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Confinement of Compressive Concrete Element with Nickel-Titanium Wires

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ABSTRACT In this research axial loading tests were conducted on RC concrete cylinders strengthened by prestressing shape memory Nickle-Titanium wires and significant results were obtained concerning the stress-strain curves, maximum stress, peak strain and initial young modulus (elastic modulus). These experimental results and test data would be an initial step toward the investigation of shape memory wires for the purpose of their application in the strengthening concrete columns.

1 INTRODOCTION

Designing more efficient building structures and strengthening the existing buildings which are exposed to different loading conditions, lead engineers to use flexible, adaptable and of course smart systems. Shape memory alloy (SMA) as a kind of these smart materials, have been known in recent decades and have not been used much in the building industry until very recently. Research on smart or intelligent material systems has been going on for over a decade. But it has been mainly in the field of mechanical engineering or focused on space structures. Recently the study of smart materials to apply to civil engineering has become a hot issue. To list some of these studies, health monitoring of members, self-repairing, actuating structural members are of interest. These aim to make the structures more highly characterized by using new technology and to make structural performance higher by using smart materials. We are studying the possibility of applying smart materials to civil structures from the viewpoints of strengthening the regular compressive members in reinforced concrete structures by using shape memory wires as a kind of theses smart materials. The first investigations on active confinement performance were done by applying the lateral confinement using a constant hydraulic pressure as an active confinement kept constant during the loading history [Harries, K. A. and Kharel, G (2002)]. The active confinement of concrete cylinders or reinforced concrete columns using martensitic, Ti-49.7Ni (at %), or austenitic, Ti-50.3Ni (at %), Nickle-Titanium wires is nearly a new idea that have been tested in this research. The recovery stress of the SMAs is utilized to apply the prestressing force in the spirals, which, in turn applies large active confining pressure on the column, the idea of this method has been proposed by Janke et all (2005) for the first time.

2 THEORETICAL BACKGROUND

Confinement can be categorized into two main types of active and passive confinement. For the confined concrete columns with steel reinforcement or external jackets, the nature of confinement is of passive type. In other words, the confining pressure is induced by the transverse dilation of concrete or the Poisson effect. In some cases of passive confinement, an initial active confining pressure may also be present, for instance by injecting an expansive grout between a column and an external jacket. However, the induced active pressure is small relative to the additional passive confinement engaged by the concrete dilation [Harries, K. A.; and Kharel, G (2003)].

The history of confinement goes back to as early as 1903, as A. Considère described the confinement effects on concrete columns. In the 1960s, Feeser and Chinn (1962), as well as Martin CW(1968) , examined concrete cylinders which were laterally prestressed in their study they used thin continuous wires. They showed that prestressing the wires delayed the deviation of the cylinder's axial load-deformation curve from the elastic behaviour curve. In other words, the elastic range was extended. They also reported that, in their experiments, the amount of prestress had only a slight influence on axial capacity. The ratio of initial confining pressure caused by prestress Ri to unconfined concrete compressive strength fc0 was between 0.01 and 0.41. In contrast, the extensive research of Gardner et al(1992) showed that prestressing continuous spiral confining wires can significantly increase the load-bearing capacity, even for columns under eccentric loads. Here, the ratio of Ri to f_{co} ranged from 0.12 to the rather high value of 0.74. Other studies of prestressed confinement include suggestions for technical implementation. Krstulovic, Opara and Thiedemann (2009) used post-tensioned shape-memory alloy (SMA) wires in order to increase the axial capacity of relatively small compact concrete cylinders. They suggested that lateral prestress reduces micro-crack formation, which corresponded with previous results of tri-axial testing [Mortazavi et al (2003)]. For the case of active confinement the general solution of a cylinder subjected to a determinate system of radial pressures and of axial shears over the curved surface was first analyzed by Filon(1902) and Priestley et al (1995), In order to calculate the confining pressure, the tensile strengths of the different materials are needed. For the ultimate strength of wrapping material, The equation from Xiao et al. (2000) is used:

