- Technical Paper -

FEASIBILITY OF SELF-REPAIR NETWORK SYSTEM IN CONCRETE BEAMS WITH Cu-Al-Mn SUPERELASTIC ALLOY BARS

Kshitij C. SHRESTHA [*1], Sanjay PAREEK[*2], Toshihiro OMORI[*3] and Yoshikazu ARAKI[*4]

ABSTRACT

Experimental works were done to assess the seismic behavior of smart self-repairing concrete beams reinforced with newly developed Cu-Al-Mn superelastic alloy (SEA) bars in combination with epoxy network system. SEA reinforced concrete (RC) beams demonstrated strong capability of recentering with comparable normalized strength and ductility compared to conventional steel RC beam specimen. Self-repair network applied on pre-tested SEA-RC beam showed complete healing of previous cracks confirmed by origination of new cracks on reloading.

Keywords: smart structures, self-repair concrete beam, Cu-Al-Mn superelastic alloy bars, epoxy network, three-point cyclic loading

1. INTRODUCTION

Reinforced concrete (RC) structures, after sufficiently large earthquake event, undergoes considerable amount of damage showing large regions of cracks. The RC structure works effectively in resisting the excitation and ensuring the life safety of inhabitants, but after the event it shows large residual drifts, caused by plastic yielding of the steel reinforcing bars used, affecting the structure's stability. An immediate occupancy of residents is usually out of context in such scenario. Furthermore, retrofitting of these damaged structures is normally difficult and in some situations impractical due to large residual drifts and excessive damages. Either retrofitting or demolishing of such structures, both involves considerable amount of cost.

The present study concentrates on development of smart self-repairing concrete that can solve the above mentioned problems with possibility of effective immediate occupancy with considerably lower amount of cost involved. A smart self-repair concrete here represents the one which is capable of first deformation recovery with minimal residual cracks and second complete healing of previous cracks.

First, control over the residual drifts and large residual cracks can be done with the application of superelastic alloy (SEA) bars over conventional steel reinforcement as main reinforcement elements in RC structure. A typical schematic representation of this mechanism on ST-RC and SEA-RC beams can be seen in Fig. 1. Majority of previous researches over this study [1-2] have concentrated on use of NiTi alloy SEA wires or bars whose application is largely limited due their high cost and low machinability. Here, the authors propose application of newly developed Cu-Al-Mn SEA bars [3-4] whose production cost are significantly lower to NiTi SEA bars and are also highly superior in machinability.

Secondly, healing of cracks is attained through proper injection of epoxy resin through the self-repairing network. In the present study, the network system previously proposed by Pareek et al. [5] as shown in Fig. 2 is used in combination with SEA bars as reinforcing elements in order to perform healing of cracks. The network provided is simply a duct which runs through the length of the specimen; better than the brittle fiber networks provided in other literatures [6].

2. SPECIMEN AND MATERIALS

Concrete beam specimens of size 80x120x420mm as shown in Fig. 3 are prepared of two different types, SEA-RC and ST-RC beams. The placing of main reinforcements and shear bars are clearly shown in the figures. Additionally, there is also a duct (network) of 6mm diameter located at 20mm from the bottom of specimen for the purpose of epoxy injection during the self-repairing process. The authors tried to prepare both the specimens with rounded bars and end-bents as shown in Fig. 3(b), but it was found during the preparation of SEA-RC specimens that bending of SEA bar-ends was difficult due to their SE property. Hence, threaded SEA bars were placed straight as shown in Fig. 3(a) for SEA-RC beam. The properties of materials used during the experimentation are described as below:

*1 Post-doctoral Researcher, Dept. of Architecture and Architectural Eng., Kyoto University, Dr.E., JCI Member
*2 Assoc. Prof., Dept. of Architecture, College of Eng., Nihon Univ./TU Delft, Netherlands, Dr.E., JCI Member
*3 Assist. Prof., Dept. of Material Science and Eng., Tohoku University, Dr.E.
*4 Assoc. Prof., Dept. of Architecture and Architectural Eng., Kyoto University, Dr.E., JCI Member

2.1 Concrete

The composition of cement (Ordinary Portland), sand and water for the mortar is 1:4.4:0.6. Here, the ratio of sands with particle sizes of (≦2.5mm) 1:2 (2.5-5.0mm) were used as aggregates for mortar specimens. Cylindrical test pieces of the mix concrete with diameter 50mm and height 100mm are prepared for compressive strength tests. Here, the average value of compressive strength is 23.62MPa with standard deviation of 2.86MPa.

