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Cyclic Tensile Loading Tests on RC Members with Super-Elastic Cu-Al-Mn Alloy Bars

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ABSTRACT

Super-elastic alloys (SEA) are unconventional alloys that restore their shape to the original condition when unloaded after large deformation. When SEA bars are used in a steel-reinforced bridge column, especially in its plastic hinge region, it could be expected to reduce the residual displacement of the column after a large earthquake. As a new type of SEA, Cu-based SEA bars have been developed, having good manufacturability and low material cost, as compared to Ni-Ti SEA which has been used as a reinforcement in the bridge columns. However, the fundamental behavior of RC members having SEA bars, such as being subjected to tensile and compressional forces, has not been investigated.

In this study, a series of cyclic tensile loading tests of RC specimens was conducted to investigate the tensile behavior of RC members having a SEA bar as longitudinal reinforcement. This study investigates the effect of the bond between the SEA bar and concrete on the RC member by using two different SEA bars; a round SEA bar and a threaded SEA bar. Crack distributions in the concrete specimens with a SEA bar were also examined. The test results showed that the specimens with the SEA bar in the RC member had significantly reduced residual displacement as compared to the conventional steel RC specimens. In the specimen with a SEA bar spliced with steel bars, only a single crack was observed along the specimen and the damage was concentrated in this crack, as opposed to the conventional steel RC specimen where the cracks were distributed along the specimen.

Keywords: Super-elastic Alloy Cu-Al-Mn, residual displacement, Cyclic loading test, RC structure

INTRODUCTION

After a large earthquake, it is essential to ensure the functionality of the transportation network for evacuations and rescue activities. In particular, bridges play a crucial role in the transportation system. Once the bridge is damaged, it takes a long time to restore the damage, which may lead to a long-lasting malfunction of a community. Therefore, it is necessary to recover the bridge function as soon as possible after an earthquake.

The Kobe Earthquake in 1995 caused extensive damage to many bridges designed by the static seismic intensity design method considering elastic behavior. The residual angle of the column was observed to be more than 1 degree (1.75% drift displacement) in approximately 100 columns after the earthquake. Even if the damage to the superstructure was limited, these entire bridges had to be demolished and reconstructed [1]. Also, in the 2016 Kumamoto Earthquake, there was extensive damage to the bridges, including the residual displacement of the columns. Therefore, there still exist issues in the post-seismic recovery of bridges due to the residual displacement; hence a new type of bridge column is needed to reduce the residual displacement subjected to an earthquake.

Super-Elastic Alloys (SEA) have been developed in recent years. SEAs have the unconventional property of returning to their original shape after undergoing large deformation when unloaded. As a new type of SEA, Cu-based SEA bars have been developed [2], having good manufacturability and low cost, as compared to Ni-Ti SEAs that have already been used as reinforcement in the bridge columns [3]. Using SEA bars with such unconventional properties as the longitudinal reinforcement of RC members is expected to reduce the residual displacement of RC structures after an earthquake. To reduce the residual displacement of the RC column, shaking table tests and cyclic loading tests of the RC column using SEA bars at the plastic hinge region have been conducted [4, 5].

However, the fundamental behavior of RC members having SEA bars, such as being subjected to tensile and compressional forces, has not been investigated. In order to use SEA as longitudinal reinforcement of RC members, it is essential to understand the tensile and compressional behavior of RC members subjected to bending during an earthquake. Although the tensile properties of SEA bars have been well understood, the tensile properties of RC members having a SEA bar as longitudinal reinforcement have not been investigated.

In this study, a series of cyclic tensile loading tests of RC specimens was conducted to investigate the tensile behavior of RC members with a SEA bar. When SEA bars are used in the plastic hinge region of RC columns, the SEA bar has to be connected. Therefore, in this study, the effect of a SEA bar connected to steel bars upon the behavior of the RC member was investigated. Also, to investigate the impact of bonding of the SEA bar, a round bar and a threaded bar were used in the RC specimens.