$$\sigma_u = \frac{t}{a}\sigma_s \tag{1}$$

where: σ_u is confinement strength, σ_s is the ultimate strength of the jacket, t is the thickness of wrapping material, a is the radius of column. In active confinement the important variable in order to determine the behavior of a confined concrete column is the lateral confining pressure due to the action of the jackets. The confining pressure is not constant along the radial and the axial axes of the column and it is qualitatively assumed to have its lower value at the mid-section between the ties. The initial confining pressure on the concrete caused by prestress is calculated using Eq. σ_i (2)[Sheikh et al.(1982)]:

$$\sigma_i = \frac{T}{S.a} \tag{2}$$

where T being the mean tensile force during phase transformation of SMA spiral. Nominal T is the desired tensile force and S is pitch of spiral confinement and a is cylinder radius, S and a are 1 mm and 60 mm respectively in this research, The ratio of σ_i to f_{co} for the prestressed specimens in this research was between 0.12 and 0.17.

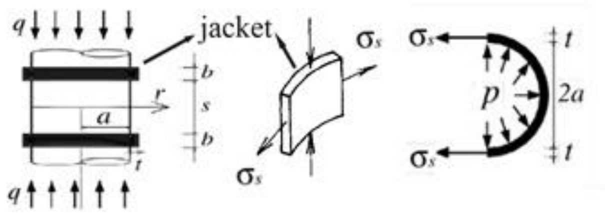

Figure 1: Cylinder loaded by axial pressure and confined by active lateral pressure [Mortazavi et al (2003)].

3 EXPERIMENTAL PROGRAM

3.1 Materials

3.1.1 Concrete Cores

The materials consumed in this study for casting unconfined concrete cylinders were typical kinds of Portland cement type I-425, aggregates with maximum size of 12.5 mm the mixture proportions were considered for normal strength. The mixture proportions of experimental specimens are presented in Table I. For obtaining normal strength concrete, cement content were 307kg/m^3 and w/c ratio was 0.6 respectively. The water content in the mixture were designed as to reach a consistent workability and a slump between 70 mm to 90 mm.

Cylinders with 120 mm height and 57.6 mm diameter were used to determine the compressive behaviour of unconfined concrete cores and also to provide cores with different strengths needed for jacketing. The mixing procedure for the concrete cores was the following: cement and aggregates were added and mixed, and then the concrete mixture was casted in the molds. Specimens were then covered with a wet burlap cloth, and were left in forms for 1 day. After demolding, all specimens were cured in the water at the room temperature for 28 days. The specimens needed for wrapping were left in the laboratory for another 7 days, while other specimens were capped and tested immediately.

Table 1-Formulation of the concrete mix used for the compression test

Grain size	Size distribution	kg/m^3
From 0 to 4 mm	50%	940
From 4 to 11.2mm	50%	940
Cement	CEM I-425	307
Water	Water–cement ratio = 0.6	187.3
Apparent density		2475

3.1.2 Ni-Ti Wires

The SMA wires were supplied by Phase Transformation Lab, School of Metallurgy and Material Engineering, University of Tehran. According to the supplier, the chemical composition of the wires was 50.2% nickel and 49.8 % titanium. The wire section was square in size of 1 mm×1mm. The conventional vacuum arc-melting technique with tungsten electrode on a water-cooled copper crucible was employed to prepare these alloys. After several remeltings for homogenization, the ingot was hot forged and then homogenized at 1273 K for 12 hrs. A rod mill was used for hot rolling at 1273 K from section size of 10 mm ×10 mm to 1 mm ×1 mm through 24 passes. The wire was cold-rolled to obtain reduction percentage of 20. For shape setting, the wire was fastened around the cylinder with 5.4 mm diameter then annealed at 773 K for 30 min.

Table 2- Material properties of the used SMA-wires (NiTi wire, diameter about 1 mm) obtained from the tensile tests

Parameter	Value
Martensite phase T _25 _C ultimate strength	800 MPa
Elastic modulus	25,000 MPa
Strain at yield strength	1 %
Austenite phase T _90 _C ultimate strength	800 MPa
Elastic modulus	40,000 MPa
Strain at yield strength	2.5 %

3.2 Preparing the Samples

SMA wires were stetted as a shape of spiral, were wrapped around the concrete cores (fig2). In order to fix the spiral around the cores and maintain the wire tension, steel anchoring clamps were mounted at the two ends of the concrete cylinders, these clamps were 20 mm high and 2 mm thick.