2.2 Reinforcing bars

Two different types of main reinforcement bars are used. For ST-RC beams, non-threaded 6mm diameter SR235 bars are used and for SEA-RC beams, threaded 6mm diameter Cu-Al-Mn SEA bars are used as bottom main reinforcements. Here the SEA bars are obtained after performing threading on originally 12mm diameter bars. The tensile tests done on the SEA bars showed the Young's modulus of around 25GPa and first transformation (yield) stress of around 200MPa.

2.3 Epoxy resin

Epoxy resin is used as self-repairing agent through the network as described in the previous section. Two types of epoxy resin are used for this purpose, having differences in their viscosity. The properties of the epoxy resins used are given in Table 1. Here, the choice of epoxy resin is made on the basis of crack widths that need to be repaired [7].

Table 1 Characteristics of epoxy resin

Epoxy resin type	Hardening mechanism	Thixotropic Index	Specific Gravity g/cm^3,23°C	Viscosity mPa.s, 23°C
L	Moisture	1.0	1.15	150
M	Sensitive	2.2	1.07	1900

3. TEST PROCEDURE

3.1 Test Plan-1

Two different test plans were decided based on their respective goals. Test plan-1 involves cyclic 3-point loading tests on SEA-RC and ST-RC beams to distinguish the recovery property of the two specimens involved. The sole purpose of the test is to state the applicability of SEA bars over conventional steel bars as reinforcing elements in reinforced concrete when subjected to repeated cyclic loading. It should be noted that the test plan-1 does not involve application of any self repair network. Specimens used are SEA-UR1 and ST-UR1 where UR represents the unrepaired specimen.

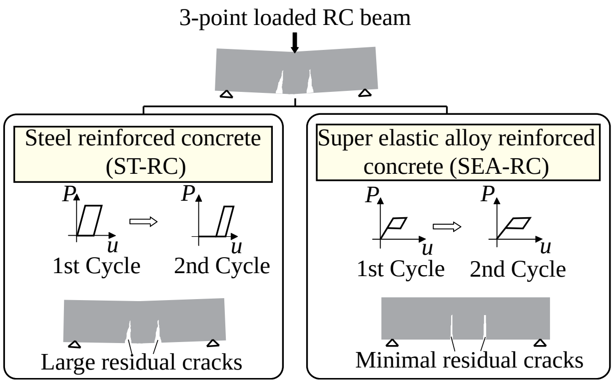


Fig.1 Classification of RC beam based on reinforcing elements and hysteretic response characteristics

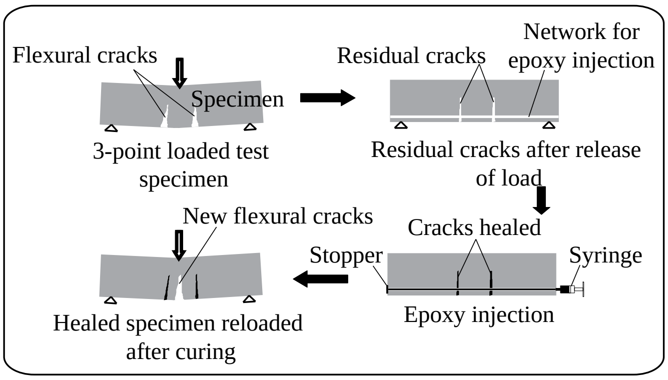
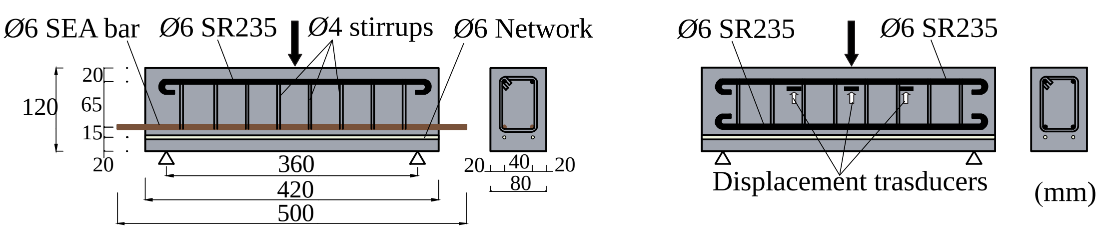


