IOP PUBLISHING SMART MATERIALS AND STRUCTURES
Smart Mater. Struct. **17** (2008) 025020 (7pp) doi:10.1088/0964-1726/17/2/025020

Self-repairing performance of concrete beams strengthened using superelastic SMA wires in combination with adhesives released from hollow fibers

Yachuan Kuang[1,2] **and Jinping Ou**[2,3]

[1] School of Civil Engineering and Architecture, Central South University, Changsha, Hunan 410075, People's Republic of China
[2] Dalian University of Technology, Dalian, Liaoning 116024, People's Republic of China
[3] School of Civil Engineering, Harbin Institute of Technology, Harbin, Heilongjiang 150090, People's Republic of China

E-mail: kuangyachuan@mail.csu.edu.cn

Received 12 April 2007, in final form 5 December 2007
Published 19 February 2008
Online at stacks.iop.org/SMS/17/025020

Abstract

By taking advantage of the superelastic effect of shape memory alloy (SMA) and the cohering characteristic of repairing adhesive, a smart self-repairing concrete beam with damage self-repairing performance has been developed. In order to verify the potential self-repairing capacity of smart concrete beams reinforced with SMA wires and brittle fibers containing adhesives, static loading tests were conducted. Experimental results show that the superelastic SMA wires added self-restoration capacity to concrete beams, the deflection of the beams reversed and the crack closed almost completely after unloading. After the release of adhesive from the broken-open fibers into the cracks from the first loading, stress was redistributed to the uncracked section where a new crack was formed, while the sealed crack remained closed during reloading for the smart concrete beams reinforced with SMA wires and brittle fibers containing adhesives. While the original cracks experienced reopening, the load was carried directly by the wires during reloading for concrete beams reinforced with SMA wires.

1. Introduction

Concrete is a widely used structure material. Generally, reinforced concrete structural members combine the compressibility of concrete with the tensile characteristic of reinforcing steel bars, enabling these members to resist compression, bending, and shearing forces. However, these concrete members can suffer permanent damage after incurring great deformation, manifested as cracking in the concrete and buckling of the reinforcing bars. Therefore, repairing damage and cracks, and ensuring the safety and reliability of the structural system, are essential for large-scale and important concrete structures when the structures are still in-service.

Due to the demand for repairing damage and cracks in real time, ensuring the safety and reliability of concrete structures, self-repairing concrete has become a very important research topic and has been developed rapidly in recent years. Self-repairing concretes have embedded adhesives which are released from hollow fibers inside the concrete when and where cracking of the matrix and the fibers occurs [1–7]. It has been shown that the adhesive effectively improves the strength of cracked portions of the concrete and increases its ability to deflect in a ductile manner under loading. However, the width of the tensile cracks in such materials cannot be easily tuned. Localized fracture leads to continued increases in crack width under decreasing tensile loading, and rapidly exhausts the amount of chemical available for crack sealing and concrete rehealing. Thus, for the proposed self-repairing concept to work, it is critical that the tensile crack width be controlled. Otherwise, large hollow fibers will be needed, which in turn negatively modify the mechanical properties of the concrete.

Shape memory alloy (SMA) exhibits stable superelasticity above a reverse transformation finish temperature, and therefore can adequately work as a superelastic material to

0964-1726/08/025020+07$30.00

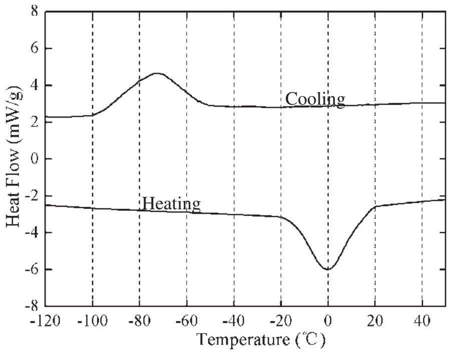


Figure 1. DSC curve for titinol SMA.

