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Effect of Confining Pressure Due to External Jacket of Steel Plate or Shape Memory Alloy Wire on Bond Behavior Between Concrete and Steel Reinforcing Bars

Eunsoo Choi[1], Dongkyun Kim[1], and Kyoungsoo Park[2,*]

[1] *Hongik University, Department of Civil Engineering, Seoul, 121-791, Korea*
[2] *Yonsei University, Department of Civil and Environmental Engineering, Seoul, 120-749, Korea*

For external jackets of reinforced concrete columns, shape memory alloy (SMA) wires are easy to install, and they provide active and passive confining pressure; steel plates, on the other hand, only provide passive confining pressure, and their installation on concrete is not convenient because of the requirement of a special device. To investigate how SMA wires distinctly impact bond behavior compared with steel plates, this study conducted push-out bond tests of steel reinforcing bars embedded in concrete confined by SMA wires or steel plates. For this purpose, concrete cylinders were prepared with dimensions of 100 mm × 200 mm, and D-22 reinforcing bars were embedded at the center of the concrete cylinders. External jackets of 1.0 mm and 1.5 mm thickness steel plates were used to wrap the concrete cylinders. Additionally, NiTiNb SMA wire with a diameter of 1.0 mm was wound around the concrete cylinders. Slip of the reinforcing bars due to pushing force was measured by using a displacement transducer, while the circumferential deformation of specimens was obtained by using an extensometer. The circumferential deformation was used to calculate the circumferential strains of the specimens. This study assessed the radial confining pressure due to the external jackets on the reinforcing bars at bond strength from bond stress-slip curves and bond stress-circumferential strain curves. Then, the effects of the radial confining pressure on the bond behavior of concrete are investigated, and an equation is suggested to estimate bond strength using the radial confining pressure. Finally, this study focused on how active confining pressure due to recovery stress of the SMA wires influences bond behavior.

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1. INTRODUCTION

Bond strength in reinforced concrete (RC) columns with lap-spliced reinforcement at the bottom is critical to produce yield of reinforcing bars and ductile behavior of a column. In general, however, the thickness of cover concrete is not sufficient to provide lateral confining pressure to induce pull-out failure mode in the lap-spliced zone.[5] Therefore, splitting failure usually occurs at the lap-spliced zone, and the reinforcing bars slip before yielding.[6] In this case, external jackets, such as steel plate, fiber reinforced polymer (FRP) sheets, or shape memory alloy (SMA) wires, can be used to increase bond strength.[1,4,7]

As an external jacket, SMA wires use recovery stress due to a shape memory effect to tightly adhere to the concrete surface.[3] Behaviors of SMA wires are different from behaviors of steel plates and FRP sheets because SMA wires can produce active confining pressure on concrete, whereas steel plates and FRP sheets only provide passive confining pressure induced by bulging of concrete. Note that recovery stress developed by the shape memory effect provides active confining pressure. Choi and others conducted bond tests between steel reinforcing bars and concrete confined by steel plates or SMA wires and discussed

*Author to whom correspondence should be addressed.

the results.[4,7] The aims of the present study are to compare the effects of SMA wires and steel plates on the bonding of steel and concrete and assess the influence of active confining pressure of SMA wires on bond strength.

2. MATERIALS, SPECIMENS, AND TEST SET-UP

2.1. SMA and Steel Properties

For SMA applications in civil structures that are exposed to a wide variation of temperature, wide temperature hysteresis is desirable.[8] Since prestrained SMA wires of NiTiNb generally demonstrate relatively wide temperature hysteresis compared with that of NiTi SMAs, this study utilized SMA of $Ni_{47.4}Ti_{37.86}Nb_{14.69}$ (wt.%). The SMA of NiTiNb was prepared by high-frequency vacuum-induction melting and was hot-rolled into wires with a diameter of 1.07 mm at 850 °C. The diameter of the hot-rolled wire was reduced to 1.0 mm by cold drawing without an intermediate annealing step; the process produced area reduction of 14.5%. The cold-drawn SMA wire showed the following temperature windows; $M_s = -17.6$ °C, $M_f = -74.3$ °C, $A_s = 104.9$ °C, and $A_f = 139.2$ °C. Thus, the temperature hysteresis $(A_s - M_s)$ was 122.5 °C.