Fig.2 Self-healing repair system



(a)SEA-RC beam (b)ST-RC beam

Fig.3 Specimen reinforcement details

3.2 Test Plan-2

Test plan-2 studies on application of self repairing network on SEA-RC beams. For this purpose, three different types of loading magnitudes are sought out to study the healing mechanism on three different levels of crack widths. Fig. 4 shows the complete flow of work involved during this test. As shown in the figure, the test involves three SEA-RC self-repair (SR) specimens, namely SEA-SR2, SEA-SR3 and SEA-SR4 where SR represents the self-repaired specimen. The three SEA-SR specimens are subjected to three different deformation load levels to represent a wider range of loading conditions as well as check effectiveness of the self-healing network on different residual crack widths. Here, forced displacement were applied to the specimens with rotation angles for the specimens, θ_{max} =1/133radian for SEA-SR2 specimen, θ_{max} =1/66radian for SEA-SR3 specimen and θ_{max} =1/50radian for SEA-SR4 specimen. It should be noted that test plan-2 does not involve tests on specimen with conventional steel bar. Previously reported work [7] clearly showed that use of conventional steel bars in RC beams resulted in large residual cracks where the proposed self-repair system does not work effectively.

After the first cycle of loading test, the specimen is checked for the presence of cracks using ultra sonic crack detector. In terms of deformation load levels as well as crack widths, SEA-SR2 specimen is subjected to the least of all with residual crack width of less than 0.2mm needed for network healing. For this level of crack width, the specimen is injected with L-Epoxy as shown in Fig. 5 at normal room temperature around 20˚C. The proper choice of epoxy resin is decided based on extensive experimental works done previously [5,7]. The specimen is kept at normal room temperature for 3-4 hours and then placed inside the oven at 40˚C (60%RH) for accelerated curing for 3 days. Before placing the specimen inside the oven, the excessive epoxy in the network is ejected through pressurized air pump.

Similar self-healing procedure is followed for SEA-SR3 specimen, the only difference being the use of M-Epoxy to heal relatively larger crack width. In case of SEA-SR4, multiple cracks of different sizes are observed. Hence, the healing process involved two step injection process where first the L-Epoxy is injected to heal the micro cracks of size less than 0.2mm and afterwards M-Epoxy is injected for crack size larger than 0.2mm.

After the completion of curing period, each specimen is checked for whether the cracks are healed or not. Crack detection processes involved ultrasonic crack detector and colored water injection through network. Finally each beam specimen is subjected to the same previously defined deformation load level to check on the effectiveness of self-healing network.

4. RESULTS AND DISCUSSIONS

4.1 Applicability of SEA bars over steel bars (Test plan-1)

Fig. 6 shows the crack patterns and results for cyclic loading performed on SEA-UR1 and ST-UR1 as per test plan-1. Both the specimens showed an initial peak response representing the tensile cracking of concrete beam. Afterwards the behaviors differed with progressive incremental loading. It should be noted that there is variance in shapes of reinforcing bars placed in the two specimens as mentioned formerly in Section 2; hence there exists discrepancy for comparing the two. However, a good reference comparison can be expected in terms of their global responses.

Post reinforcement yielding, ST-UR1 specimen started showing excessive residual deformations and cracks upon unloading mainly contributed by plastic deformations of the steel reinforcing bars. SEA-UR1 specimen on the other hand showed comparatively better response with significant enhancement in crack recovery capacity. Comparisons of the experimental response with theoretical assumption are also made with formulations based on computations of load carrying capacity taking into account the nominal yield stresses and the fracture stresses of the reinforcing bars used. Here, yield and fracture stress values for the SEA bars were taken to be 200MPa and 300MPa respectively. Similarly, for SR-235 steel bars, yield and fracture stresses of 235MPa and 380MPa were adopted for computations. Figs. 7 and 8 show the comparison on the crack widths for the two specimens involved measured using crack-scale. Large residual crack widths were seen for ST-UR1 specimen with average recovery of cracks around 34%. SEA-UR1 specimen demonstrated strong capability of recentering with average recovery of cracks of 87%.

