コンクリート工学年次論文集，Vol.35，No.1，2013

- Technical Paper -

ACTIVATED NETWORK SELF-HEALING OF REINFORCED CONCRETE BEAMS WITH SUPER-ELASTIC ALLOY BARS

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ABSTRACT

Experimental works are reported to assess the response of reinforced concrete (RC) beams under repeated loading, with different reinforcing bars. A three-point loading was done with increasing loading magnitudes and comparisons are made on crack recovery capabilities and feasibility of activated network healing, of three different types of reinforced concrete beams; first with the steel deformed bars, secondly with steel threaded bars and finally with superelastic alloy (SEA) threaded bars. Strong crack recovery and effective self-repair was achieved for the SEA-RC beam specimens.

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

1. INTRODUCTION

Repair of damaged reinforced concrete (RC) structures, post earthquake events, is normally difficult and in some situations impractical due to large residual drifts and excessive damages. Either repair or demolishing of such structures, both involves considerable amount of cost and time.

The present study proposes a smart activated network self-repairing concrete that can solve the above mentioned problems with possibility of effective repair at considerably lower amount of cost and within shorter period. A smart self-repair concrete here represents the one which is capable of, first, deformation recovery with minimal residual cracks through application of superelastic alloy (SEA) reinforcing bars (rebars) and second, complete healing of previous cracks through proper injection of epoxy resin through a self-repairing network. In the present study, the network system previously proposed by Pareek et al. [1] is used in combination with SEA bars as reinforcing elements in order to perform healing of cracks.

The author's previous work on similar topic has been presented formerly [2]. This study presents a more systematic and detailed work, using newly developed Cu-Al-Mn SEA bars [3], with better mechanical characteristics. Additionally, comparison on the use of three different types of rebars has been made and applicability of network healing on each type of specimens has been examined.

2. SPECIMENS AND MATERIALS

Fig. 1 shows the concrete beam specimen used for the tests with size 80x120x420mm. Three different types of main bottom reinforcing bars are used, i. Steel deformed bars (SD345), ii. Steel threaded bars (ST) and iii. Superelastic alloy (SEA) bars. The beam specimens are named correspondingly as SD-RC, ST-RC and SEA-RC specimens from here onwards. 3 numbers of specimens were prepared for SD-RC and ST-RC, and SEA-RC involved 4 number of test specimens. The placing of main reinforcements and shear bars are shown in the Fig. 1. 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 properties of materials used during the experimentation are described as below:

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. Six cylindrical test pieces of the mix concrete, with diameter 50mm and height 100mm, are prepared for compressive strength tests. Here, the average value of the compressive strength was 24.7MPa with the standard deviation of 1.8MPa.

2.2 Reinforcing bars

Three different types of main rebars are used. For SD-RC beams, 6mm diameter SD345 bars are used and for ST-RC beams, threaded 6mm diameter steel bars are used as bottom main reinforcements. For SEA-RC beams, threaded 6mm diameter SEA bars are used. Here, the SEA bars are obtained after performing threading on originally 8mm diameter bars. Fig. 2 shows the results on corresponding representative rebar

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samples. The cyclic tensile tests done on the SEA bars showed the Young's modulus of around 25GPa and first transformation (yield) stress of around 200MPa. SD and ST rebars showed yield stress at around 400MPa and 330MPa respectively. Table 1 shows comparison on the mechanical properties for SD, ST and SEA rebars used. The strain measurements in Fig. 2 are slightly overestimated because the strain was calculated using the relative displacement between the grips of the testing machine. All the rebars used have either deformed or threaded surface, hence they offer good bond behavior with the surrounding concrete.

2.3 Epoxy resin

Epoxy resin is used as a self-repairing agent through the network. 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 2. Here, the choice of epoxy resin is made on the basis of crack widths that need to be repaired [4].

3. TEST PROCEDURE

The test procedure involved three-point cyclic bending tests on RC beam specimens with the test set-up as illustrated in Fig. 1. Two different test plans, Test Plan-1 and Test Plan-2, were devised based on their respective goals.