As presented in Figure 1, the NiTiNb SMA wire with 5% prestrain was heated to 200 °C, which generated recovery stress of 241.5 MPa. The temperature was then decreased to room temperature (20 °C), which reduced the recovery stress to the residual stress of 174.5 MPa. The SMA wire in Figure 1 was exposed to cyclic tensile loading under the residual stress. The residual stress of the SMA wire contributed to active confining pressure on the concrete, and the developed stress due to additional strain provided passive confining pressure.

A factory-manufactured NiTiNb SMA wire was tested to measure the recovery and residual stress, and the obtained values were 246.9 MPa and 147.1 MPa, respectively. In this case, the assigned prestrain was estimated as 4.7%. For stainless steel plates, the yield strength and Young's modulus were measured as 280 MPa and 200 GPa, respectively.

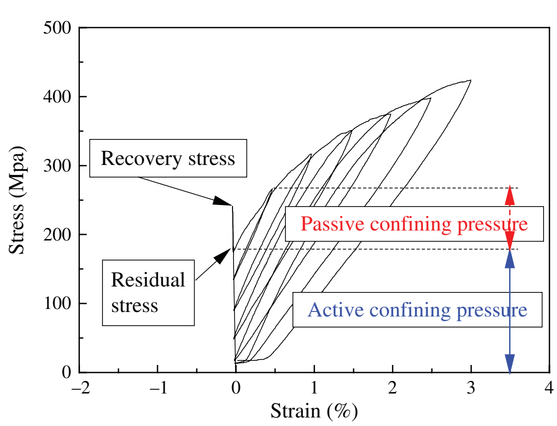

Figure 1. Cyclic tensile behavior of the SMA wire under residual stress.

2.2. Specimens and Test Set-Up

Concrete cylinders with the diameter of 100 mm and the length of 200 mm were fabricated with a D22 reinforcing bar (nominal diameter of 22.2 mm) at the center of each cylinder specimen. The measured peak strength of the concrete was 30 MPa. The total length of the bars was 260 mm, which left a 60 mm length protruding beyond the top surface of the specimens. Along the embedded bar, the middle 150 mm length of the bars was bonded with concrete, while the 25 mm length at both the top and bottom of the specimens was wrapped with oil paper. Such preparation removes stress-concentration on the top and bottom surfaces of the concrete specimens and leads to bonding failure between concrete and rebar.

To provide confining pressure to the concrete cylinders, external jackets of SMA wire and steel plates were utilized. Then, four types of specimens were prepared:

(1) plain concrete (PL) specimens without external jackets,
(2) specimens jacketed by SMA wires (SMA),
(3) specimens jacketed by steel plates with the thickness of 1.0 mm (ST-1.0), and
(4) specimens jacketed by steel plates with the thickness of 1.5 mm (ST-1.5).

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Jacketing methods for the SMA wires and steel plates have been fully explained in previous studies.[2,3]

Figure 2 demonstrates the test set-up for the three types of specimens, while Figure 3 describes the test configuration and dimensions of the specimens. Axial compressive loading was applied at the top of a bar under the displacement control. A displacement transducer measured slip of the reinforcing bar at the bottom of the specimen, and an extensometer in the circumferential direction measured bulging of the specimen at the middle, which was used to calculate circumferential strain during the push-out test.