THE SPECIMEN AND TEST METHOD

Test specimens

Specimens with a square cross-section of 100 mm × 100 mm have the SEA bar or steel bar at the center of the section as shown in Figure 1. The specimens in Figure 1(a)-(c) and (d)-(e) are called Plastic hinge specimens and SEA specimens, respectively. Figure 1(a) represents a conventional steel-reinforced concrete (Steel RC) specimen to be compared with specimens with SEA

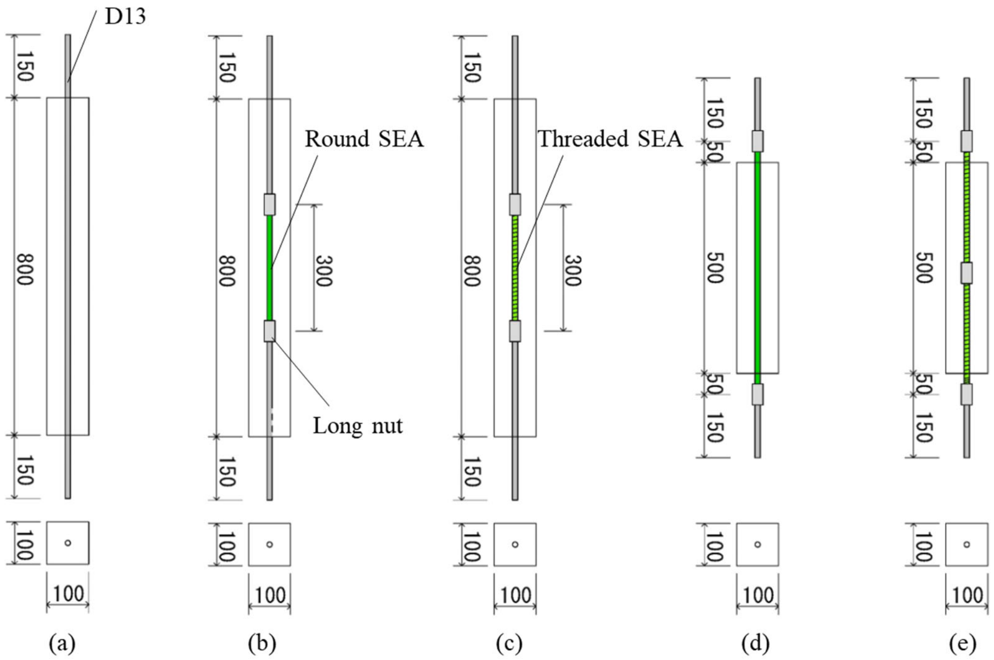

Figure 1. Details of the specimens: (a) Steel RC, (b) Round SEA-RC, (c) Threaded SEA-RC, (d) Round SEA, (e) Threaded SEA.

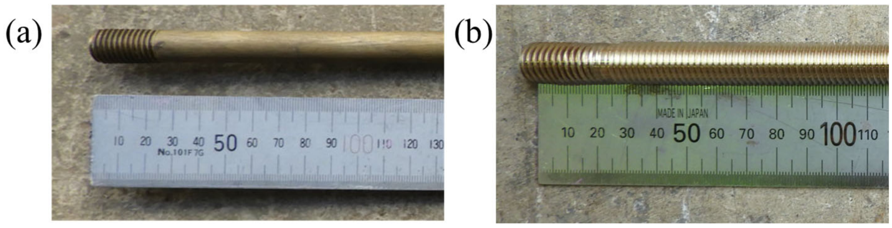

Figure 2. SEA bars used in the speciments: (a)round SEA bar, (b) threaded SEA bar.

bars. Two different SEA surfaces were used to investigate the impact of bonding of a SEA bar in RC members: a round SEA bar with a smooth surface and a threaded SEA bar with threading on the entire length, as shown in Figure 2. Since the SEA bar is assumed to be used in the plastic hinge region of the RC column and also its size is limited, the SEA bar has to be connected to steel bars. Therefore, two specimens shown in Figure 1(b), (c), Round SEA-RC and Threaded SEA-RC, were used to investigate the effect of connecting SEA and steel bars with long nuts in an RC member. Also, to understand the behavior of SEA itself in an RC member, the round SEA and threaded SEA specimens were made, as shown in Figure 1(d) and (e). Concrete specimen length is 800 mm for the Plastic hinge specimens and 500 mm for the SEA specimens. The longitudinal reinforcement used in each specimen is a D13 steel bar, a round SEA bar with a diameter of 12.4 mm and a threaded SEA bar with M14 machine threading along the entire length.