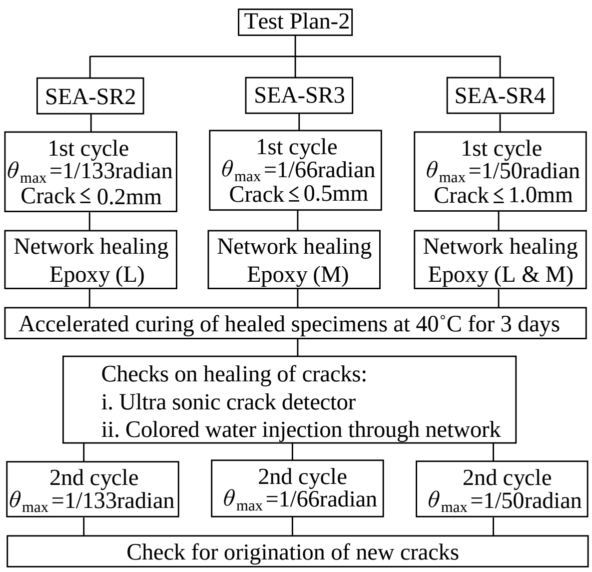
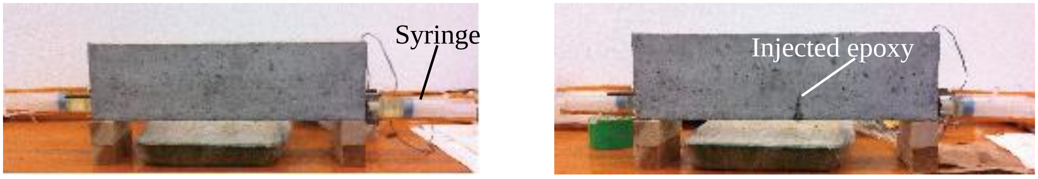
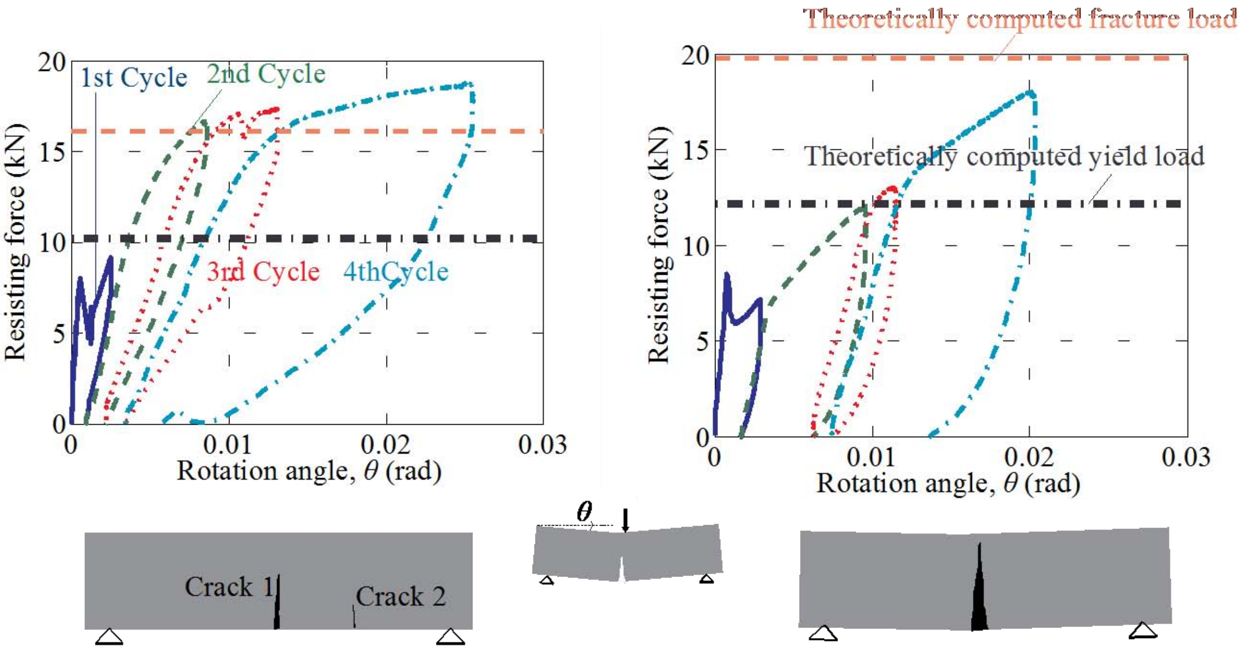


