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Lateral reinforcement of welded SMA rings for reinforced concrete columns

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ABSTRACT

This study conducts a series of compressive tests of concrete cylinders confined by shape-memory alloy (SMA) rings to provide lateral confinement for reinforced concrete columns. $Ni_{50}Ti_{41}Nb_9$ (at.%) SMA bars with a diameter of 3 mm and a length of 446 mm were prepared and strained to 7% before welding. Three of the six confined cylinders were heated to 200 °C to introduce recovery stress in the SMA rings, which was predicted to provide active confinement of concrete. The behavior of two welded bars with a resulting diameter of 6 mm were tested and compared with that of the continuous SMA bars without welding. The continuous SMA bars showed the typical behavior of martensitic SMAs, such as an elastic range, a transformed state, and hardening behavior due to austenite. However, the welded bars were fractured at the welding point at or just after elastic range. The concrete cylinders confined by the SMA rings showed greater peak strength and larger failure strain compared to the plain concrete cylinders. However, the stress-strain curves of the confined cylinders showed stepping behavior due to the sequential fracturing of the SMA rings. The heated SMA ring cylinders did not show greater peak strength than the unheated SMA ring cylinders, indicating that active confining was not effective.

1. Introduction

Shape–memory alloy (SMA) wire jackets can provide active confining pressure due to the shape–memory effect as well as passive confining pressure with the application of strain and thus can increase the peak strength and failure strain of concrete [1,2]. This contributes to an increase in the displacement ductility when used in the reinforced concrete (RC) columns of bridges [3], which is the most important benefit as it protects RC structures from seismic attacks. Previous studies proved the effectiveness of SMA wire jackets through concrete cylinder tests and bending tests of lap-spliced RC columns jacketed by SMA wires. Choi et al. [4] also compared the performance of a SMA wire and steel jacket and found a similar trend regarding the increment of the peak strength. Choi et al. [5] also investigated the behavior of SMA wires in tension under residual stress that provided external confining pressure on surface such as concrete. The SMA wires in the previous studies were used as external jackets to wrap the outside surface of concrete and thus were applicable only for seismic retrofitting. This study attempts to apply SMA rings as a type of lateral reinforcement for concrete structures used in new construction projects. The SMA rings were embedded inside concrete between steel reinforcement and the concrete surface as a secondary form of lateral reinforcement. In this case, the rings can be placed more densely, and material segregation is avoided simultaneously. Secondary lateral reinforcement of the SMA rings can delay the buckling of longitudinal reinforcing bars in RC columns and can therefore increase the displacement ductility. This study conducted axial compressive tests of concrete cylinders confined by embedded SMA rings and investigated the effect of the SMA rings.

2. SMA rings and cylinder specimens

This study used $Ni_{50}Ti_{41}Nb_9$ (at.%) SMA instead of NiTi SMA given that NiTiNb SMAs show wider temperature hysteresis and are more adaptable for SMA civil applications when the shape–memory effect is exploited. First, SMA bars with a diameter of 3 mm and a length of 446 mm were manufactured with 7% prestrain due to cold drawing. The transformation temperatures of the NiTiNb SMA were as follows: $M_s = -17.6\,^\circ C$, $M_f = -74.3\,^\circ C$, $A_s = 104.9\,^\circ C$, and $A_f = 139.2\,^\circ C$. Thus, the NiTiNb SMA was suitable for the application of a shape–memory effect for civil structures as the A_s value was higher than the highest air temperature value, for example 40 °C, implying so that the shape memory effect would be preserved and because the M_s value was lower than the lowest air temperature, such as −10 °C, so as to maintain the developed recovery stress.