Figure 3 presents the splicing details between a SEA bar and a steel bar. Steel bars and SEA bars with 25 mm length rolling threaded ends were connected using 50 mm long nuts as splicing as shown in Figure 3. Steel bars and SEA bars were threaded as M12 and M14, respectively. In the SEA specimens, the joint was made with a long nut outside the concrete section to fix the specimen to the loading machine. For the Threaded SEA specimen, since it is difficult to make SEA bars longer than 500 mm, two threaded SEA bars with 300 mm length were used and connected at the center of the specimen.

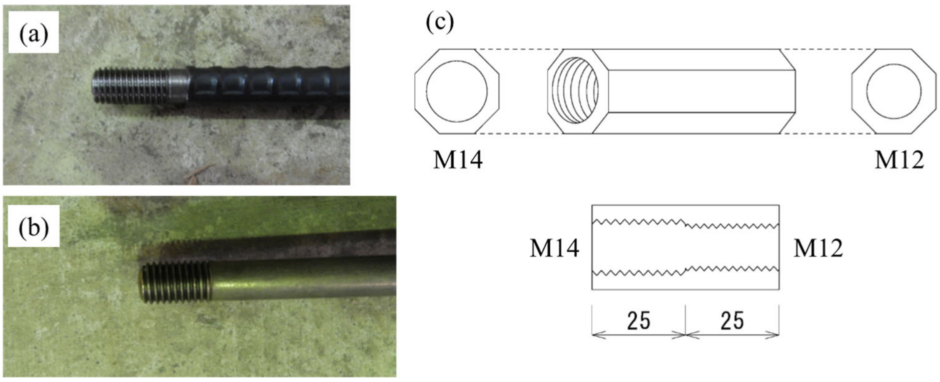

Figure 3. Splicing details: (a) rolling thread at steel bar end, (b) rolling thread at SEA bar end, (c) details of the splicing.

Materials

Figure 4 shows the stress-strain relationship from the tensile test results of the SEA bars used in the specimens. From Figure 4, SEA bars restore their shape to the original condition when unloaded after being subjected to a large strain of more than 3.5%, and the residual strain becomes almost zero. Table 1 shows the apparent yield stress and elastic modulus of each SEA bar. Note that the apparent yield stress of SEA bar is similar to the yield stress of steel bar. The average apparent yield stress and elastic modulus of SEA bars are 188 N/mm^2 and 32.1 kN/mm^2, respectively, which are about half of the steel yield stress and one-sixth of the steel elastic modulus. The yield stress of the D13 (SD295) steel bar was 367 N/mm^2 from the tensile test. The

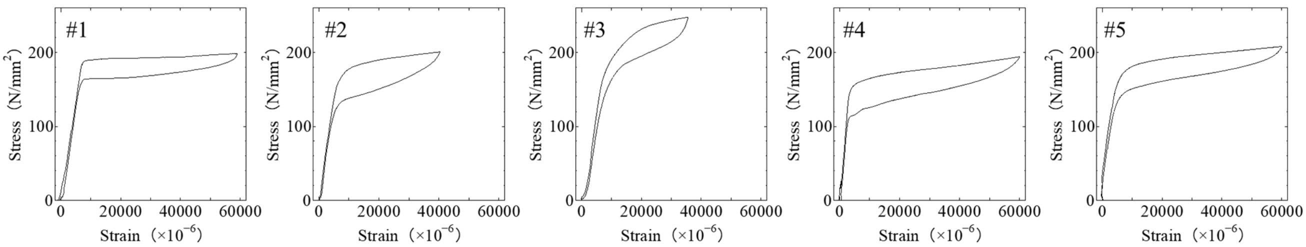

Figure 4. Hysteresis curves of SEA bars

Table 1. Tensile test results of SEA bars

SEA number	Specimen	Apparent yield stress (N/mm^2)	Elastic module (N/mm^2)
#1	Round SEA-RC	188	25.9
#2	Threaded SEA-RC	179	28.3
#3	Round SEA	222	28.8
#4	Threaded SEA (upper)	186	25.0
#5	Threaded SEA (lower)	166	52.5

compressive stress, tensile stress, and elastic modulus of the concrete on the day of the loading test are 52.2 N/mm^2, 3.9 N/mm^2, and 31.3 N/mm^2, respectively.

