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Health monitoring and rehabilitation of a concrete structure using intelligent materials

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Abstract
This paper presents the concept of an intelligent reinforced concrete structure (IRCS) and its application in structural health monitoring and rehabilitation. The IRCS has multiple functions which include self-rehabilitation, self-vibration damping, and self-structural health monitoring. These functions are enabled by two types of intelligent (smart) materials: shape memory alloys (SMAs) and piezoceramics. In this research, Nitinol type SMA and PZT (lead zirconate titanate) type piezoceramics are used. The proposed concrete structure is reinforced by martensite Nitinol cables using the method of post-tensioning. The martensite SMA significantly increases the concrete's damping property and its ability to handle large impact. In the presence of cracks due to explosions or earthquakes, by electrically heating the SMA cables, the SMA cables contract and close up the cracks. In this research, PZT patches are embedded in the concrete structure to detect possible cracks inside the concrete structure. The wavelet packet analysis method is then applied as a signal-processing tool to analyze the sensor signals. A damage index is defined to describe the damage severity for health monitoring purposes. In addition, by monitoring the electric resistance change of the SMA cables, the crack width can be estimated. To demonstrate this concept, a concrete beam specimen with reinforced SMA cables and with embedded PZT patches is fabricated. Experiments demonstrate that the IRC has the ability of self-sensing and self-rehabilitation. Three-point bending tests were conducted. During the loading process, a crack opens up to 0.47 inches. Upon removal of the load and heating the SMA cables, the crack closes up. The damage index formed by wavelet packet analysis of the PZT sensor data predicts and confirms the onset and severity of the crack during the loading. Also during the loading, the electrical resistance value of the SMA cable changes by up to 27% and this phenomenon is used to monitor the crack width.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Recent years have seen increasing research efforts in using shape memory alloy (SMA) materials, in particular Nitinol, for civil structural controls. It has been demonstrated that the SMA in forms of bars, wires, and rods can be used as anchorages, isolators, braces, restrainers, and connection elements for civil structures. Tamai *et al* (2003) demonstrated the advantage of a 10 mm diameter SMA bolt anchorage for a concrete column over a conventional steel anchorage. Wilde *et al* (2000) utilized SMA bar dampers to form an isolation system for elevated highway bridges. DesRoches and Delemont (2002) applied a full-scale SMA restrainer in a simply supported bridge for seismic retrofit. Leon *et al* (2001) utilized 30 mm diameter SMA tendons to enhance steel beam–column connections. On the other hand, health monitoring of civil structures using piezoceramics receives equal attention. Soh *et al* (2000) surface-bonded piezoceramic patches to carry out health monitoring during the destructive load testing of a prototype reinforced concrete (RC) bridge. Saafi and Sayyah (2001) proposed the so-called active damage interrogation (ADI) technique to conduct health monitoring of composite reinforced concrete structure. Song *et al* (2004) conducted health monitoring of a 6.1 m long reinforced concrete bridge bent-cap by imbedding four PZT transducers inside one end of the concrete. The experiment result proves that the proposed method can predict the onset of cracks.

In this paper, by taking the advantage of shape memory alloy and piezoceramics, the concept of intelligent reinforced concrete structure (IRCS) is proposed. The structure is reinforced with martensite SMA cables via post-tensioning. The martensite SMA cables can experience large elongation via recoverable plastic deformation and absorb energy during this process. Heating the SMA cables causes their own contraction and closes the crack in the IRCS. Embedded PZT patches along with the wavelet packet analysis method are used to detect the onset and severity of cracks in the structure. In addition, the value of the electrical resistance of the SMA cables can also be used to estimate the crack width. The IRCS therefore has multiple functions, which include self-rehabilitation, self-structural health monitoring, and self-vibration damping. A concrete beam specimen with reinforced SMA cables and with embedded PZT patches is fabricated and experiments are performed to demonstrate its ability of self-sensing and self-rehabilitation.