Table 3-Samples specification

Specimen	Compressive Strength (MPa)	SMA wrapped
Z1-A	20	no
Z1-B		no
Z2-A	20	no
Z2-B		yes
Z3-A	25	no
Z3-B		yes
Z5-A	25	no
Z5-B		Yes
Z7-A	25	no
Z7-B		Yes

3.3 Experimental Procedure

All specimens were tested by MTS universal machine and a data acquisition system. Loading was applied monotonically in a displacement control mode with a constant rate of 0.016 mm/sec, which corresponds to a strain rate of 0.008 per min. The load was applied to the entire cross section, including the concrete core and the SMA wrapping. The assembled computer data acquisition system was used to record the data. The acquired data included the applied axial load, P and the axial deformation of the concrete; the values of displacements between the loading plates were used for obtaining complete stress-strain curves. The specimens were loaded almost up to the strain at which all of the specimens were softened.

Figure 2: SMA wire wrapped around the concrete cores and anchored with steel clamps

4 EXPERIMENTAL RESULTS AND DISCUSSIONS

Axial stress versus axial strain curvatures of confined concrete are shown in Figs. 3(Z3 & Z7) for the specimens with two different unconfined concrete strengths. The average axial stress-strain relationships that obtained for unconfined concrete cylinders are also shown in Fig 4. As shown in this figures, the most interesting issue is the big deformation of SMA confined cylinders in comparison with unconfined samples, also shown that the initial portions of stress-strain responses of the confined concrete is linear. After achieving the unconfined concrete strength, the axial stress–strain relationships of most of the specimen show that softened and exhibited an almost big linear deformation without change in stress, then a new increasing in

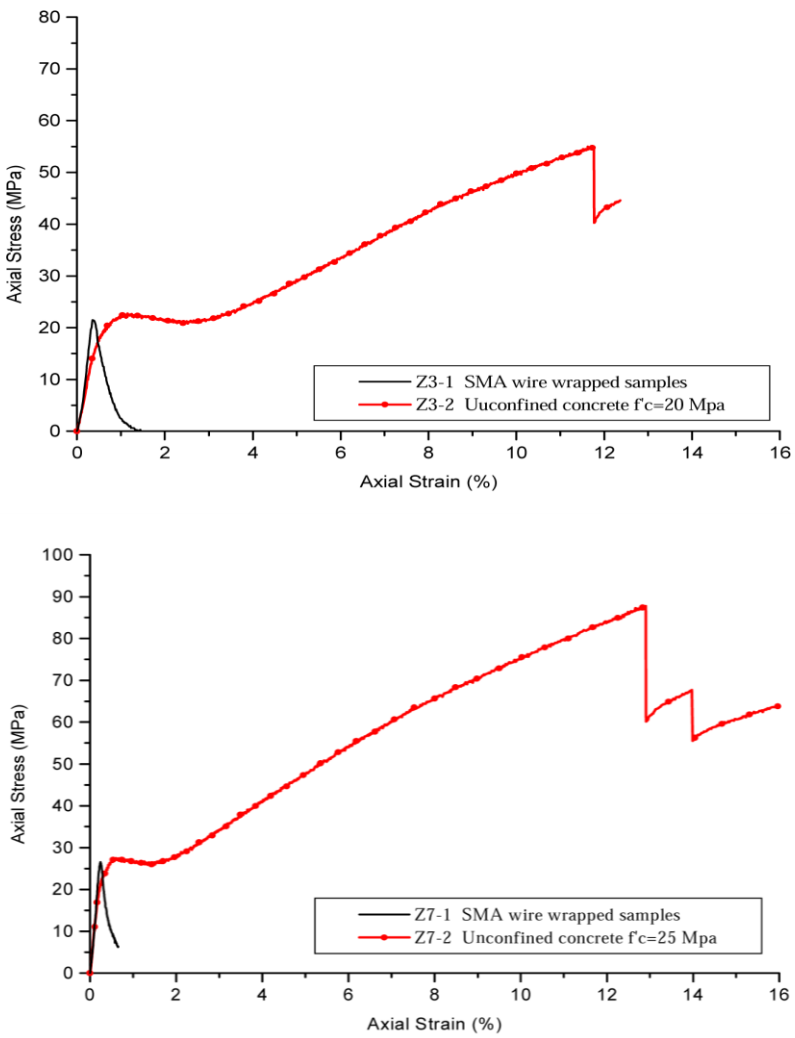

Figure3: Axial stress-strain curves of unconfined and confined cylinders for reference cylinder strength of Z3) f'c=20 Mpa and Z7) f'c=25 Mpa