Cyclic loading tests and instrumentations

Figure 5 presents a test setup. In a series of tests, the specimens were set vertically, and the steel bars at the ends of the specimens were fixed to the loading device. The loading protocols for each specimen are shown in Table 2. For the Plastic hinge specimens, first, a load was applied until the first crack occurred, and after that, loading was controlled by the displacement of the concrete member. For the Round SEA and Threaded SEA specimens, a load of 20 kN, which is about the apparent yield strength, was applied first, and the following loading was conducted by displacement control based on the SEA bar displacement. In the Steel RC specimen, the yield displacement δ was used for a cyclic displacement. In the other specimens, a cyclic displacement was incremented by 1 mm, and then the displacement increment of 2 mm was used when the loading displacement exceeded 10 mm. The number of cycles was three in the first two or three displacement-controlled loading cycles, while once in the other loadings.

Figure 5. Test Setup.

Table 2. Loading protocol

Specimen	Loading	Cycle Numb.
Steel RC (Plastic hinge specimen)	Crack load (27kN)	1
	$1\delta_y$ (0.45mm) and $2\delta_y$ (0.90mm)	3
	$3\delta_y$ (1.35mm), $5\delta_y$ (2.25mm), $7\delta_y$ (3.15mm), $9\delta_y$ (4.05mm), $11\delta_y$ (4.95mm), $13\delta_y$ (5.85mm) and measurement limit (16mm)	1
Round SEA-RC (Plastic hinge specimen)	Crack load (34kN)	1
	1mm, 2mm and 3mm	3
	4mm, 5mm, 6mm, 7mm, 8mm, 9mm, 10mm, 12mm, 14mm, 16mm, 18mm, 20mm and SEA bar rupture (21.4mm)	1
Threaded SEA-RC (Plastic hinge specimen)	Crack load (25kN)	1
	2mm and 3mm	3
	4mm, 5mm, 6mm, 7mm, 8mm, 9mm, 10mm, 12mm, 14mm, 16mm, 18mm, 20mm and 22mm	1
Round SEA (SEA specimen)	20kN	1
	7mm and 8mm	3
	9mm, 10mm, 12mm, 14mm, 16mm, 18mm, 20mm, 22mm and 24mm	1
Threaded SEA (SEA specimen)	20kN	1
	2mm and 3mm	3
	4mm, 5mm, 6mm, 7mm, 8mm, 9mm, 10mm, 12mm, 14mm, 16mm, 18mm and 20mm	1

The load, strain of reinforcing bars and concrete displacement of the specimens were measured in the tests. Figure 6 schematically presents the instrumentations for displacement. For the SEA specimens, the displacement of the SEA bar was also measured. The concrete displacement is the relative displacement between the concrete block edges, which was calculated from the displacement of CD1 and CD2 as shown in Figure 6. The SEA bar displacement is the relative displacement of the SEA bar ends, which was calculated from the displacement of SD1 and SD2. Figure 7 presents the instrumentations for strain gauges of the reinforcing bar. The strain gauges were attached to each specimen at 40 mm intervals. As shown in Figure 7(a), a set of two strain gages was attached at the opposite side of the section, and the axial strain of the reinforcement was taken as the average of these two. In order to ensure that the strain gauge attachment did not affect the bond between the reinforcing bars and the concrete, the strain gauges were attached to the grooves as shown in Figures 7(a) and (b). The grooves were filled with epoxy resin to protect the strain gages as shown in Figures 7(a) and (c). For the Plastic hinge specimens, pi-gauges were instrumented on the concrete surface of the specimens to measure the crack width. The crack initiation was measured when the crack was first detected by the pi-gauges.

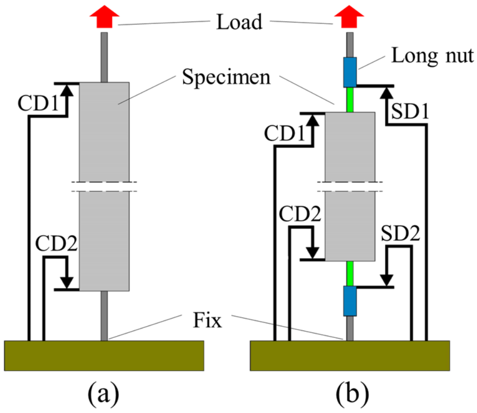

Figure 6. Instrumentations for displacement: (a) Plastic hinge specimens, (b) SEA specimens.