2. Concepts of intelligent concrete structures

This paper presents the concept of intelligent reinforced concrete structure (IRCS) using shape memory alloys and piezoceramics. The IRCS has multiple functions which include self-rehabilitation, self-vibration damping, and self-structural health monitoring. These functions are enabled by two types of smart materials: the piezoceramics and shape memory alloys (SMAs). In this research, a special type of piezoceramic called PZT (lead zirconate titanate), which possesses a strong piezoelectricity effect, and a special type of SMA called Nitinol, which has good corrosion resistance and large actuation stress, will be used. By taking advantage of the shape memory effect of Nitinol, this approach uses martensite SMA and wire cables. The proposed concrete structure is reinforced by martensite Nitinol cables using the method of post-tensioning. The martensite Nitinol significantly increases the concrete's damping property and its ability to handle large impact. In presence of cracks due to explosions or earthquakes, by electrically heating the SMA cables, the SMA cables contract and close up the cracks.

PZT can be used as both an actuator to emit signals in a wide frequency band and as a sensor to receive these signals. In this research, PZT patches are embedded in the concrete structure. In the process to detect possible internal cracks inside the concrete structure, a PZT patch is used as an actuator to generate waves and other distributed PZT patches are used as sensors to record the received vibration signals. The wavelet packet analysis method is then applied as a signal-processing tool to analyze the recorded sensor signals. The energy vector and damage index are defined to describe the damage severity for health monitoring purposes. In addition, by monitoring the electric resistance change of SMA cable, the elongation of the SMA cable and the crack width can be estimated. This information can also be used for health monitoring.

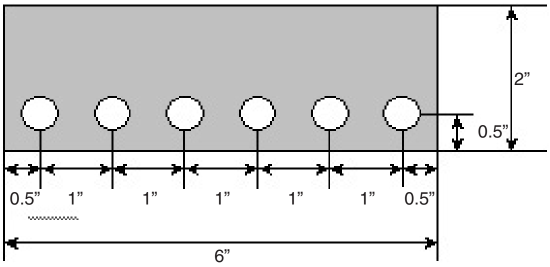

Figure 1. Cross-section view of the specimen.

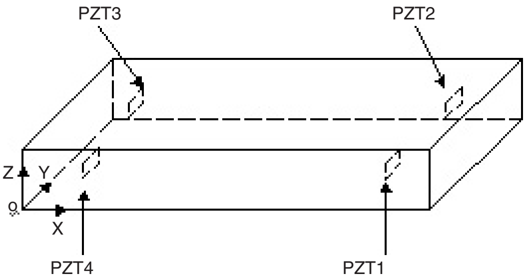

Figure 2. The spatial position of the PZT transducers.

3. Specimen and experimental set-up

3.1. The specimen

To verify the concept of IRCS, a specimen of a concrete beam or slab with dimensions of 13.5 × 6.0 × 2.0 inch^3 was reinforced with martensite Nitinol SMA wire cable using the post-tensioning method. The SMA wire has a diameter of 0.015 inch and has transformation temperatures of 90 °C Af (austenite finish temperature). The SMA wire has a 0.2 Ω inch^{-1} resistivity under no mechanical or thermal loading. The wires are grouped into strands/cables of seven wires for a total diameter of 0.045 inch. A total of six cables are placed into the specimen via pre-cast conduits. The six conduits to accommodate SMA cables are 0.5 inch in diameter. The layout of these six conduits is shown in figure 1. The spacing between the cables is 1 inch in the cross-section view. For the convenience of electrically actuating the six SMA cables, they are serially connected. Special fixtures have been fabricated to assist the post-tensioning procedure. During post-tensioning of the specimen, the SMA cables are strained by 2%. The SMA cables can be heated through electrical resistance or Joule heating. The temperature of the cables is monitored by thermocouples bonded to the cables. Four PZT transducers (PZT1, PZT2, PZT3 and PZT4) are embedded into the specimen for structural health monitoring purposes as shown in figure 2. Their detailed spatial coordinates are shown in table 1. During a health monitoring process, one PZT transducer will be used as an actuator to generate a wave signal,

