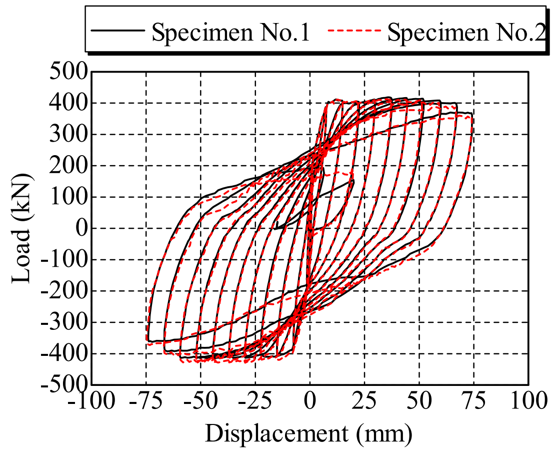


Figure 4: Load-displacement curves of initial loading.

Figure 5: Damaged part after initial loading.

5 REPAIR MATERIALS AND REPAIR METHOD

Two kinds of cement based materials were used in this study; one was SHCC, and the other was UHP-SHCC. Both materials can be sprayed.

For SHCC, all powder was premixed, and polyethylene (PE) fiber (high strength polyethylene fiber, tensile strength: 2700MPa, Young's modulus: 88GPa, length: 12mm, diameter: 0.012mm) of 0.75% in volume and polyvinyl alcohol (PVA) fiber (tensile strength: 1600MPa, Young's modulus: 40GPa, length: 12mm, diameter: 0.012mm) of 0.75% in volume were used.

For UHP-SHCC, water to binder ratio (W/B) was 0.22, and volume fraction of PE fiber, which is the same with fibers in SHCC, was 2.5%.

Table 3 tabulates the material properties of

Table 3: Material properties of used repair materials.

	Comp. strength (MPa)	Young's modulus (GPa)	Tensile strength (MPa)	Strain at tensile strength (%)
SHCC (10 days)	26.5	14.1	3.7	0.9
UHP-SHCC (5 days)	61.6	21.2	5.3	0.86

repair material. SHCC was tested at the age of 10 days, and UHP-SHCC was tested at the age of 5 days. Note that the tested age was corresponding to the loading age of second loading. Compressive strengths of SHCC and UHP-SHCC were 26.5 MPa and 61.6 MPa, respectively. The compressive strength was obtained from the cylindrical specimens having the size of 50 mm in diameter and 100 mm in length.

Figure 6 illustrates the tensile test results of SHCC and UHP-SHCC dumbbell shaped specimens (5 specimens each), which were also made by spraying. Note that tested cross section was 30 x 13 mm^2. Averaged tensile strengths of SHCC and UHP-SHCC were 3.7 and 5.3 MPa, respectively. Both materials exhibited pseudo strain hardening and multiple fine cracking, in addition to higher strain capacity over 1%.

The damaged wall specimens were brought to the original position (residual displacement of 0 mm). The damaged cover concrete was removed by using a hammer. And small amount of water was sprayed to prevent dry out of repair materials.

Both materials were sprayed to be the cross section same as the un-damaged one (i.e. 500 mm x 1200 mm). Note that the approximate thickness of the repaired layer was equal to about 60mm.

After the repair, SHCC and UHP-SHCC were cured for 10 days and 5 days, respectively. After the curing, cyclic loading was carried out again for the repaired specimens.

6 SECOND LOADING FOR REPAIRED SPECIMENS

6.1 Load-displacement curves and failure behavior

Figures 7 and 8 show the load-displacement curves of the specimens repaired by SHCC and UHP-SHCC, respectively. And each figure includes zoom-up of the initial part of the curves.

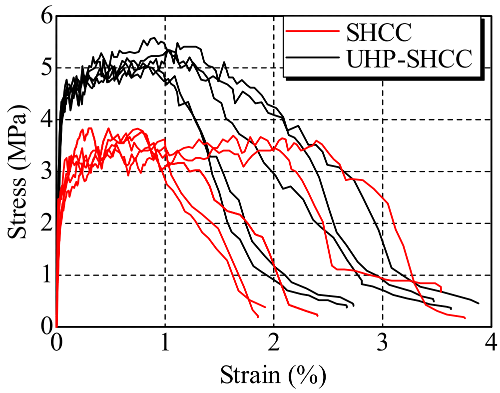
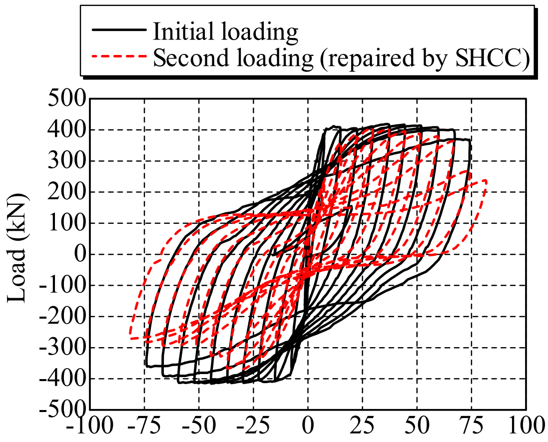