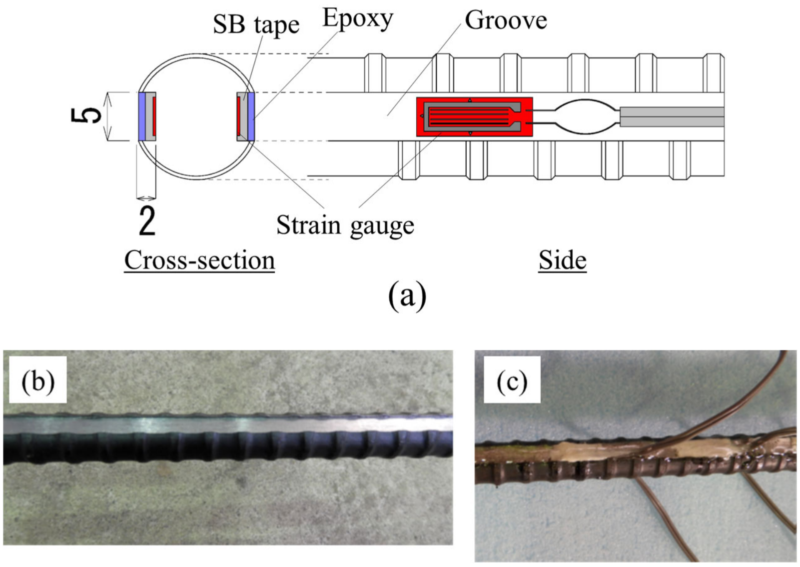

Figure 7. Instrumentations for strain gauges of reinforcing bar: (a) strain gauge installation details, (b) groove of reinforcing bar, (c) epoxy coating.

TEST RESULTS

Observed damage

The test in the Round SEA-RC specimen was terminated because the SEA was ruptured at the concrete displacement of 21.4 mm. In the other tests, the test was conducted up to the displacement limit which was from the capacity of displacement meters. The damage condition of the specimens after the test is shown in Figure 8, and the crack observations were illustrated in Figure 9 with 50 mm meshes. In the steel RC specimens, after a single crack occurred around the center height of the specimen, cracks were distributed over the entire height of the specimen as shown in Figure 8(a). In the Round SEA-RC and Threaded SEA-RC specimens, only a single crack occurred at the SEA section, and this crack widely opened as shown in Figure 8(b) and (c), respectively. No cracks in concrete were observed in the Round SEA specimen during the test as shown in Figure 9(d). Since the round SEA bar has small bond stress in concrete, the bond between the SEA bar and the concrete was lost, and the SEA bar was pulled out of the concrete. In the Threaded SEA specimen, cracks were observed in the upper side concrete as shown in Figure 9(e). This shows that the threaded SEA bar distributes cracks in the concrete due to the bonding. The observation of cracks mainly in the upper side of the specimen could be attributed to the fact that the elastic modulus of the SEA bar used on the upper side is about half of the SEA bar used on the lower side.

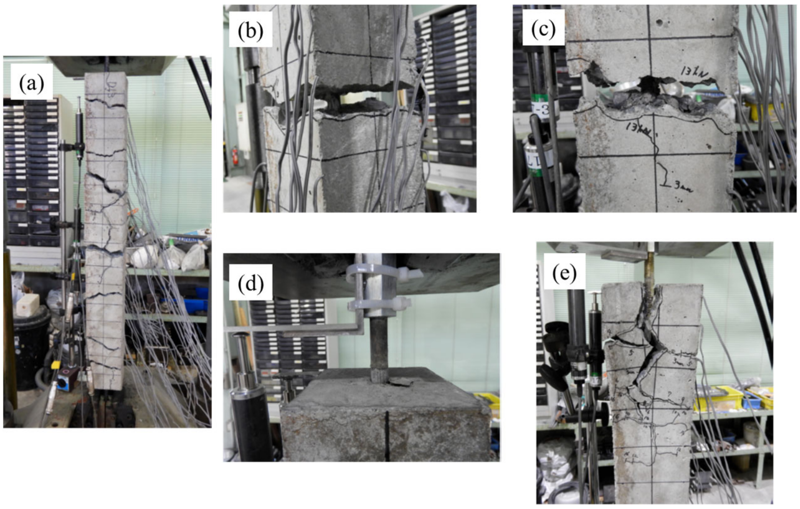

Figure 8. Crack damage condition of specimens: (a) steel RC, (b)round SEA-RC, (c)threaded SEA-RC, (d)round SEA, (e)threaded SEA.