Test Plan-1 involved repeated cyclic loading on one set of each type of RC beam specimens, namely, SD-RC1, ST-RC1 and SEA-RC1 without application of any self-repair. The repeated cyclic loading was performed in increasing order of displacement load with rotation angles, θ_1 =1/150rad, θ_2 =1/75rad and θ_3 =1/40rad. The purposes of this test were to study the crack recovery properties of each type of the specimens and to examine the effectiveness of SEA-RC beam over RC beams with other steel rebar types.

Test Plan-2 studies the feasibility of the self-repair network system on each type of RC beam specimens. Effectiveness of the self-repair network on RC beam specimens, subjected to three different deformation load levels, were studied (rotation level θ_1 =1/150rad, θ_2 =1/75rad and θ_3 =1/40rad). Three sets of SEA-RC beam specimens were tested and checked for self-repair at all three different load levels. SD-RC and ST-RC beam specimens showed residual crack width values exceeding 3mm, when loaded at deformation load level with rotation angle, θ_3. For this reason, self-repair system was done for only two sets of SD-RC and ST-RC specimens, loaded at first two deformation load levels (θ_1 and θ_2). The details on the specimens for Test Plan-2 are presented in Table 3 and the work flow adopted is shown in Fig. 3.

After the primary loading of the beam specimens, the second phase of Test Plan-2 involved the network healing process through epoxy injection. The type of epoxy is defined by the size of residual crack widths as given in Table 3.

Crack widths, not exceeding 0.4mm, were healed with L-Epoxy [4] and the ones exceeding this value were healed with combination of both L and M-Epoxies, where application involves first L-Epoxy injection and afterwards M-Epoxy injection. The epoxy injection was followed by accelerated curing of the specimens for 3 days at 40˚C (60%RH). The degree of self repair performed on the respective healed specimens was measured using ultrasonic pulse velocity testing instrument. The rate of crack healing was computed by the observed transit time using the instrument at six different positions in the tested specimen as illustrated in Fig. 4.

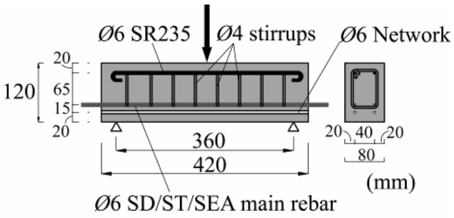


Fig.1 RC Specimen detail and test set-up

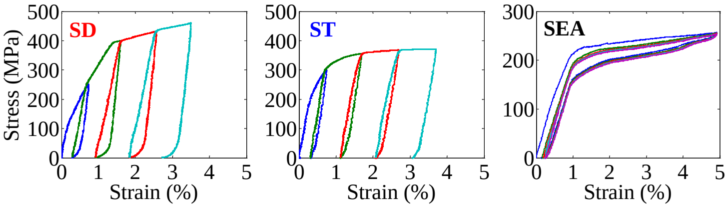


Fig.2 Cyclic tensile test results on SD, ST and SEA rebars

Table 1 Mechanical properties of reinforcing bars used

Reinforcing bar type	Elastic modulus, GPa	Yield/Transformation stress, MPa	Recovery strain, %	Fracture strain, %
SD	200	400	0.1	18~20
ST	200	330	0.1	18~20
SEA	25	200	8	18