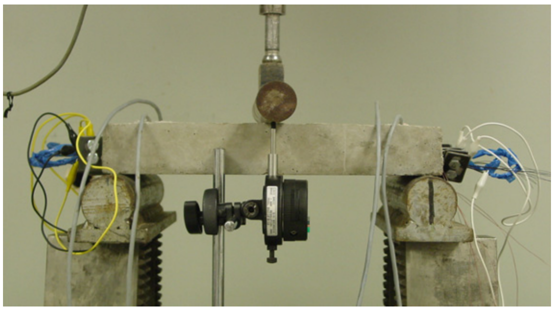

Figure 3. Three-point bending test of an IRC specimen.

Table 1. Spatial coordinates of the PZT transducers.

	X	Y	Z
PZT1	12.00″	1.50″	1.25″
PZT2	11.31″	4.75″	1.25″
PZT3	1.88″	4.50″	1.25″
PZT4	1.75″	1.625″	1.25″

and the other three will be used as sensors to receive the signals of the induced vibration. If cracks occur between the actuator and the sensor, the strength of the signal detected by the sensor will decrease. It is worthwhile to point out that any one of these four PZT transducers can be used as actuators or sensors.

3.2. The experimental set-up

To test the self-sensing and self-rehabilitating capacity, the specimen is subjected to a three-point bending test, as shown in figure 3. The test will be conducted till the concrete specimen has a large crack. The span between the bottom two supports is 12 inch. The three-point bending test in this configuration will normally induce a crack at the middle plane of the beam. The central deflection of the beam is measured by a digital displacement gauge arranged between the specimen and a reference point on the non-moving frame of the testing machine. To electrically heat the SMA cables, a programmable power amplifier (Agilent model No 6542A) is used in the experiment. A high voltage amplifier is used as the amplifier to actuate piezoelectric transducers. A computer based real-time digital data acquisition system is used to record experimental data.

4. Piezoelectric patch based health monitoring method

Four piezoceramic patches (transducers) were embedded into the concrete before casting for health monitoring purposes. One embedded piezoceramic patch is used as an actuator to generate waves and the other piezoceramic patches are used as sensors to record the received vibration signals. In this paper, the wavelet packet analysis method is applied as a signal-processing tool to analyze the sensor. An energy vector is formed based on the wavelet packet analysis. The damage index is formed by calculating the root-mean-square deviation (RMSD) between the healthy-state energy vector and damage-state energy vector.

4.1. Background of wavelet packet analysis

Wavelet packet analysis is used as signal-processing method to analyze the sensor signal. In wavelet analysis, a signal is split into an approximation and a detail. The approximation is then itself split into a second-level approximation and detail, and the process is repeated. In wavelet packet analysis, the details as well as the approximations are split.

4.2. The formation of the damage index

4.2.1. Energy vector. Samuel and Pines (2001) utilized a normalized energy metric based on wavelet packet analysis for the fault classification of helicopter gearbox. In this paper, a energy vector is directly used instead of the normalized energy vector. The sensor signal S is decomposed by an n-level wavelet packet decomposition into 2^n signal sets $\{X_1,\ X_2, \ldots, X_{2^n}\}$ with

$$X_j = [x_{j,1}, x_{j,2}, \ldots, x_{j,m}], \tag{4.1}$$

where m is the number of sampling data.

The energy of the decomposed signal, $E_{i,j}$, is calculated as

$$E_{i,j} = \|X_j\|_2^2 = x_{j,1}^2 + x_{j,2}^2 + \cdots + x_{j,m}^2 \tag{4.2}$$

where i is the time index (window index), and j is the frequency band ($j = 1 \ldots 2^n$).