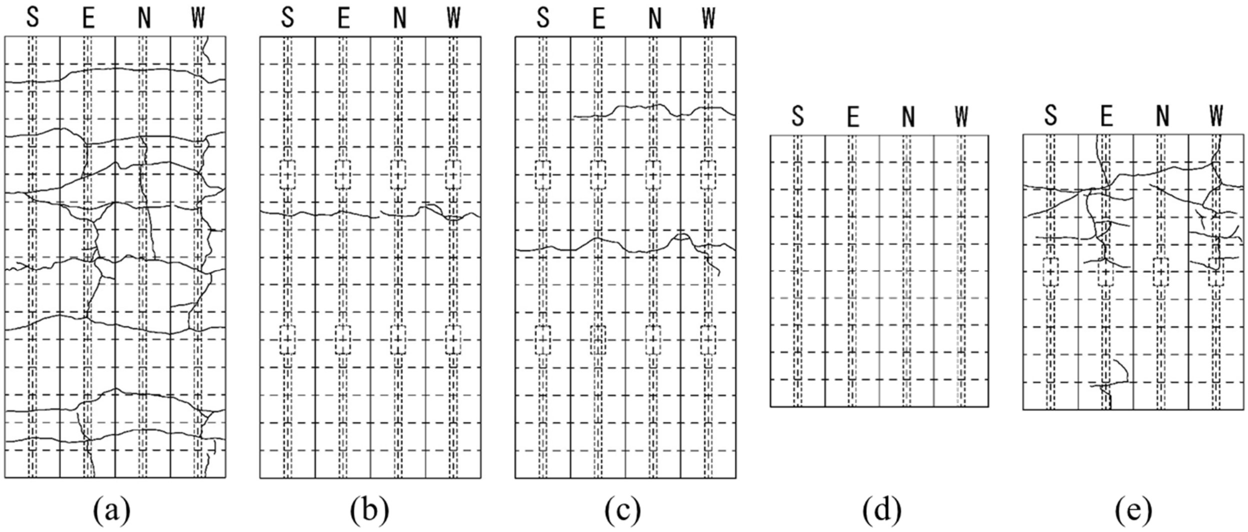

Figure 9.: Cracks observed on specimens: (a) Steel RC, (b)Round SEA-RC, (c)Threaded SEA-RC, (d)Round SEA, (e)Threaded SEA.

Longitudinal strain distribution in reinforcing bar

Figure 10 shows the strain distribution along the reinforcing bars at each loading stage. In the Steel RC specimen shown in Figure 10(a), the strains at both ends increased before the crack occurred, but once a single crack occurred at the center of the specimen, the strain at the center was thought to be increased extensively, although it was only measured up to the crack occurrence at the center. In the Threaded SEA-RC specimens shown in Figure 10(c), the strain was also concentrated at the center in the SEA section; however, the strains in the steel bars at both ends of the specimen were smaller than the ones observed in the Steel RC specimen. The strains at the steel bar ends were also small in the Round SEA-RC specimen. This is because the apparent yield stress of the SEA bar is smaller than the yield stress of the steel, so the strain was concentrated in the SEA bar. Therefore, when the SEA bar, having lower apparent yield stress than the yield stress of the steel bar, is used in the plastic hinge of the RC column, plastic deformation of the reinforcing steel bars connected to the SEA bar could be prevented. In the Threaded SEA specimen, the strains of SEA on the upper side of the specimen were generally larger than that on the lower side, which corresponds to the crack distribution that occurred on the upper side of the specimen, as previously shown in Figure 9(e). Also, unlike the other specimens, the strain at the middle height of the specimen is low as shown in Figure 10(d) because there was a long nut splice in this location.