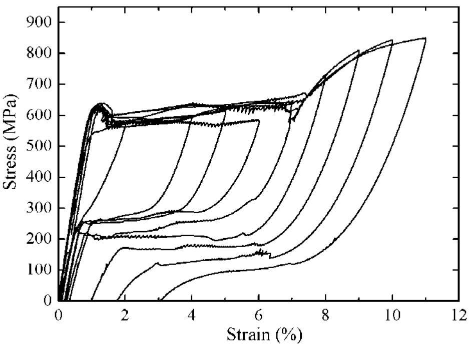


Figure 2. Stress–strain curves of SMA wire.

handle macro-size cracks for structural use in buildings [8–11]. This motivates us to develop a type of a smart self-repairing concrete to increase the survivability in the case of earthquakes and typhoons, and maintain structural durability by regaining mechanical properties (repairing) and water tightness (sealing) of concrete structures, in combination with the deflection self-restoration characteristics of the SMA wires and the adhesive due to the cohering characteristic. The concrete becomes smart since it has the ability to self-repair.

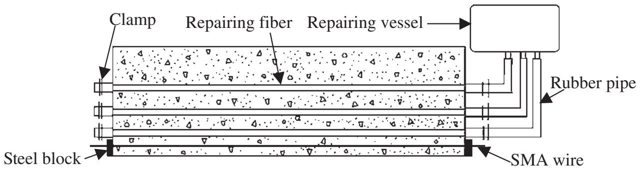


Figure 3. Smart self-repairing concrete using embedded SMA wires and fibers containing adhesives.

2. Superelasticity of SMA and smart self-repairing concrete

2.1. *Characteristics of materials*

Shape memory alloy (SMA) is a smart material with two useful forms: a shape memory form which enables a prescribed shape change upon heating, and a superelastic form. Recent years have observed increasing research efforts in using shape memory alloy materials for civil structures to survive extreme events such as earthquakes [12–16]. The most common shape memory alloy is an alloy of nickel and titinol called nitinol. This particular alloy has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance.

The transformation temperature is set for SMA to exhibit superelasticity at room temperature. The SMA wire used in this study is a Ni-50.8 wt% Ti wire made in China. The differential scanning calorimetry (DSC) tests result shows that the martensite start temperature M_s was $-56.1\,^\circ$C, the martensite finish temperature M_f was $-84.6\,^\circ$C, the reverse transformation start temperature A_s was $-15.5\,^\circ$C, and the reverse transformation finish temperature A_f was $12.1\,^\circ$C (figure 1). The ultimate tensile strength was about 920 MPa and the ultimate strain was about 19%. Figure 2 shows the measured stress–strain relationship of the SMA wire. The SMA wire exhibited good superelasticity.

2.2. *Smart self-repairing concrete*

By taking advantage of the superelastic effect of SMA and the cohering characteristic of the repairing adhesive, we embedded SMA wires and brittle fibers containing adhesives into concrete during fabrication to form smart self-repairing concrete, as shown in figure 3. To obtain enough adhesive for repairing cracks, the fibers will be connected with a vessel by rubber pipes containing repairing adhesive. The adhesive in the vessel can be supplied and regained. In the presence of damage and cracks due to earthquakes or typhoons, fibers around the cracked areas rupture. Once these mobile loads are removed, the superelasticity of SMA wires will recover the deflections and deformations of the structural members. At the same time, the switch of the repairing vessel containing adhesives is turned on and repairing adhesives flow out from the broken-open fibers, to fill/repair the crack.

3. Experimental design and method

The specimens used in this experiment were reinforced normal concrete beams (100 mm sides in cross-section and 400 mm in length). The maximum aggregate size was 6 mm for all the specimens. Figure 4 shows the details and dimensions of the specimen. The main reinforcements were SMA wires (500 mm long and 2.0 mm in diameter in the tensile area). The diameter of the hoops was 3 mm and their pitch was 50 mm. There was no bond between the SMA wires and concrete. Steel blocks were attached on the both ends of beam and the SMA wires were fixed in holes of the steel blocks through the frictional forces generated between the screws and the SMA wires. Five specimens were tested (table 1): a concrete beam reinforced with five main bars of SMA evenly arranged at the bottom of the section along the longitudinal axis (specimen L1); a control concrete beam with two main bars of 4.0 mm diameter steel wires arranged at the bottom of the section (specimen L2); a similar beam to L1 with seven main bars of SMA (specimen L3); a concrete beam reinforced with five main bars of SMA and four adhesive-filled brittle fibers

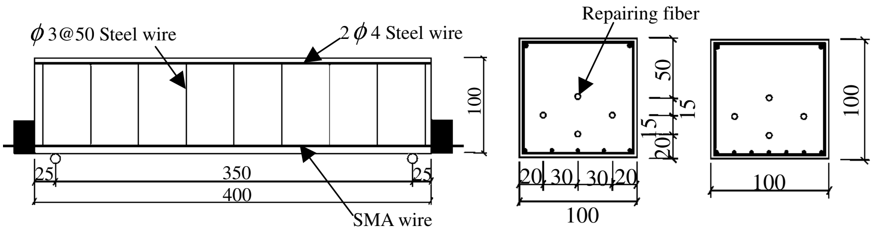


Figure 4. Detail and dimensions of the smart self-repairing concrete beam.