The energy vector at time index i is given as

$$E_i = [E_{i,1}, E_{i,2}, \ldots, E_{i,2^n}]. \tag{4.3}$$

4.2.2. Damage index. RMSD is a suitable damage index to compare the difference between the signatures of the healthy state and a damage state. In this paper, the damage index is formed by calculating the RMSD between the energy vectors of the healthy state and the damage state. The energy vector for the healthy state is $E_h = [E_{h,1}, E_{h,2}, \ldots, E_{h,2^n}]$. The energy vector for the damage state at time index i is $E_i = [E_{i,1},\ E_{i,2}, \ldots, E_{i,2^n}]$. The damage index at time i is defined as

$$I = \sqrt{\sum_{j=1}^{2^n} (E_{i,j} - E_{h,j})^2 \bigg/ \sum_{j=1}^{2^n} E_{h,j}^2}. \tag{4.4}$$

5. Experimental results

5.1. The experimental process

Using the experimental set-up as shown in figure 3, the load for the three-point bending test is first incrementally increased at 100 lb per step till the concrete beam experiences a brittle fracture (crack). After the crack appears, the load will be dramatically reduced due to the crack of the beam. The specimen will be subjected to the second phase of loading. During this phase, the load will be increased at a much less increment (20 lb per step). With the increase of the load, the martensite SMA wires will be elongated and the crack will be widened. The increase of the load will be stopped when the crack width at the bottom surface reaches 0.47 inch, which corresponds a 0.36 inch elongation of the SMA cables (13.5 inches long). Including this elongation and the 2% strain

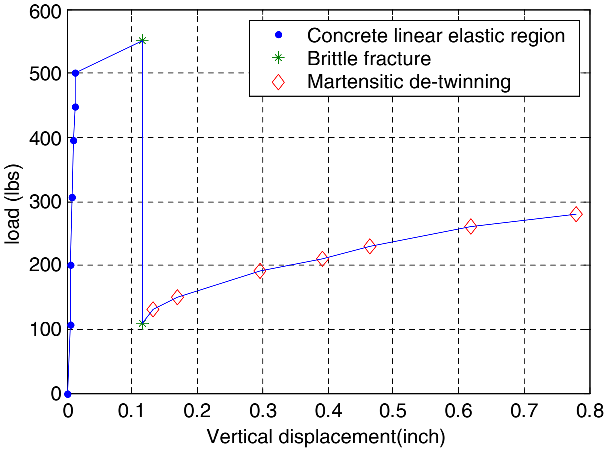

Figure 4. Load versus vertical displacement.

of the SMA cables during the post-tensioning process of the concrete beam, the SMA cables will experience a maximum strain just slightly under 5%, which is a suggested ceiling value for repeated operations. After this crack width is achieved, the load will be removed and the crack remains. In reality, a concrete structure may experience large cracks in cases of earthquakes or explosions. In the next stage, the concrete beam will experience the rehabilitation process to close up the crack.

To close up the crack, the SMA cables will be electrically heated at the phase transformation temperature of 90 °C. This will enable the transformation of the de-twinned martensite to austenite, accompanied by the contraction of the SMA cables and the close-up of the crack. The heating of the cables is accomplished by Joule heating.

5.2. Experimental results

The experiments are conducted as described in the previous section. The load–vertical deflection curve of the beam without using electric current is shown in figure 4. The first portion of the curve is linear and corresponds to the elastic deformation of the beam. Concrete is a brittle material; therefore it breaks without any previous plastic deformation. This phenomenon can be observed in this figure by the sudden drop in load that follows the linear elastic deformation of the concrete. After the fracture, with the increase of the load, the crack continues to widen. This results in the elongation of the SMA cables, which corresponds to the de-twinning of the martensite SMA cables. During the elongation process, the SMA cables absorb external energy and increase the damping of the structure. The axial displacement, or elongation, of the cables can be calculated from the vertical displacement. The increase of the load stops when the crack width at the bottom surface reaches 0.48 inch, which corresponds to about a total of 5% strain of the SMA cable.