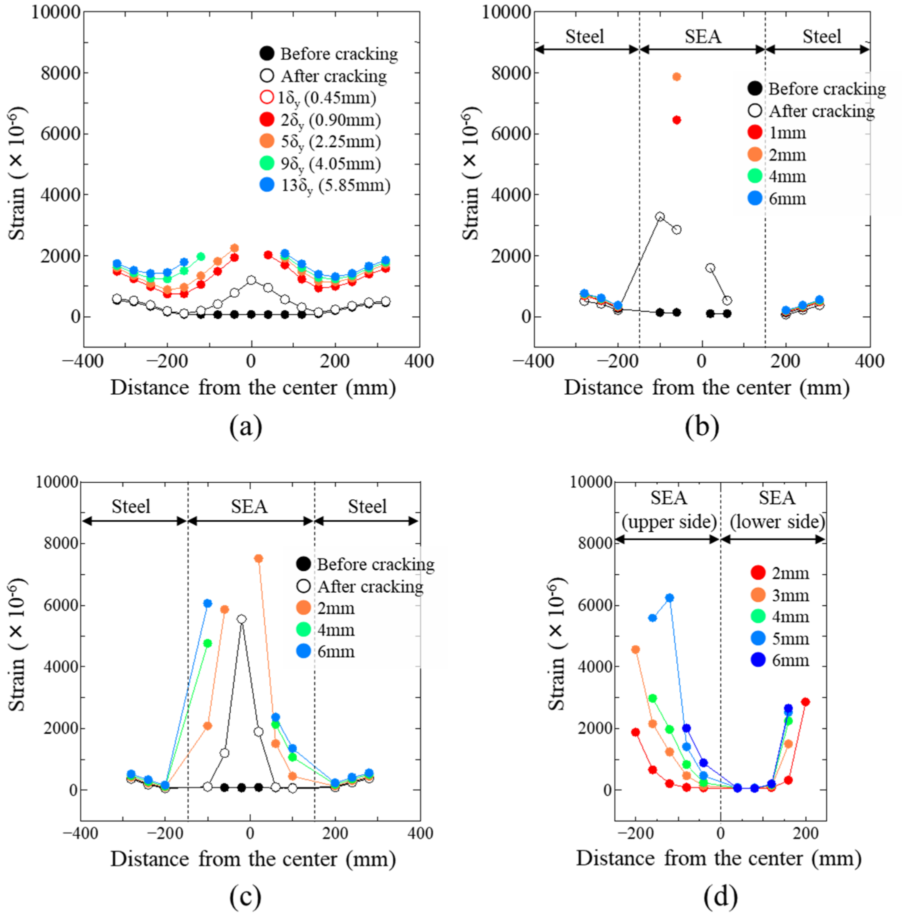

Figure 10. Strain distribution along the reinforcing bars: (a) Steel RC, (b) Round SEA-RC, (c) Threaded SEA-RC, (d) Threaded SEA.

Load-Displacement relationship

Figure 11 shows the load-concrete displacement relationship for each specimen. Note that displacement in Figure 11(a), (b) and (e) is shown up to 16 mm due to the measurement limit, 21.4 mm due to the rupture of the SEA bar, and 9 mm due to the measurement limit, respectively. The cracking load from the tests was 27kN, 34kN, and 25kN for the steel RC, Round SEA-RC, and Threaded SEA-RC specimens, respectively. The expected cracking load which was calculated by multiplying the cross-sectional area by the tensile stress of the concrete was 39.1kN, which is higher than the experimental results. This is because the expected cracking load is assumed the full crack at the section, whereas the cracking load from the tests was not the full section crack but the initiation of the crack in the specimen.

After cracking occurred in the Round and Threaded SEA-RC specimens, the strain was concentrated in the SEA bar at the crack location as previously shown in Figure 8(b) and (c), respectively; hence the hysteresis curve became similar to the tensile test result of the SEA bar. In Figure 11, the residual displacement was conventionally observed after yielding in the Steel RC specimen, but the residual displacement in the Round SEA-RC and Threaded SEA-RC specimens was close to zero due to the super-elastic material property of the SEA bar. As shown in Figure 11(d), the displacement of the concrete section in the Round SEA specimen was almost zero because SEA was pulled out of the concrete due to the low bond between the SEA bar and concrete. In contrast, as shown in Figute 11(e) for the Threaded SEA specimen, the threading of the SEA increased the bond to the concrete, which transferred the tensile force of the bars to the concrete and caused the concrete displacement.

A comparison of the residual displacement of the Plastic hinge specimens is shown in Figure 12, where residual displacement is defined as the displacement at which the load became zero after unloading at the first cycle of each loading cycle. The residual displacement of the RC specimen at a 6 mm displacement was 5.1mm, while the one of both SEA-RC specimens was 0.4mm. Therefore, the residual displacement was reduced by 92% using the SEA bar as compared to the conventional steel RC specimen.