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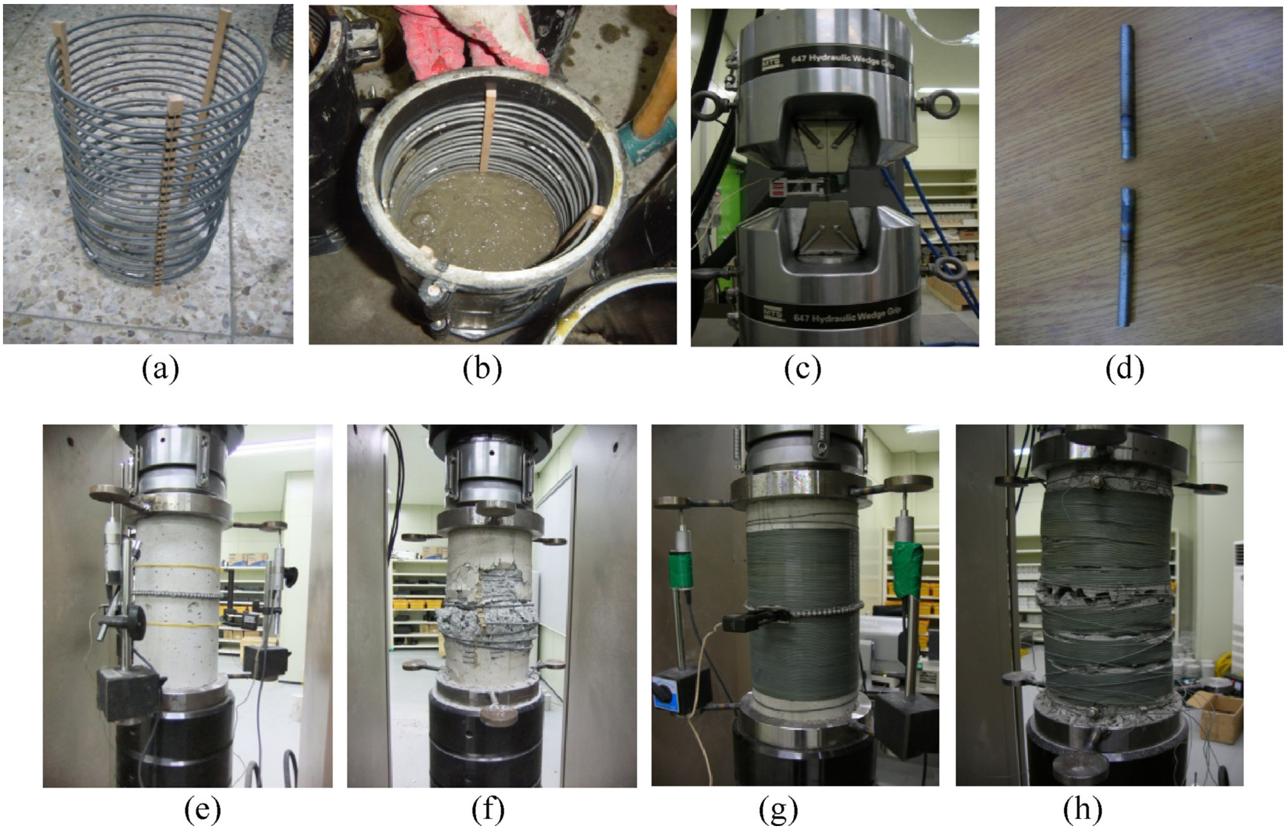

Fig. 1. (a) The suite of SMA rings. (b) SMA rings in a mold. (c) Tensile test of a welded SMA bar. (d) Fracture of a welded SMA bar. (e) Test set-up for a cylinder with SMA rings. (f) Failure of a cylinder with SMA rings. (g) Test set-up for a cylinder confined by a SMA wire jacket. (h) Failure of a SMA wire jacketed cylinder.

The SMA bar was bent into a circle and then welded at each end to make a ring using tungsten inert gas (TIG) welding with argon gas. A suite of 25 rings with a pitch of 10 mm was fixed by three wood posts and placed in a concrete mold, as shown in Fig. 1(a) and (b). The size of a concrete cylinder was 150 mm in diameter and 300 mm in height. Three plain and six confined concrete cylinders were prepared, and three of the six confined specimens were heated to 143 °C to induce recovery stress into the SMA rings. The concrete cylinders were submerged in water for 28 days for curing and subsequently dried in air. To heat the three confined specimens to 200 °C, an electronic oven was preheated to 150 °C and the specimens were then placed inside the oven for 2 h and the temperature of the oven was increased to 200 °C. The SMA rings were placed just below the concrete surface and were therefore heated by air convection. The measured temperature on the concrete surface after heating for 2 h was 143 °C. Also, this study prepared two welded and two continuous SMA bars with a diameter of 6 mm and a length of 200 mm to investigate the tensile behavior; the 3 mm bars were too thin for the tension tests and thus 6 mm bars were used.