Figure 5 shows the crack with a width of 0.48 inch at the bottom surface. Figure 6 shows that this crack closes up after applying electrical current to heat the SMA cables to just above 90 °C. This demonstrates the rehabilitation capacity of this concrete beam reinforced by martensite SMA cables.

Figure 5. During loading: the crack can be obviously seen.

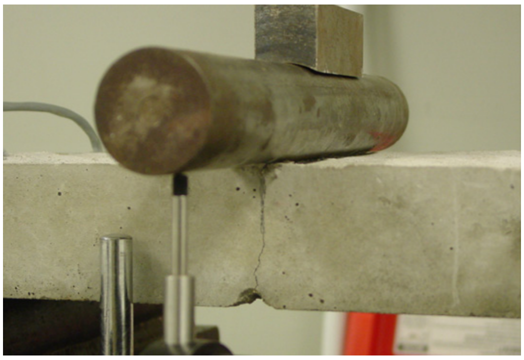

Figure 6. After heating: the crack closes up.

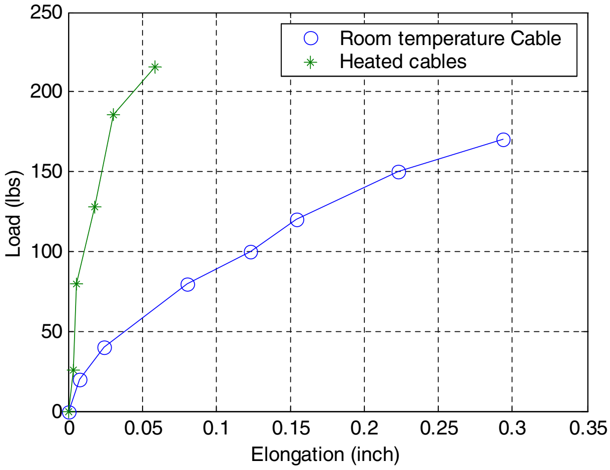

Figure 7. Elongation of the SMA cables.

After the close-up of the crack using electric currents, three-point bending tests continue on the beam in two situations: with and without the applied currents. Figure 7 shows the experimental results in terms of the relationship between the applied load and the elongation of the SMA cables (the crack width where the SMA cables are located). Comparing these two curves, it is clear that the case with the heated cable has a much larger Young's modulus than the case without heating the cable. This results from the fact the austenite SMA cable at high temperature is much stronger than its martensite counterpart at a lower temperature.

Table 2. Tests used for health monitoring using PZT transducers.

Test No	Load (lb)	Displacement (inch)	Test No	Load (lb)	Displacement (inch)
1	0	0	10	150	0.169
2	107	0.0055	11	190	0.2958
3	200	0.0062	12	210	0.3915
4	300	0.0074	13	230	0.4642
5	400	0.0114	14	260	0.6198
6	450	0.0127	15	280	0.7794
7	500	0.0137	Test 16: SMA is heated; load is 676 lb		
8	550	0.115	Test 17: no load; SMA is fully heated; crack closes		
9	130	0.1324	Test 18: crack partially open, no heating		

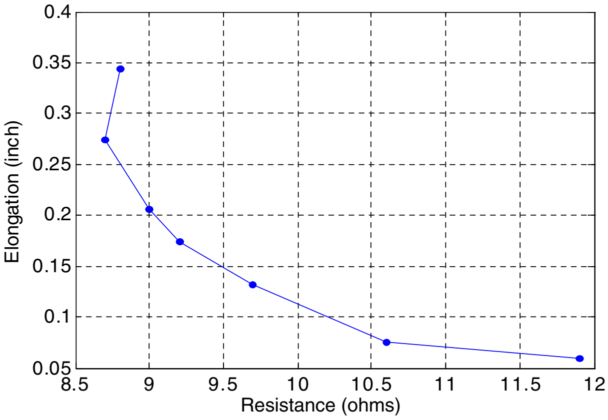

Figure 8. Elongation versus electrical resistance.