Table 2 Characteristics of epoxy resin

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

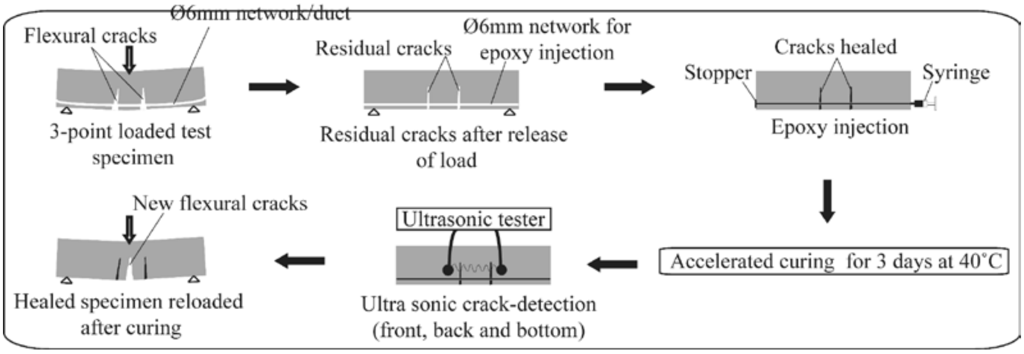


Fig.3 Work-flow for the present study on the self-repair network system (Test Plan-2)

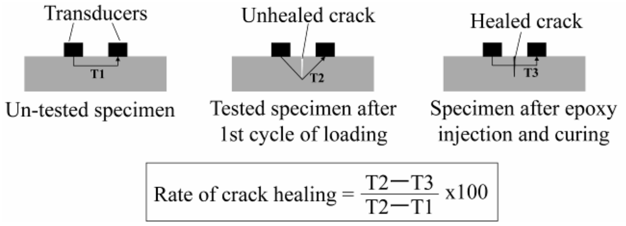


Fig.4 Transit time detection using ultrasonic tester for computation of rate of crack healing

4. RESULTS AND DISCUSSIONS

4.1 For Test Plan-1 – Crack recovery characteristics

Fig. 4 shows the results for the cyclic loading performed on SD-RC1, ST-RC1 and SEA-RC1 as per Test Plan-1. The value of the resisting force observed varied with the type of the rebars used in the specimens, as each of them has a unique strength and deformation characteristic, as illustrated in Fig. 2.

Each of the specimens showed an initial stiff response, until the concrete tensile cracking at the bottom of the tested beam specimen. Post initial cracking and subsequent reinforcement yielding, SD-RC1 and ST-RC1 specimens started showing excessive residual deformations and large residual cracks upon unloading mainly contributed by plastic deformations of the corresponding rebars. SEA-RC1 specimen on the other hand showed comparatively better response with significant enhancement in crack recovery capacity. Fig. 4 (right) shows the comparison on the crack widths for the three specimens involved, measured using crack-scale. Fig. 5 shows the pictures of cracked specimens at the instants of the loaded and unloaded positions. Large residual crack widths, in exceedence of 3mm, were seen for SD-RC1 and ST-RC1 specimens, for deformation level, θ_3 =1/40rad. SEA-RC1 specimen demonstrated strong capability of crack closing with residual crack widths within 0.5mm, even for the maximum deformation level of the loading.

4.2 For Test Plan-2 – Effectiveness of self repair network system

The details on the loading magnitudes, corresponding residual crack widths and subsequent healing mechanism adopted for each of the specimens in Test Plan-2 are illustrated in Table 3. Fig. 6 shows the restoring force curves and the crack width measurements for all the tested specimens.

For SD-RC2 specimen, a residual crack width of 0.15mm was observed and L-Epoxy was chosen for the healing. For SD-RC3, with residual crack width of 0.5mm, L and M-Epoxies were chosen. ST-RC2 and ST-RC3 specimens also went through similar healing process. SEA-RC2 and SEA-RC3 specimens showed residual crack widths of 0.06mm and 0.3mm respectively and both adopted L-Epoxy network healing. SEA-RC4, with crack width of 0.5mm, was injected with L and M-Epoxies. For ST-RC3 specimen, the crack width observed was 1.0mm which is comparatively higher among the rest of the specimens.

After accelerated curing for 3 days at 40˚C (60%RH), each of the specimens was reloaded to the defined deformation load level as illustrated in Table 3. A possible crack healing of the specimen can be confirmed if new cracks appear at different locations during the reloading process. The cracking patterns for each of the specimens before and after the reloading are shown in Fig. 7. All the specimens showed origination of new cracks with exception of ST-RC3 specimen, where the old crack reopened.