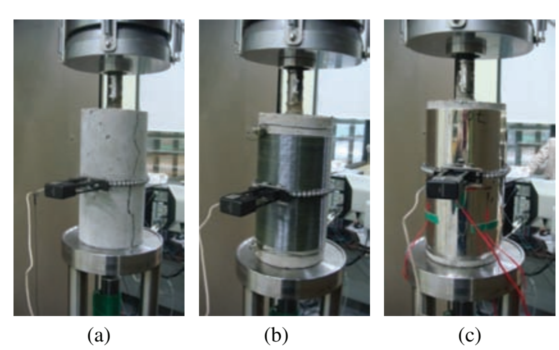

Figure 2. Specimen and test set-up for (a) plain concrete, (b) SMA wire jacket, and (c) steel plate jacket.

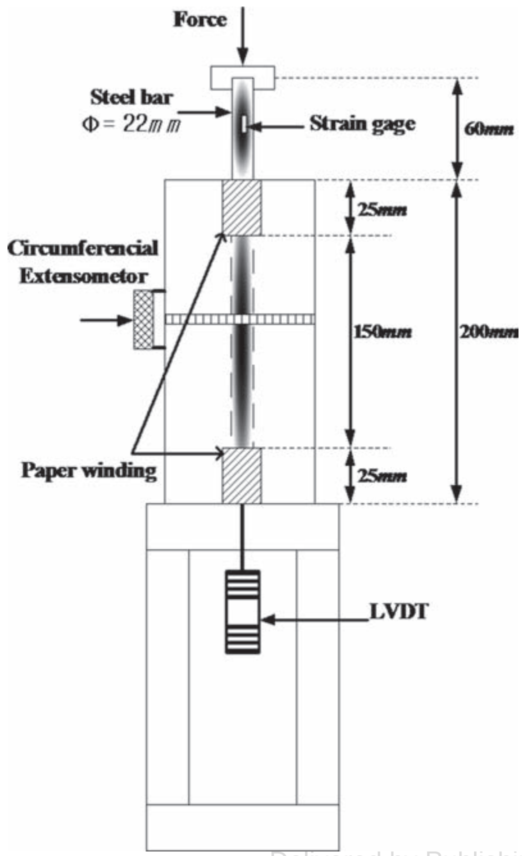

Figure 3. Schematics of test configuration.

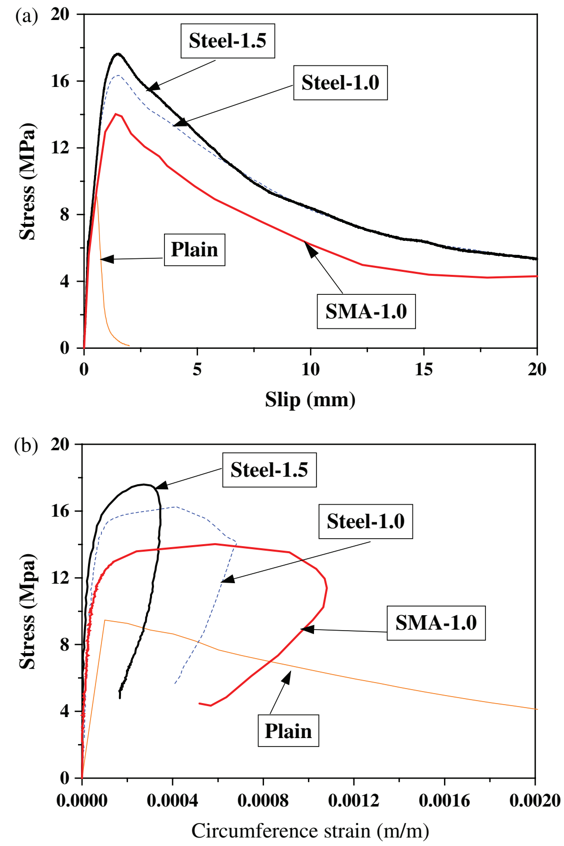

Figure 4. Relationships for (a) bond stress versus slip, and (b) bond stress versus circumferential strain.