3. Test set up and results

For the tensile tests of the SMA bars, an extensometer with a gage length of 25 mm was placed in the middle of the specimens. The stress–strain curves are shown in Fig. 2(a). The continuous specimens showed plateau stress after the onset of martensite detwinning and elastic hardening deformation after they reached a fully detwinned martensite state; this behavior was very typical for martensitic SMA wires or bars [6]. However, the welded SMA bars were fractured just before reaching plateau stress. The welded part in the bars was fractured as shown in Fig. 1(d). TIG welding, a type of arc welding, can lead to the embrittlement of a NiTi SMA welded bar due to the reactions with oxygen, nitrogen and hydrogen at a high temperature. Wu et al. [7] found that a NiTiNb SMA wire welded using TIG welding was fractured at the fusion area. They also noted that obvious cleavage steps could be observed, implying brittle fracturing. The result with the welded bars in this study corresponded precisely to the previous observation. Wu et al. also indicated that the welding point of NiTiNb SMA wires can be changed to show proper mechanical properties such as tensile strength and elongation with a proper annealing treatment. In general, the corresponding strain for displacement ductility of 4–5 on lateral reinforcing bars in an RC column is smaller than 0.5%. Therefore, thus, the welded SMA bars in this study with fracture strains of 0.53% and 0.95% will not be fractured under these conditions. Thus, this study did not anneal the welded SMA bars to recover the shape–memory effect.

The set-up for the compressive tests of the concrete cylinders is shown in Fig. 1(e). An extensometer and three displacement transducers were used to measure the axial deformation of the specimens. The gage length of the extensometer was 100 mm and the displacement transducers were located between two sole plates at the top and bottom of each cylinder. The stress–strain curves are shown in Fig. 2(b)–(e). In these figures, 'SMA-H' represents the concrete cylinder confined by the SMA rings and heated later. The average peak strength of plain concrete was 35.1 MPa, and the corresponding strain was 0.0024. The average peak strengths of the 'SMA' and 'SMA-H' specimens were 41.4 and 40.8 MPa and the corresponding strains were 0.0116 and 0.0108, respectively. Thus, the SMA rings increased the peak strength by 17.9% and 16.2% for each case and the peak strain by 4.8 times and 4.5 times relative to the plain concrete case. These results matched the findings for the concrete confined by external jackets such as a steel plate or SMA wire