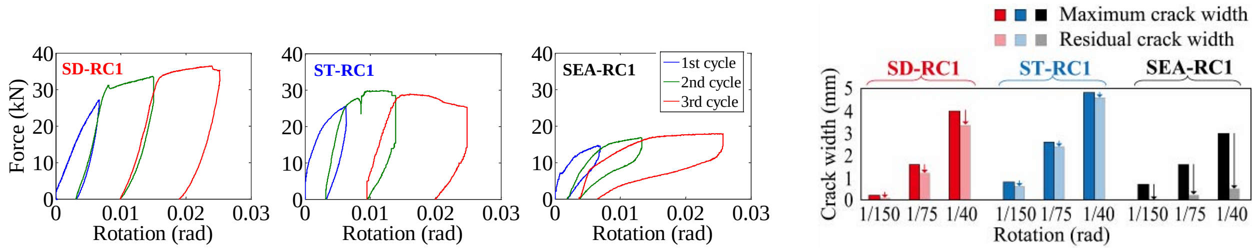
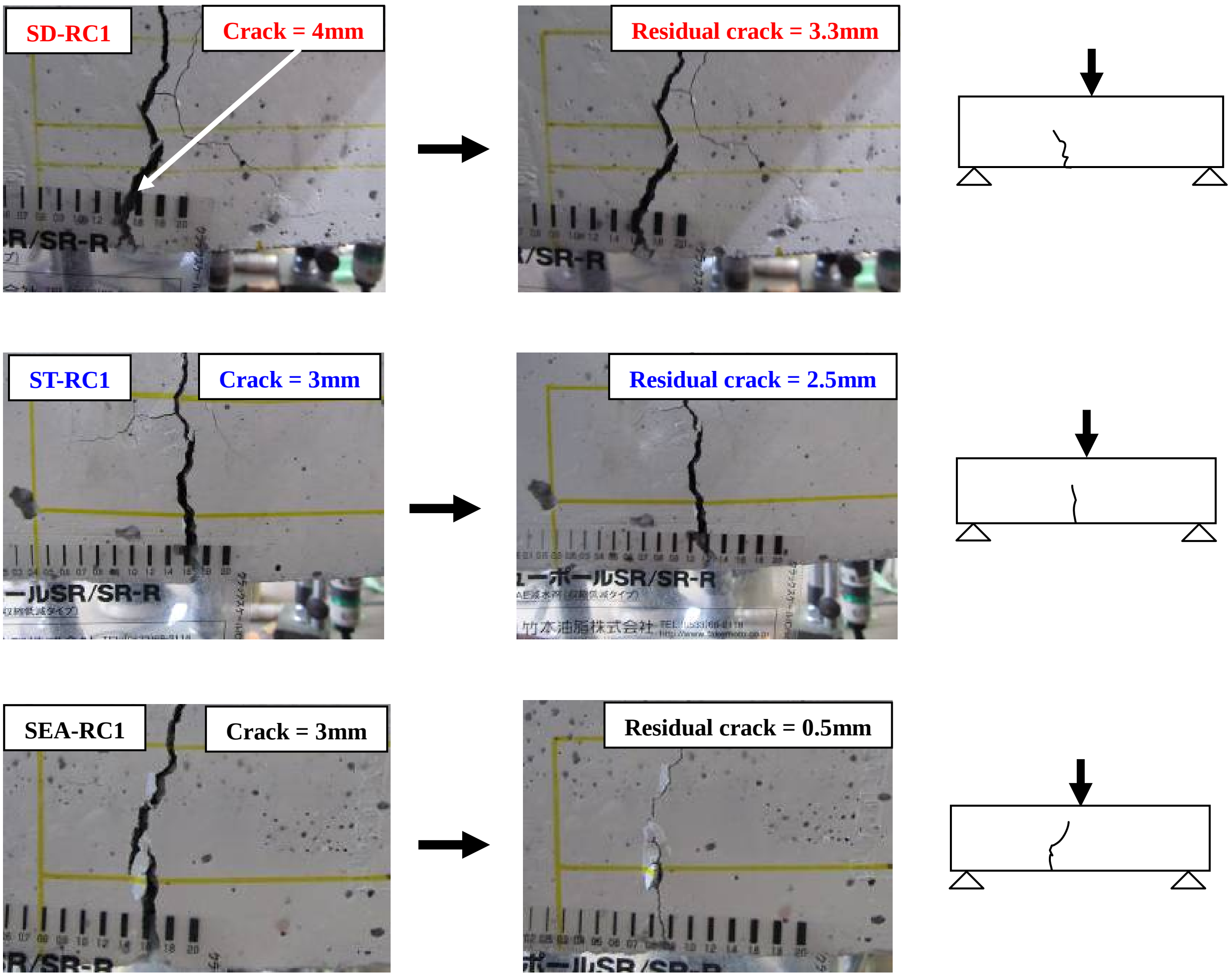


