Fracture Mechanics of Concrete and Concrete Structures -
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Experimental investigation of compressive concrete elements confined with shape memory Ni-Ti wires

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ABSTRACT: Strengthening of columns is of great importance in repair and retrofit of concrete structures since the failure of a column has serious consequences for structural stability. Strengthening of concrete cylinders with shape memory alloys to improve their ductility and compressive behavior is nearly a new idea. According to this approach, upon external heating, a martensite-to-austenite phase transformation takes place and the material undergoes large shrinkage strains. This strain energy can be used to generate a significant prestreessing force in concrete. In this research axial loading tests were conducted on RC concrete cylinders strengthened by prestressing SMA wires, after transforming from martensite to austenite phase by actuating them and significant results were obtained concerning the stress-strain curve, maximum stress, peak strain and initial young modulus (elastic modulus). The experimental results and test data would be an initial step toward the investigation of shape memory wires for the purpose of their application in strengthening concrete columns.

1 INTRODOCTION

Designing more powerful structures and strengthening the existing buildings in different 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 rather 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 mechanic 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.

It is well known that both strength and ductility of concrete compressive members can be greatly improved by confinement using some kind of 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 [1]. Active confining the concrete cylinders or reinforced concrete columns using martensitic, Ti-49.7Ni (at %), or austenitic, Ti-50.3Ni (at %), shape-memory-alloy wires is nearly a new idea that have been proposed and 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 in 2005 by Janke et all. [2] for the first time.

2 THEORETICAL BACKGROUND

Confinement can be categorized into two main types of active and passive confinement. For the 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 [3].

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 [4], as well as Martin [5], 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 R_i to unconfined concrete compressive strength fc_0 was between 0.01 and 0.41. In contrast, the extensive research of Gardner et al.[6] 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 fc0 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 [7] 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 [8].

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 [9,10], 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. [11,12] 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 σ_i is calculated using Equation (2)[13]:

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

with 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 fc_0 for the prestressed specimens in this research was between 0.12 and 0.17.

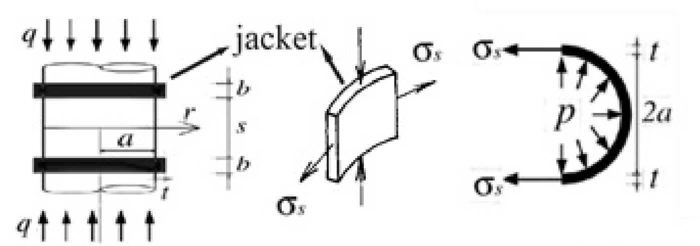

Figure 1.Cylinder loaded by axial pressure and confined by active lateral pressure.

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 concrete cores was the following: cement and aggregates were added and mixed, 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/m3
0...4 mm	50%	940
4...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 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*

As SMA wires were stetted as a shape of spiral, were wrapped around the concrete cores(Fig. 2). 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.

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, includeing 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 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 3 shows the test set up with a concrete cylinder under compressive loading.

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

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 Figurs 5(a- c) for specimens with two different unconfined concrete strengths. The average axial stress-strain relationships that obtained for unconfined concrete cylinders are also shown

Figure 3. (a) MTS universal machine, (b) Test setup.

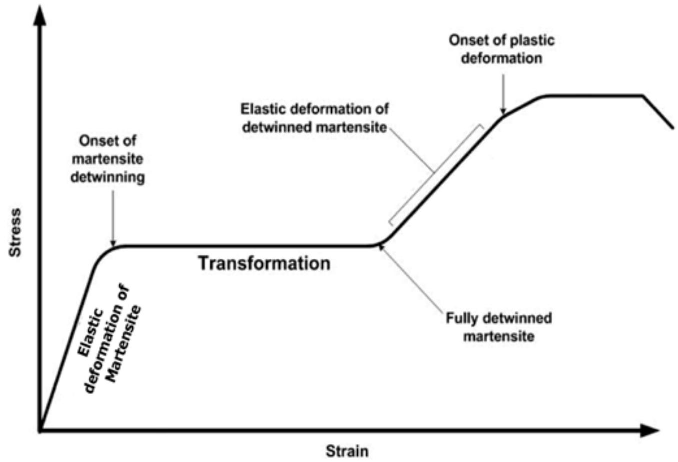

Figure 4. Simplified deformation of martensite.

in Figure 5. As shown in this figure, 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–axial strain relationships of most specimens shows that softened and exhibited an almost big linear deformtion without change in stress, then a new increasing in stress was happened similar to 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 stress-induced phase changes of original Nitinol when loaded from a parent martensitic phase(Fig. 4), on initial loading, the material is fully austenite and behaves in a linear elastic manner. However, at a strain of 1 per cent, 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 [14].