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3. TEST RESULTS AND DISCUSSIONS

Bond stress versus bar-slip or circumferential strain curves are plotted in Figure 4 for each type of specimen. Note that the curves were averaged from five replicates for each type of specimen. Bond stress τ_b around the bars, which was assumed to be distributed uniformly along the embedded length, was calculated by the following equation:[9]

$$\tau_b = F/(\pi d_b L) \quad (1)$$

where F and L are the push-out force and the embedded length of a bar, and d_b is the diameter of the steel rebar. The average bond strength of the PL specimen was 10.2 MPa. The average bond strengths of the SMA, ST-1.0, and ST-1.5 specimens were 14.6 MPa, 16.5 MPa, and 16.8 MPa, respectively. The corresponding circumferential strains ($\varepsilon_{\text{cir, bond}}$) and the maximum circumferential strain ($\varepsilon_{\text{cir, max}}$) after reaching the bond strength are shown in Table I. Developed stress in the external jacket due to bulging of concrete was assessed by using the measured circumferential strain. For the SMA wire, the tensile behavior was rigid up to the stress of 147.1 MPa. After reaching the stress, the slope of the stress-strain curve can be adopted from Figure 1; the value was 30.8 GPa. Thus, the SMA wire under residual stress showed approximately bi-linear behavior, as presented in Figure 5. In the figure, ‘A’ and ‘B’ denote the stresses of the SMA wire corresponding to the bond strength and the maximum circumferential strain.

Table I. Circumferential strains and confining pressure.

Specimen	$\varepsilon_{\text{cir, bond}}$ (1.0×10^{-4})	$\varepsilon_{\text{cir, max}}$ (1.0×10^{-4})	$\Delta\tau_b^{\max}$ (MPa)	$\Delta\sigma_n$ (MPa)	f_j (MPa)	f_l (MPa)
SMA	4.61	12.28	4.4	6.57	161.3	11.4
ST-1.0	4.15	5.89	6.3	9.42	82.0	7.48
ST-1.5	2.65	3.69	6.6	9.86	53.0	7.16

The bond strength $\tau_b^{\max}$ consisted of two parts: (1) chemical adhesion and (2) frictional resistance due to confining action caused by concrete and external jackets:[10]

$$\tau_b^{\max} = \tau_{\text{adh.}} + (2\mu/\pi)\sigma_n \quad (2)$$

where $\tau_{\text{adh.}}$ was the strength associated with chemical adhesion, and μ and σ_n were the frictional coefficient and the normal confining pressure, respectively. The frictional coefficient ranged from 0.9 and 1.2,[10] and a mean value of 1.05 was selected in this study. The difference between the bond strengths of the PL specimen and the jacketed specimens (i.e., SMA, ST-1.0 and ST-1.5) corresponds to the strength increment due to confining pressure caused by the external jacket action, i.e., $\Delta\tau_b^{\max} = (2\mu/\pi)\Delta\sigma_n$, because the plain concrete specimens are unable to provide

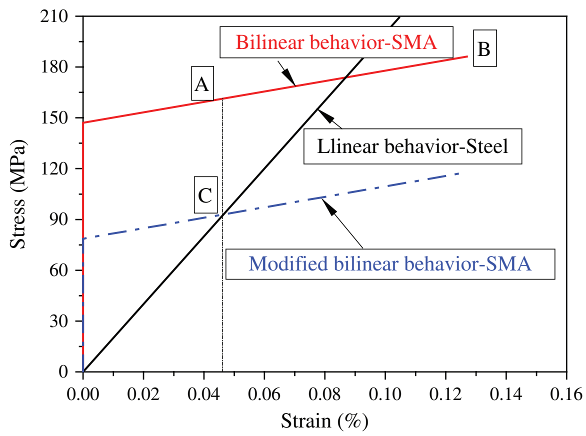

Figure 5. Bilinear behavior of the SMA wire.