Fig.4 Restoring force curve and crack width measurements for SD-RC1, ST-RC1 and SEA-RC1 specimens



Rotation angle, θ_3 =1/40rad
At release of load

Fig.5 Observations on crack recovery for SD-RC1, ST-RC1 and SEA-RC1 specimens

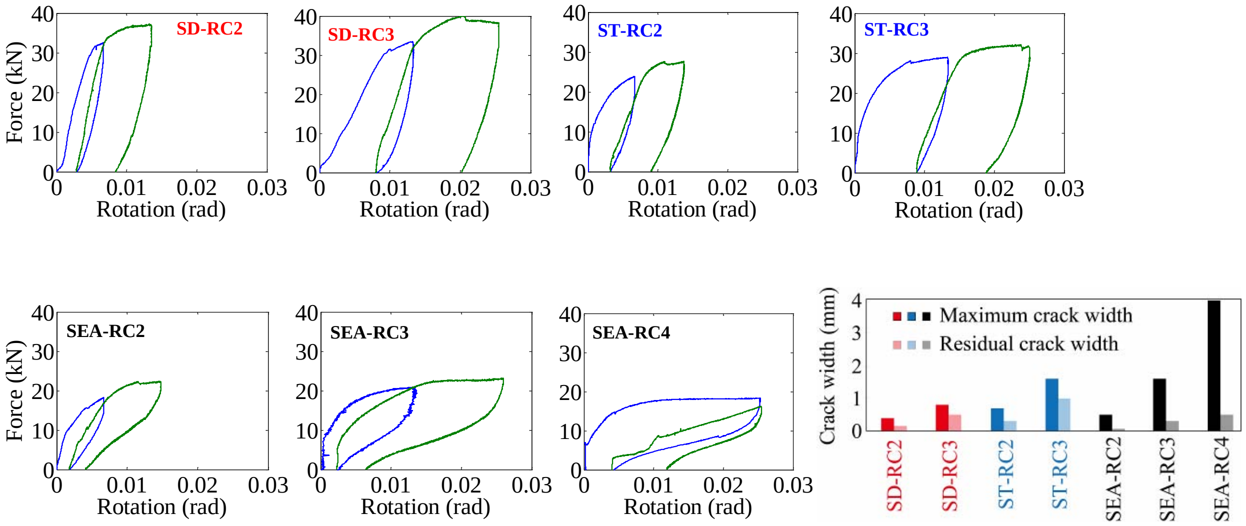


Fig.6 Restoring force curves (first and second cycles) and crack width measurements (first cycle) made for SD-RC2, SD-RC3, ST-RC2, ST-RC3, SEA-RC2, SEA-RC3 and SEA-RC4 specimens