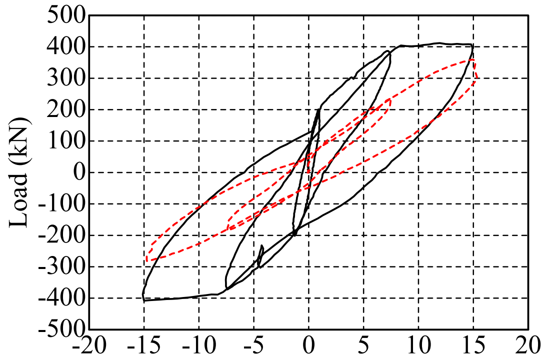
Figure 6: Tensile stress-strain curves of SHCC and UHP-SHCC (SHCC: 10 days, UHP-SHCC: 5days).

Regarding the specimen repaired by SHCC, maximum load was about 400 kN and it was almost same with that of initial loading. Initial stiffness was not recovered because of the crack located at the joint between wall and footing, as shown in Fig. 7(b). Ductility of the repaired specimen was slightly decreased, especially in negative loading direction. By observing the final failure behavior as shown in Fig.8, diagonal multiple cracking was observed in the front side of the specimen, and splitting cracks occurred adjacent to longitudinal reinforcement of tensile side. Consequently, the splitting cracks allow the buckling of reinforcement under compressive stress. Finally, delamination of repaired layer was occurred completely.

For the specimen repaired by UHP-SHCC, maximum load was about 420 kN, and it was slightly higher than that of initial loading, as shown in Fig. 9. Initial stiffness was not, however, recovered, as shown in Fig. 9(b). Regarding failure behavior, diagonal multiple cracking was observed in the front side. No

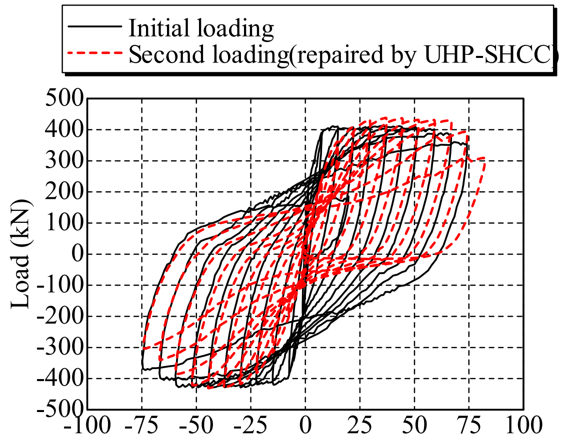


(a) Load-displacement curves

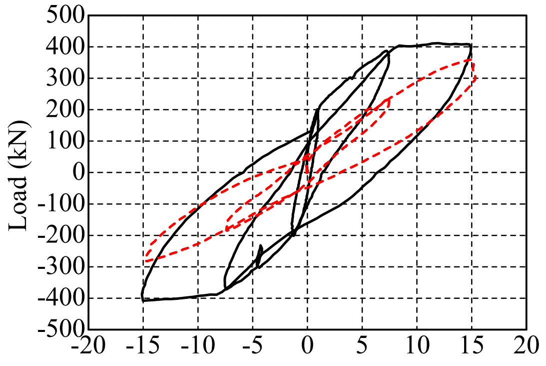


(b) Zoom-up

Figure 7: Load-displacement curves of specimen repaired by SHCC.



(a) Load-displacement curves



(b) Zoom-up

Figure 9: Load-displacement curves of specimen repaired by UHP-SHCC.

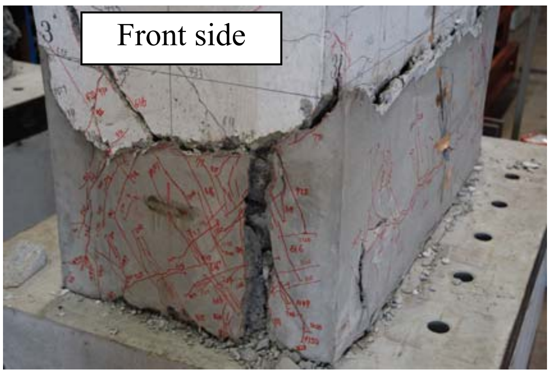


Figure 8: Final failure pattern of specimen repaired by SHCC.