Fig. 4 Test plan-2 work flow



(a) Before epoxy injection (b) After epoxy injection

Fig. 5 Network epoxy injection in SEA-SR2 specimen



(a) SEA-UR1 (b)ST-UR1

Fig. 6 Cyclic loading response for SEA-UR1 and ST-UR1 specimens

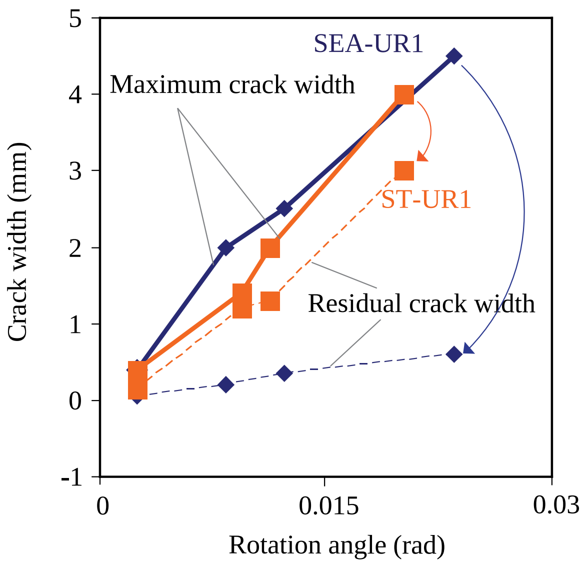
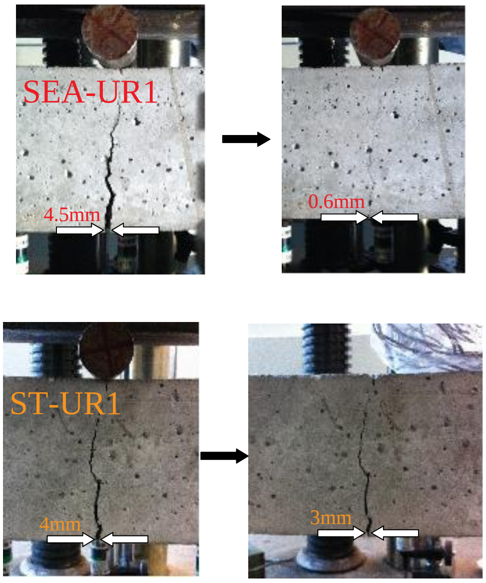


Fig. 7 Crack width comparison for SEA-UR1 and ST-UR1 specimens



Loaded situation At release of load

Fig. 8 Pictures showing crack recovery for SEA-UR1 and ST-UR1 specimens

The above observations clearly show the effectiveness of SEA bars as reinforcing elements over the conventional steel bars. The recovery of deformations shown by SEA reinforced specimen helps in providing stability to the structure and also contributes to the possible retrofitting with minor interventions to the original structure. The large residual deformations and cracks seen for steel reinforced specimen make it difficult to reuse the structure or perform its retrofitting.

4.2 Effectiveness of self repair network system (Test plan-2)

Fig. 9 shows the crack patterns and results for cyclic loading performed on SEA-SR2, SEA-SR3 and SEA-SR4 specimens as per test plan-2. Fig. 10 shows the comparison on the crack widths (Fig. 10(a)) and stiffness degradation (Fig. 10(b)) observed for each of the specimens and Fig. 11 shows the crack patterns for the self-healed specimens. Each of the SEA-SR specimens showed good recovery of deformations as given in Fig. 10(a) with 93% recovery of cracks for SEA-SR2, 86.6% for SEA-SR3 and 87.5% for SEA-SR4.

SEA-SR2 specimen showed maximum crack width of 1.4mm at maximum rotation angle of 1/133radian and residual crack width of 0.1mm at the release of first cycle of loading. With the initiation of second cycle of loading, new crack appeared as shown in Figs. 9(a) and 11. SEA-SR3 specimen showed maximum crack width of 3mm at maximum rotation angle of 1/66radian and residual crack of 0.4mm. This specimen also showed new cracks at different section of the beam to the previous ones with the initiation of second cycle. Finally, SEA-SR4 specimen had originally two cracks, 1 and 2 as shown in Figs. 9(c) and 11 at the end of first cycle. For crack 1, maximum and residual crack widths of 4mm and 0.5mm were observed respectively and similarly for crack 2, the values were 0.8mm and 0.2mm. New crack appeared approximately between the two previous cracks with the initiation of the second cycle loading.