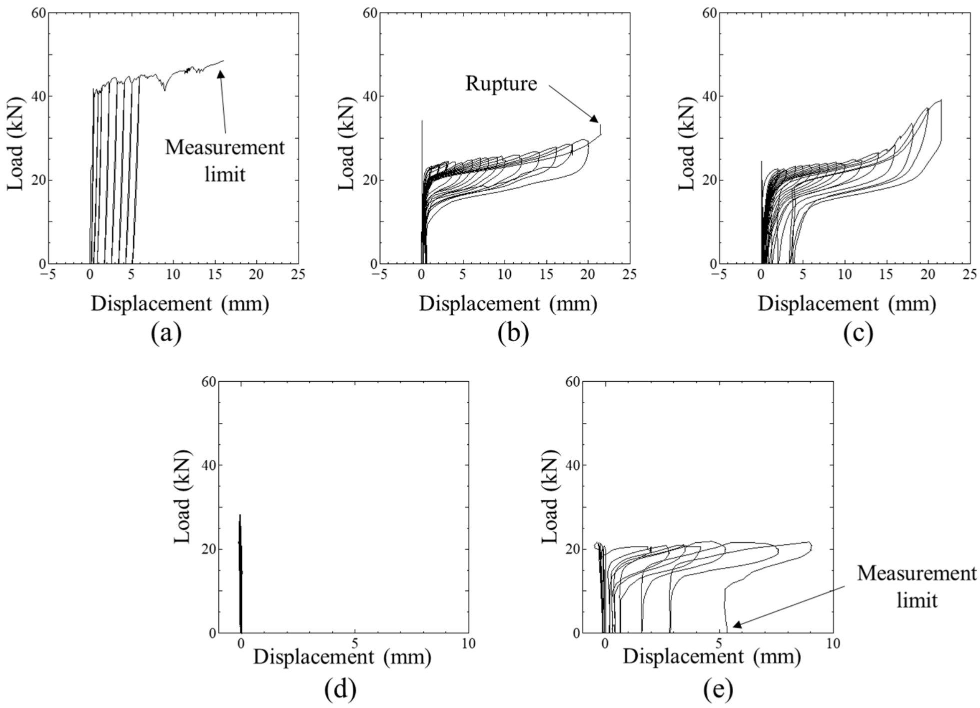

Figure 11. Load-displacement relationship: (a) Steel RC, (b)Round SEA-RC, (c)Threaded SEA-RC, (d)Round SEA, (e)Threaded SEA.

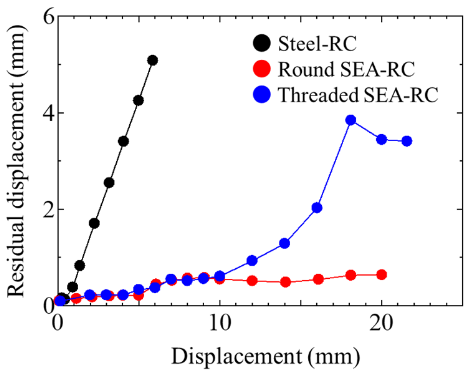

Figure 12. Residual displacement of Plastic hinge speciments.

CONCLUSIONS

In this study, a series of cyclic tensile loading tests of RC specimens was conducted to investigate the tensile behavior of RC members using a SEA bar as longitudinal reinforcement. Two types of SEA bars were used in the specimens to examine the effect of the bond between the SEA bar and concrete on the tensile behavior: a round SEA bar and a threaded SEA bar. The following findings obtained from this study are summarized below:

1. In the specimen with a SEA bar spliced with steel bars, only a single crack was observed along the specimen, and the damage was concentrated in this crack, as opposed to the conventional steel RC specimen where the cracks were distributed along the specimen.
2. A threaded SEA bar distributed cracks in the concrete due to the bonding in the concrete, whereas a round SEA bar was pulled out of the concrete due to the low bond stress.
3. When a SEA bar was connected to the steel bars, the strain was concentrated in the SEA bar, and the strain in the steel bars was small. This suggests that when the SEA bar, having lower apparent yield stress than the yield stress of the steel bar, is used in the plastic hinge of the RC column, plastic deformation of the reinforcing steel bars connected to the SEA bar could be prevented.
4. Residual displacement was significantly reduced in the RC members having a SEA bar as longitudinal reinforcement. As compared to the conventional steel RC specimen, the residual displacement was reduced by 92% after a loading displacement of 6 mm.

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