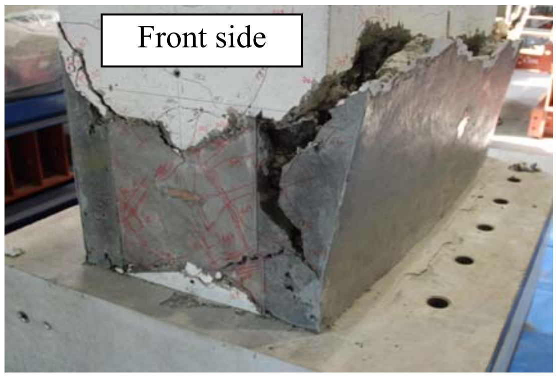


Figure 10: Final failure pattern of specimen repaired by UHP-SHCC.

crushing of the UHP-SHCC and no buckling of the longitudinal reinforcement were observed before the peak load.

After the peak load, concrete just above the interface between UHP-SHCC and concrete was damaged, and delamination of the repaired layer was observed finally, in addition of breaking of longitudinal reinforcement. In the side surface that is perpendicular to loading direction, multiple cracking was not expected. Since the weakest cross section was the joint between wall and footing, only interfacial crack opening and closing were observed during the loading.

6.2 Relationship between vertical and horizontal displacement

Figure 11 shows the relationship between vertical and horizontal displacement of the walls repaired by SHCC and UHP-SHCC. In the case of SHCC, vertical displacement of second loading was decreased with increasing of loading cycles, because buckling of longitudinal reinforcement was progressed. It seems that SHCC could not resist against progress of buckling of the longitudinal reinforcement. Regarding the specimen with UHP-SHCC, vertical displacement was increased with increasing of loading cycles, especially in positive loading direction. It means that UHP-SHCC imparts higher resistance against buckling of the longitudinal reinforcement to the specimen.

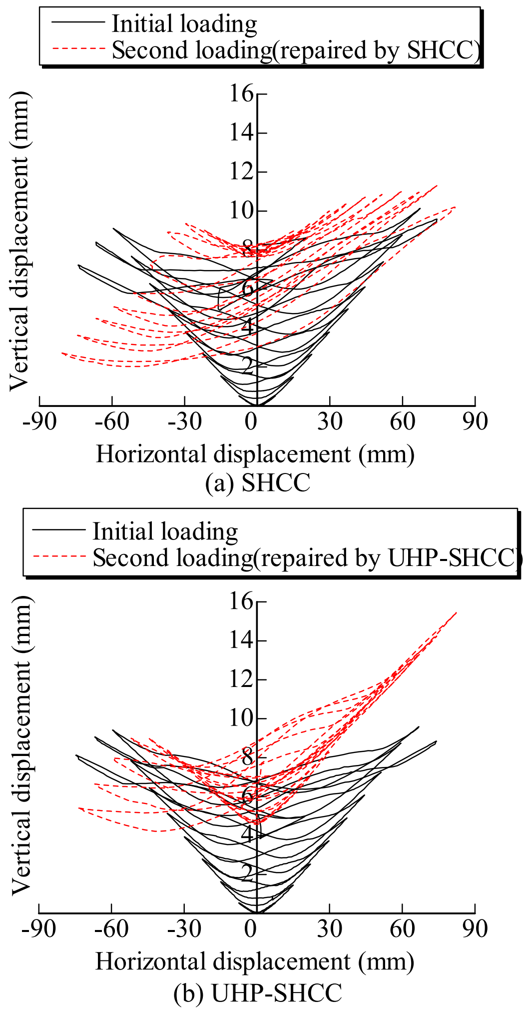


Figure 11: Vertical and horizontal displacements

7 CONCLUSIONS

The rapid jacketing technique using UHP-SHCC for damaged RC wall was developed, and cyclic loading tests were conducted. Following conclusions were obtained.

(1) The rapid jacketing technique involves only spraying of UHP-SHCC. It was confirmed experimentally that the developed technique using UHP-SHCC improve not only ultimate load but also ductility of recovered specimen.

(2) In terms of difference of repair material, material strength affects the recovery of damaged specimen. Especially, splitting crack along longitudinal reinforcement induced the buckling of longitudinal reinforcement.

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