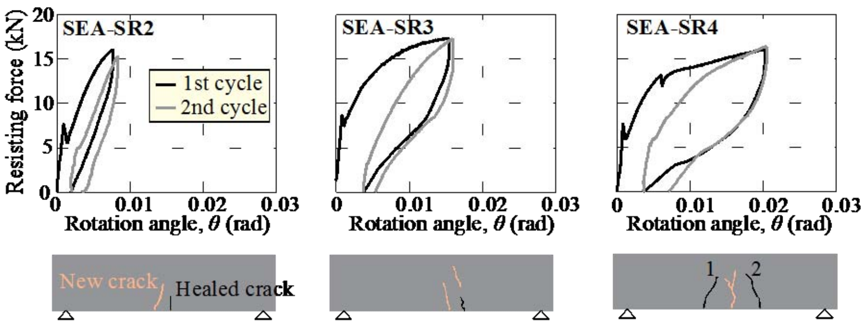
Fig. 11 shows the origination of new cracks performed with each reloading cycle and also the ultra sonic crack detection showed clearly that the proposed network system effectively fulfils the goal of healing previous cracks. Additionally, close observation of the force-rotation characteristics showed attainment of initial stiffness for the healed specimens as compared to the unrepaired specimen as shown in Fig. 10(b). For SEA-UR1 specimen, stiffness degradation of around 30% of initial stiffness was observed at the second loading cycle. The self repaired specimens, on the other hand, showed comparatively better response with stiffness degradation values of around 79%, 68% and 60% for SEA-SR2, SEA-SR3 and SEA-SR4 respectively. Both the above mentioned accounts of new crack origination and control on the initial stiffness degradation clearly demonstrate the effectiveness of the proposed self repair network on SEA-RC beams.

5. CONCLUSIONS

A feasibility study on self-repair concrete beam was done with application of self-healing network system in combination with Cu-Al-Mn SEA bars as reinforcement elements. First set of test was done to compare the deformation recovery between ST-RC and SEA-RC beam applying cyclic three-point loading. Second set of test involved SEA-RC beams with an aim to state the effectiveness of the network healing system. Here, three SEA-RC beams were tested for three different levels of crack widths. Following conclusions can be made based on these works:

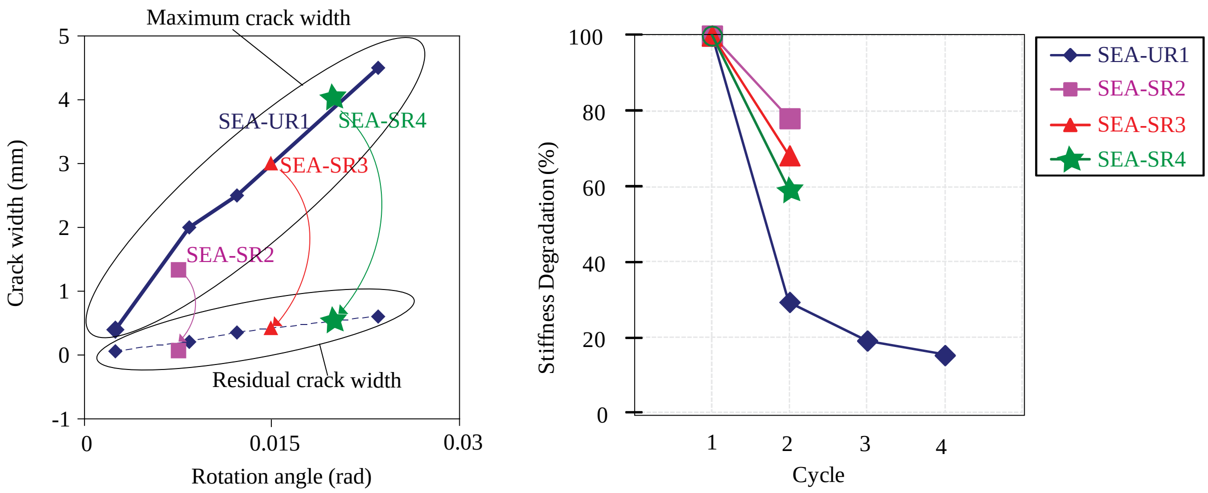
(1) Cyclic loading responses of the ST-UR1 and SEA-UR1 specimens showed distinct differentiation between the two involved. ST-UR1 specimen showed large residual deformations whereas SEA-UR1 beam showed very small residual deformations. The recentering capability of SEA-UR1 was clearly superior with average recovery of cracks of around 87%; however, only an average recovery of 34% for ST-UR1 specimen. An effective control over crack width was possible even for large deformation load level with the super elastic property of SEA bars used.