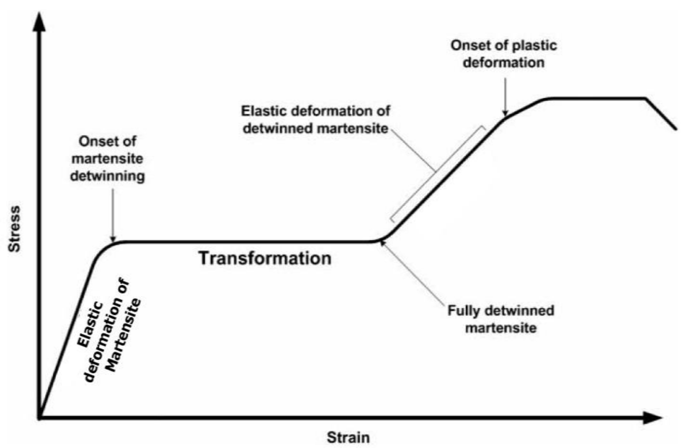

Figure 4: Simplified deformation of martensite [Evans et al.(2008)]

stress occurred similar to the strain linearly until the first rupture in SMA spiral. Such behavior of concrete confined in superelastic materials after exceeding unconfined concrete strength has not been reported yet. This behavior is almost similar to the stress-induced phase changes of the original Nitinol when loaded from a parent martensitic phase (Fig.4). on the initial loading, the material is fully austenite and behaves in a linear elastic manner. However, at the strain of one percent, there is a departure from linearity that marks the initiation of martensite formation. The transformation process is characterized by a plateau region where the material has a low Young's modulus and extends, typically to a strain of 5 percent, where the confinement material is composed fully of detwinned martensite [Evans et al. (2008)].

As shown in Fig.3, further deformation after the first rupture in SMA spiral, the stress-strain curvature around the strain of 15%, shows several drops and rises and the model does not collapse completely (i.e., the test operator had to be wait for a long time thus the test machine had been stopped manually before complete failure). It seems that, confining pressure continues after these drops and increased again. This phenomenon can be interpreted as Poisson effect on the concrete cores i.e., after a rupture in the wire the spiral untied and the core is unconfined for a moment but by further deformation concrete develops a tendency to expand laterally due to the Poisson's effect. Lateral expansion generates transverse tensile strains and longitudinal splitting cracks which eventually result in next rupture in the wire. Lateral expansion of concrete is counteracted by passive confinement pressure exerted by SMA jacket. The resulting confinement action enhances both the strength and deformability of concrete. Results showed that applying the confining pressure using the Ni-Ti SMA wires improved the ultimate compressive strength and ductility of the concrete cylinders at least by 200% and 500 %, respectively. Table 4 shows the mechanical properties of confined and unconfined concrete cylinders in two different compressive strengths.

Table 4- Mechanical properties of confined and unconfined concrete cylinders (Results of compressive strength tests).

Sample	Compressive strength (MPa)	Final strain (%)	Absorbed energy (KJ/m^3)	Elastic Modulus (GPa)
Z7 Confined	55	11.5	4100	20
Z7 Unconfined	20	0.25	32	19
Z5 Confined	75	12.5	6300	24
Z5 Unconfined	25	0.3	39	23

5 CONCLUSION

Prestressing force in the spirals, did not apply large active confining pressure on the column, because the wires was locally prestrained and did not apply big active confinement force, indeed post tensioning has caused passive confinement and further enhancement in axial bearing load, this caused increase in stiffness, ductility and strength of compressive concrete cores. Results showed that applying the confining pressure using the Ni-Ti SMA wires improved compressive strength and ductility of the concrete cylinders by 200% and 500%, respectively. The results of experimental and theoretical approaches for axial stress-strain and confinement pressure can be used in lateral cyclic and monotonic behaviour assessment of columns energy dissipation, and residual stiffness of the column that is actively confined with SMA spirals be compared to the unretrofitted and other confined columns. The experimental results and test data are of initial steps toward the investigation of Nickle-Titanium wires for the purpose of their application in strengthening concrete columns.

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