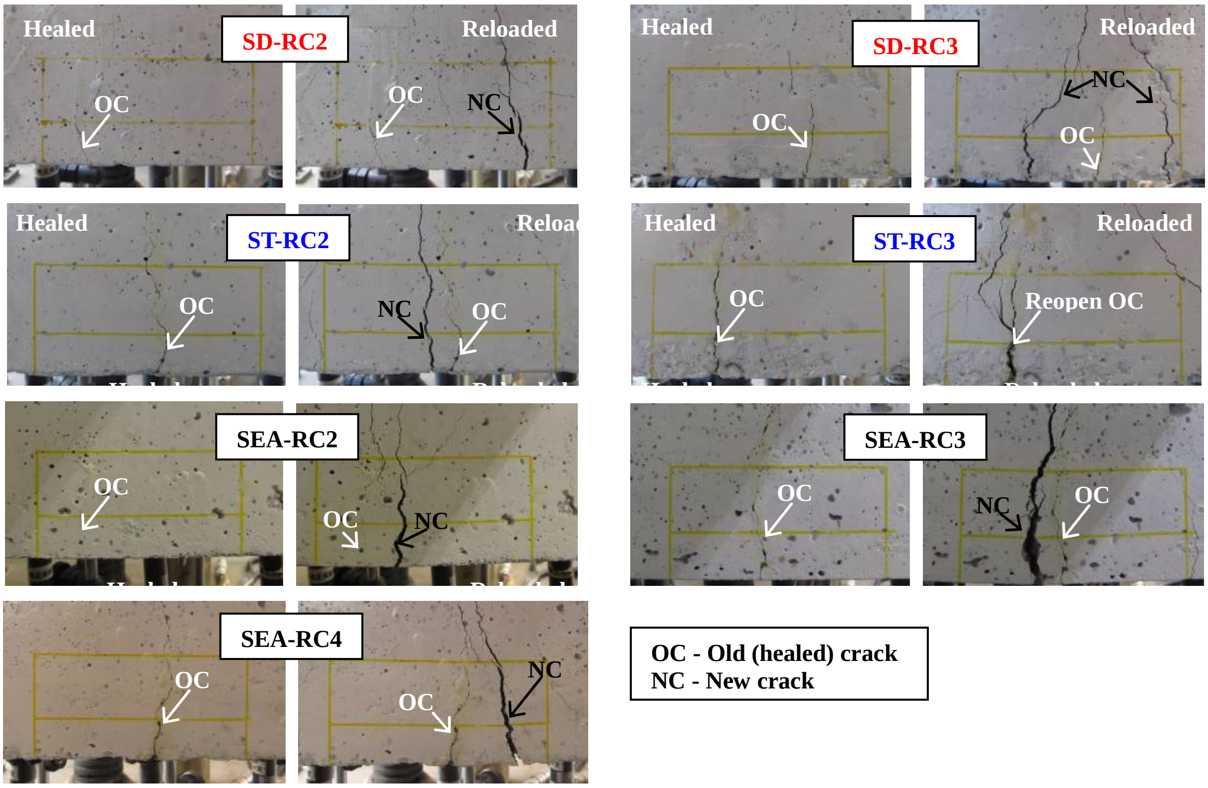


Fig.7 Crack patterns for specimens before and after the reloading

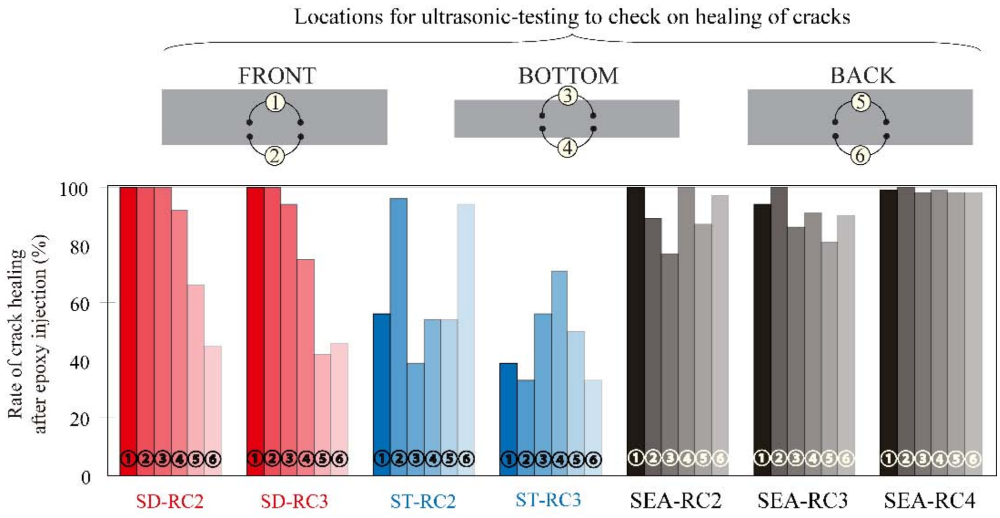


Fig.8 Results on rate of crack healing for all tested specimens

Table 3 Details on Test Plan-2

Specimen	1st cycle loading	Residual crack width	Network healing	2nd cycle loading	Cracks on reloading
SD-RC2	1/150rad	0.15mm	Epoxy(L)	1/75rad	New crack
SD-RC3	1/75rad	0.5mm	(L&M)	1/40rad	New crack
ST-RC2	1/150rad	0.3mm	(L)	1/75rad	New crack
ST-RC3	1/75rad	1.0mm	(L&M)	1/40rad	Old crack
SEA-RC2	1/150rad	0.06mm	(L)	1/75rad	New crack
SEA-RC3	1/75rad	0.3mm	(L)	1/40rad	New crack
SEA-RC4	1/40rad	0.5mm	(L&M)	1/40rad	New crack

The rate of crack healing for each of the specimens, by observing the transit time at six different locations of the specimen, is presented in Fig. 8. For all the SEA-RC specimens, the computed rate of crackhealing is above 80% at all the location points of the specimen, which clearly showed an effective healing attained for all the SEA-RC specimens. An average rate of crack healing for all SEA-RC specimens was 93.5% with standard deviation of 6.94%. For SD-RC2 and SD-RC3 specimens, moderate crack healing was observed, with strong variability in the transit time recorded at different locations as shown in Fig. 8. SD-RC specimens showed average rate of crack healing of 80% with standard deviation of 23%. ST-RC specimens showed poor healing of cracks based on the transit time recorded for both the specimens. An average rate of crack healing for ST-RC specimens was 56.2% with standard deviation of 20.3%.

The results from the ultra sonic crack detection showed a clear superiority of SEA-RC specimens, showing effective healing of cracks up to deformation load level of θ_3 =1/40rad. SD-RC specimen showed moderate crack healing up to deformation level of θ_2 =1/75rad. ST-RC specimen showed relatively poor crack healing. More importantly, the network healing of cracks by epoxy injection was found effective up to crack width of 0.5mm.