(2) Network self-repairing system worked effectively in all three SEA-RC beams based on origination of new cracks on reloading and reattainment of their initial stiffness. However, the type of epoxy used for healing depended on the size of crack width. For cracks smaller than 0.2mm, L-Epoxy was injected and for larger crack widths M-Epoxy was used for healing purpose.



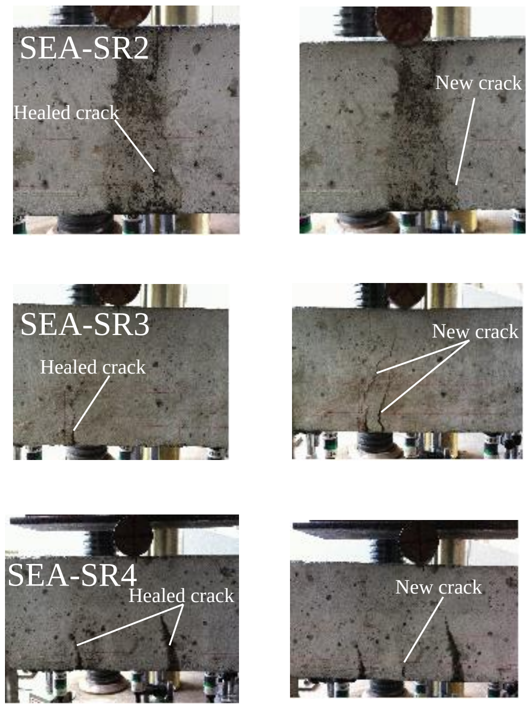
(a) SEA-SR2 (b) SEA-SR3 (c) SEA-SR4

Fig. 9 Cyclic loading response for SEA-SR2, SEA-SR3 and SEA-SR4 specimens



(a) Crack width comparison (b) Stiffness degradation comparison

Fig. 10 Comparison of crack widths and stiffness degradation for unrepaired and self-repaired specimens



Healed specimens Reloaded specimens

Fig. 11 Pictures showing healed and new cracks for self repaired SEA-RC specimens

(3) The proposed SEA-RC beam with relatively simpler and economically viable self-healing network system can be taken as a good example for preliminary investigation with possibility of further study and applications on larger scaled structures.

ACKNOWLEDGEMENT

The authors acknowledge the support provided by Kyoto University GCOE program (JSPS) and by the Obayashi foundation. We also appreciate Mr. Y. Miura for his help in conducting the experiments.

REFERENCES

[1] Song, G., Ma, N. and Li, H. N. (2006), "Applications of Shape Memory Alloys in Civil Structures", Engineering Structures, Vol. 28, 2006, pp. 1266-1274.

[2] Tajiri, S. et al.,"Reversed Cyclic Loading Test of Concrete Beams Using Pseudo-Elastic Shape Memory Alloy as Longitudinal Reinforcement", Proceeding of AIJ, C-2, 2002, pp. 155-156 (In Japanese).

[3] Araki, Y. et al., "Potential of Superelastic Cu-Al-Mn Alloy Bars for Seismic Applications", Earthquake Engineering and Structural Dynamics, Vol. 40, 2010, pp 107-115.

[4] Shrestha, K. C. et al., "Applicability of Cu-Al-Mn Shape Memory Alloy Rods to Retrofitting of Historical Masonry Constructions", Earthquakes and Structures, An International Journal, Vol. 2, 2011, pp. 233-256.

[5] Pareek, S. and Oohira, A., "A Fundamental Study on Regain of Flexural Strength of Mortars by Using a Self-repair Network System", Proceeding of 3rd International Conference on Self-Healing Materials, Bath, 2011.

[6] Kuang, Y. and Ou, J., "Passive Smart Self-repairing Concrete Beams by Using Shape Memory Alloy Wires and Fibres Containing Adhesives", Journal of Central South University of Technology, Vol. 15, 2008, pp. 411-417.

[7] Kumada H., Oohira A. and Pareek S., "A Fundamental Study on Regain of Flexural Strength of Mortars by Using a Self-repair Network System", Proceeding of JCI, Vol.33, 2011, pp. 1445-1450 (In Japanese).