By further deformation after the first rupture in SMA spiral, on about 16% axial strain stress-strain curvature shows some drops and rises occurred, it seems that confining pressure was continued after these drops and increased again after every drops and this occurs several times, this makes some post peaks in the curvatures. Results showed that applying the confining pressure using the Ni-Ti SMA wires improved ultimate compressive strength and ultimate strain of the concrete cylinders at least by 200% and 1500 %, respectively.

5 CONCLUSION

Prestressing force in the spirals, did not applies 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 ultimate strain of the concrete cylinders by 200% and 1500%, respectively.

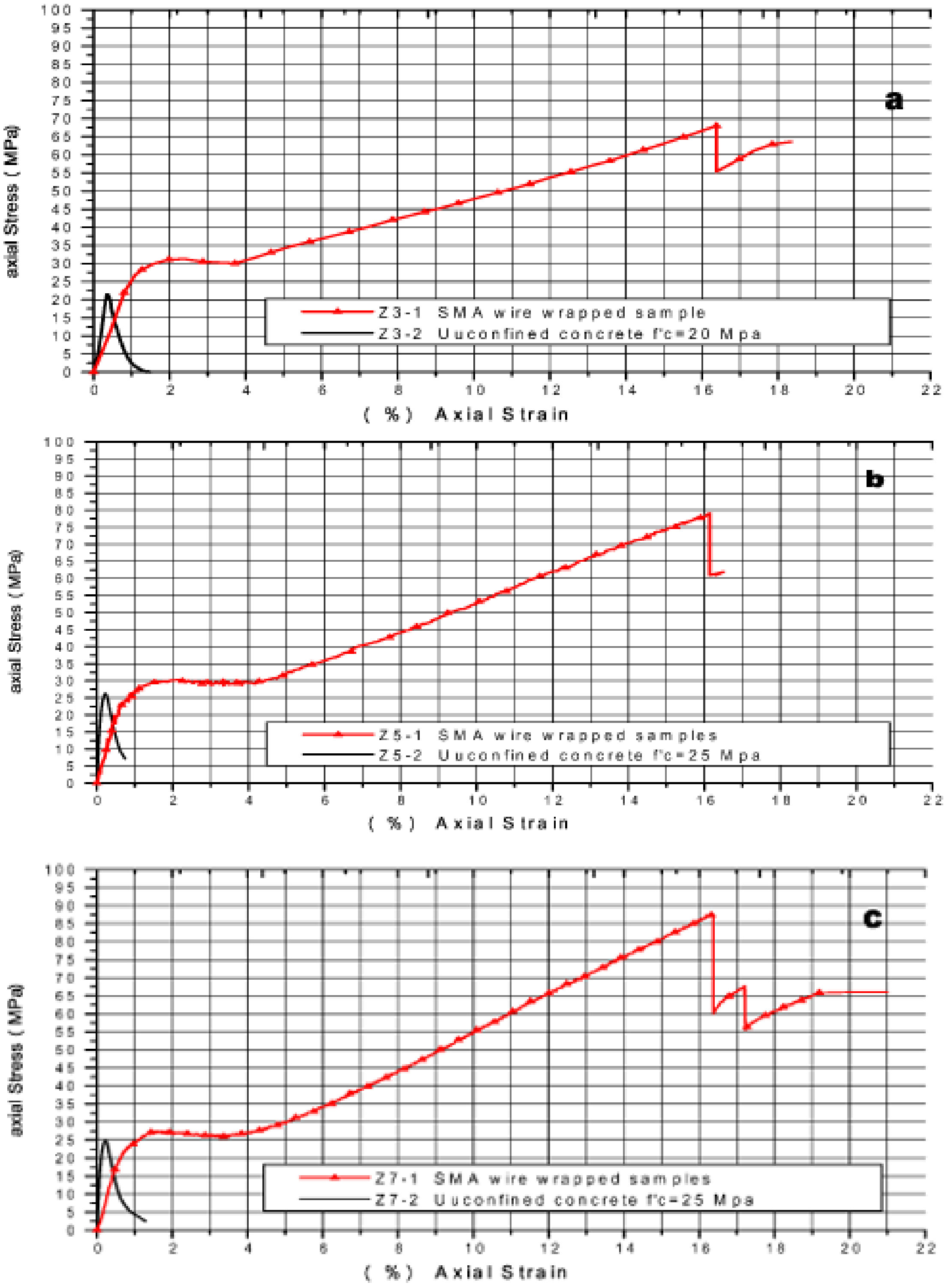

Figure 5. Axial stress-strain curves of unconfined and confined cylinders for reference cylinder strength of (a) f'c=20 Mpa and **(**b,c) f'c=25 Mpa.

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 compare to the unretrofitted and other confined columns.

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