5. CONCLUSIONS

(1) Applicability of SEA rebars over SD and ST rebars in crack recovery: SEA-RC1 specimen, under repeated cyclic loading, showed minimal residual crack width, as compared to SD-RC1and ST-RC1 specimens. Crack width on unloading from deformation level of θ_3 =1/40rad for SEA-RC1 was 0.5mm, which is practically repairable. On the other hand, for SD-RC1 and ST-RC1 specimens, the crack width levels were in exceedence of 3mm. Repair on such high values of crack widths, exceeding 3mm, is very difficult to perform, and not feasible in most of the cases.

(2) Effectiveness of network epoxy injection for crack healing: Effective healing of cracked concrete was attained though activated epoxy network injection for crack widths up to 0.5mm. New cracks were observed during reloading of healed specimens. Additionally, from ultra sonic crack detector tests, perfect healing was seen for SEA-RC specimens up to deformation level of θ_3 =1/40rad. Moderate level of healing was achieved for SD-RC and ST-RC specimens even at deformation level of θ_2 =1/75rad. Network injection was not possible in these specimens for deformation level of θ_3 =1/40rad, due to crack widths exceeding 3mm.

ACKNOWLEDGEMENT

This research was supported by Grant-in-Aid for Scientific Research (B) No. 24360226 provided Japan Society for the Promotion of Science (JSPS). The experimental works were supported by Mr. Akihiro Oohira, a graduate student of Nihon University. The SEA bars were produced by Furukawa Techno Material and provided by Prof. Kainuma and Prof. Omori of Tohoku University. These supports are gratefully acknowledged.

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