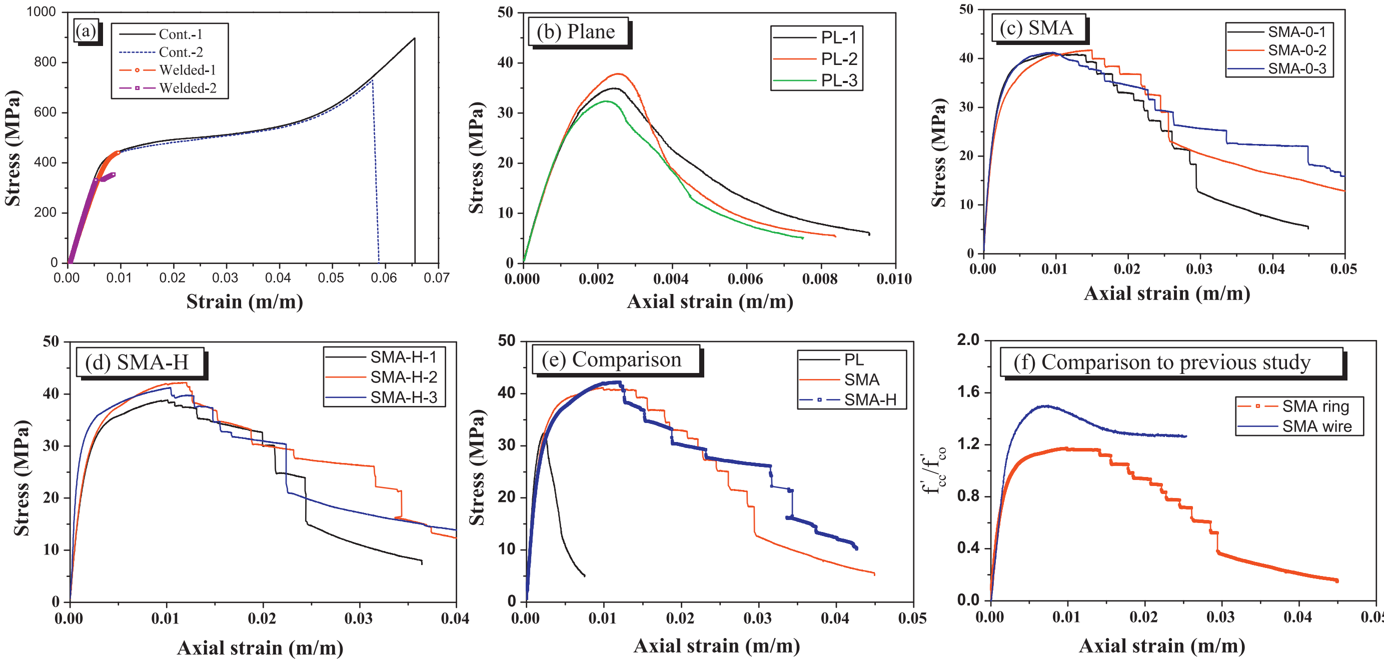

Fig. 2. (a) Tensile behavior of the welded SMA bars. Stress–strain curves of (b) plain concrete, (c) concrete confined by SMA rings, and (d) concrete confined by SMA rings with heating. (e) Comparison of the axial behavior of the three types of specimens. (f) Comparison to the results of a previous study.

[4,8]. In the tests, there were two points worthy of note. The concrete confined by SMA rings showed a sharp decrease in strength in steps after the peak strength. The concrete started to dilate quickly once it reached its peak strength and the SMA rings were then exposed to severe tensile strain in the middle of the specimens. The welded SMA rings did not show ductile behavior and thus subsequently fractured from the middle to the outside, as shown in Fig. 1(f). The strength of the confined concrete decreased abruptly upon the fracture of the SMA rings in a step-wise manner. However, the stepping behavior will not likely be a serious problem in practical applications. In Fig. 2(e), the strains that initiated stepping behavior were 1.4% and 1.2% for the 'SMA' and the 'SMA-H' specimen, respectively, which were 6 and 7 times larger than the peak strain of the plain concrete. Thus, as mentioned above, the welded SMA rings would not likely fracture during practical use. Also, the 'SMA' specimen in Fig. 2(f) demonstrated sufficient ductile behavior before stepping commenced compared to the continuous softening behavior of the concrete confined by the SMA wires.

The heated specimens with SMA rings were expected to provide active confining pressure due to the shape–memory effect. However, the heated specimens with SMA rings demonstrated a level of peak strength similar to that of the specimen without heating. Thus, it appears that the active confining pressure of the heated specimens was negligible and that the prestrained SMA bars recovered a large amount of the prestrain due to heating during the welding process.

4. Discussion

The result of this study was compared to that of a previous study which used SMA wire as an external jacket, as shown in Fig. 1(g) [4]. The compared stress-strain curves are shown in Fig. 2(f), indicating the stress ratio to the peak strength of plain concrete as a function of the axial strain. The concrete confined by the SMA wires as an external jacket showed smooth softening behavior and greater peak strength, increasing to 1.50 compared to the value of 1.17 in this study. The peak strength of the concrete confined by SMA wires or rings depended on the volumetric ratio of the SMA, the active confining pressure that developed, and the mechanical behavior of the SMA. Fig. 1(f) and (h) shows the failure state of the two types of specimens. Both types started to fail in the middle of the specimen, and the fracture of the SMA rings or wires led to the failure of the concrete.

To avoid adverse effects on the strength and shape–memory characteristics of SMA bars during the welding process, SMA rings are recommended to be jointed using a coupler, as proposed by Youssef et al. [9]. The heat of TIG welding changes the characteristics of the SMA rings. Recovering the proper properties of these rings can be difficult. However, the coupler provides an increased cross-section at the coupling point. Thus, further study is necessary to investigate the strong and weak points of each case.

5. Conclusion

This study applied SMA rings as a type of embedded lateral reinforcement of concrete for use in new construction projects. The SMA rings increased the peak strength and the failure strain of concrete to satisfactory levels. Therefore, this type of lateral reinforcement of SMA rings can be used to confine the plastic regions of RC columns. The stepping behavior was observed to have a relatively large amount of axial strain; however, the strain upon the initiation of stepping began was large enough for practical applications. SMA rings can be expected to provide active and passive confining pressure on concrete. However, the active confining pressure was not developed successfully in this study because the heat from the TIG welding process changed the characteristics of the prestrained SMA bars. Therefore, further study with coupler-joined SMA bars is necessary to produce active confining pressure and discern its effect on concrete.

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