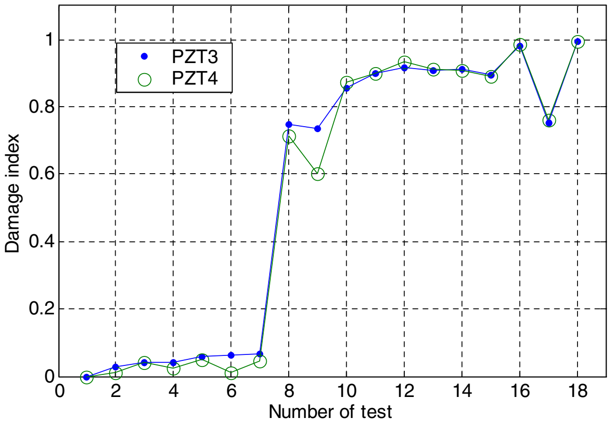

Figure 9. The damage index of PZT3 and PZT4.

For health monitoring purposes, two methods are used. The first one monitors the electrical resistance value of the SMA cables during the loading process. Figure 8 shows the relationship between the elongation and the electric resistance of SMA cables during the loading process, which corresponds to their martensite de-twinning. It is noticed that the electrical resistance value decreased with the elongation of the SMA cables and the reduction of the electric resistance value is about 27%. The electrical resistance value of SMA cables can be used to estimate the crack width and help to determine when to heat the SMA cables for rehabilitation purposes.

The second health monitoring method uses the embedded PZT patches. As the exciting signal source for the piezoelectric actuator, a sweep sinusoidal signal with a frequency range from 100 Hz to 10 kHz is used. The sampling frequency for the data acquisition system is 40 kHz. A PZT patch can act as both an actuator and a sensor. In this experiment, PZT1 is used as an actuator and both PZT3 and PZT4 are used as sensors. Figure 9 shows the values of damage indices produced using data from PZT3 and PZT4 during the tests, whose detailed information are shown in table 2, in different phases of the experiments. The formulas in section 4.2 are used to calculate the values of the damage indices. Since the crack grows in the middle plane of the beam, the results from both PZT3 and PZT4, which are on the same side of the crack, should be similar. Figure 9 confirms the similarity of these two damage-index curves.

From figure 9, it is clear that the values of the damage indices start from zero and increase slowly with the load increase till reaching test 7. Small values of damage indices indicate that there are no cracks in the specimen. Between test 7 and test 8, the values of the two damage indices increase 800%, which indicates the onset of the crack. This indication is consistent with experimental observation. From test 9 to test 16, the damage indices slowly increase with the load increase till the damage indices reach 1.00, which means 100% loss of transmission energy. In test 17, the SMA cables are heated and the crack closes up. The damage indices drop to 0.77, which indicates an increase in transmitted energy due to the reduction of the crack width. In test 18, the damage indices return to 1.00, which indicates the crack opens again. This also confirms the real status of the beam—the crack opens and SMAs are not heated.

6. Conclusions

This paper presents a new concept of intelligent reinforced concrete structure (IRCS) by using shape memory alloys and piezoceramics. The structure is reinforced with martensite SMA cables via post-tensioning. The martensite SMA cables can experience large elongation via recoverable plastic deformation and absorb energy during this process. In the case of crack appearance in the structure, heating the SMA cables will close the crack. Embedded PZT patches along with the wavelet packet analysis method are used to detect the onset and severity of cracks in the structure. In addition, the value of the electrical resistance of the SMA cables can also be used to estimate the crack width. A concrete beam specimen with reinforced SMA cables and with embedded PZT patches is fabricated. Experiments are performed and successfully demonstrate the ability of self-sensing and self-rehabilitation of the IRCS.

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