confining action. The estimated normal confining pressure is shown in Table I. For the SMA wire jacket, the bond strength increment was relatively small; thus, the increased normal confining pressure was also smaller than that of the two steel-jacketed specimens. Note that the normal confining pressure on the bars can be calculated directly as follows (this is usually called lateral confining pressure, f_l):

$$f_l = \frac{2f_j A_j}{sd_b} \tag{3}$$

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where f_j and A_j are hoop stress in the jacket and the cross-sectional area of the jacket, respectively. Additionally, s is the spacing between wires, and the spacing of 1 mm was employed in this study. The hoop stress in the jacket can be calculated from the measured circumferential strain and the stress-strain behavior in Figure 1. The calculated values of f_j at bond strength are shown in the sixth column of Table I. The lateral confining pressure of the specimens was estimated using Eq. (3), and the value of the SMA wire jacket was 11.4 MPa, which was the largest among the three values. This result did not coincide with the calculated normal confining pressure. The bond strength of the SMA wire jacketed specimen was smallest; thus, the corresponding lateral confining pressure should be estimated as the smallest value. It appears that the residual stress of 147.1 MPa did not fully contribute to the generation of active confining pressure since there would be a small gap between the SMA wire and concrete surface, and then some residual stress was lost during tightening due to the shape memory effect.

In order to account for the residual stress loss of the SMA wire, the hoop stress of the SMA wire can be inversely estimated by using the normal confining pressure. In this case, the SMA wire stress corresponding to the bond strength was 92.9 MPa, which is marked as 'C' in Figure 5. After removal of the developed stress of 14.2 MPa due to strain from the 92.9 MPa, the remaining residual stress was then estimated as 78.7 MPa, which was 53.5% of the original value. The modified bilinear behavior of the SMA wire is shown in Figure 5. The contribution of the residual stress of 78.7 MPa in the SMA wire to increase the bond strength was 5.5 times larger than the developed stress of 14.2 MPa due to strain. Therefore, the estimated active confining pressure was 5.56 MPa, and the passive confining pressure was 1.01 MPa. Based on these observations, the contribution of active confining pressure of the SMA wire appears to be critical to increasing the bond strength.

For the steel jacket, there was a difference between normal $\Delta\sigma_n$ and lateral f_l confining pressure. It appears that there was uncertainty in the frictional coefficient and measurement of the circumferential strain. In particular, the circumferential strain increased abruptly around the bond strength; thus, it was not easy to capture the exact strain corresponding to the bond strength. The steel jackets showed similar bond strengths; thus, they provided similar lateral or normal confining pressure. Therefore, the circumferential strain of the 1.5 mm steel jacket was approximately 1.5 times smaller than that of the 1.0 mm steel jacket. In addition, it was found that increased confinement exceeding a critical value did not further increase the bond strength.

4. CONCLUDING REMARKS

This study analyzed the bond behavior between concrete and steel reinforcing bars with external jackets of steel plates or SMA wires. SMA wire jackets provided active confining pressure between concrete and reinforcing bars, while steel plates only provided passive confining pressure due to developed strain. The lateral confining pressure on steel reinforcing bars was directly estimated by using the measured circumferential strain, while the normal confining pressure was indirectly estimated by using the frictional coefficient. Note that the differences between the two estimated confining pressure values are observed, which could be resulted from the uncertainty of the frictional coefficient and measurement of the circumferential strain.

This study also found that almost half of the residual stress of the SMA wire appeared to be lost during the jacketing process. Thus, the active confining pressure induced by the residual stress was also reduced by half. Young's modulus of the SMA wire under residual stress was relatively small compared with that of steel; thus, the contribution of passive confining pressure of the SMA wire jacket to the improvement of the bond strength was not significant. However, active confining pressure of the SMA wire jacket was critical to increase the bond strength. The contribution of the active confining pressure was 5.5 times larger than that of the passive confining pressure. If the entire residual stress of the SMA wire were retained, the bond strength would increase further, which leads to improving the performance of an external jacket with SMA wires. Therefore, it is necessary to prevent loss of residual stress during the jacketing process with SMA wire.

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