Table 1. Basic characteristic of the specimens.

Test specimen	Sides in cross-section (mm)	Length (mm)	Main reinforcements
L1	100	400	Five main bars of SMA
L2	100	400	Two main bars of 4.0 mm diameter steel wires
L3	100	400	Seven main bars of SMA
L4	100	400	Five main bars of SMA and four adhesive-filled brittle fibers
L5	100	400	Seven main bars of SMA and four adhesive-filled brittle fibers

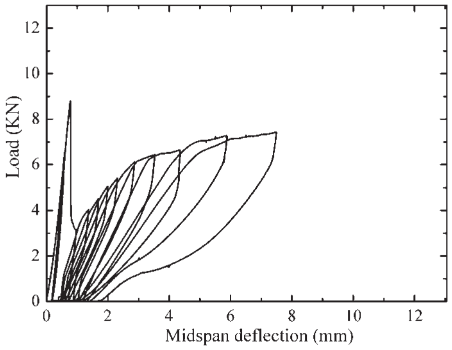


Figure 5. Load versus mid-span deflection in specimen L1.

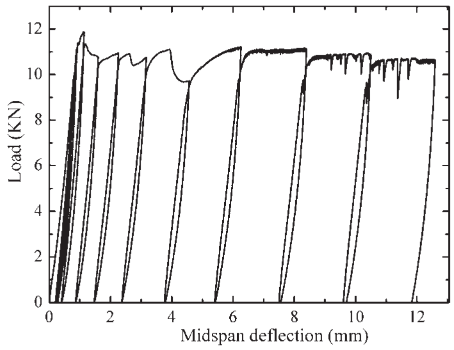


Figure 6. Load versus mid-span deflection in specimen L2.

(specimen L4); a concrete beam reinforced with seven main bars of SMA and four adhesive-filled brittle fibers (specimen L5). Four adhesive-filled glass fibers (6.0 mm in diameter and 0.6 mm in thickness) were distributed along the longitudinal axis below the neutral axis of the beam. A low viscosity epoxies adhesive served as the sealing/repairing chemical. The adhesive had a tensile strength of 25 MPa and shear strength of 18 MPa. The concrete cover of the wires was 9 mm.

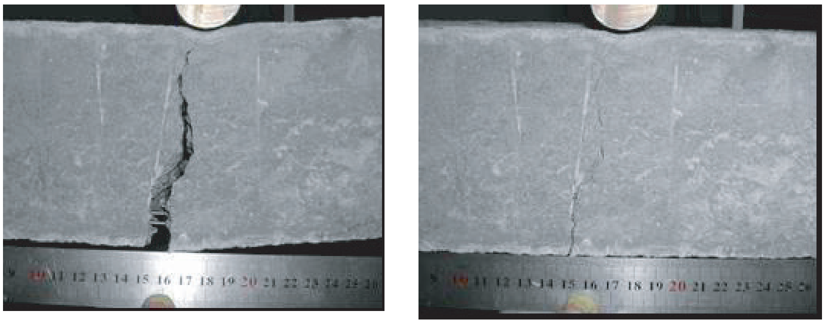
The specimens were tested at the age of 28 days. Concrete cubes were made from the same concrete used in the beams. The mean compressive strength of the cubic specimens (100 mm in sides) at 28 days was 54.3 MPa. Bending tests were conducted with MTS equipment at the Harbin Institute of Technology. A concentrated load was applied to the center of the beam with a static deformation rate, in the direction orthogonal to the beam's axis. The span of the beam was 350 mm by placing the center of the bottom supports 25 mm away from the edges. The external load and the deflection at the center of the specimen orthogonal to its axis were recorded automatically by a data acquisition system. A crack scale was used to measure the crack widths at each peak loading and unloading point under loading cycles.

4. Experimental results and analysis

4.1. Self-repairing performance of beams reinforced with SMA wires

Figures 5 and 6 show the relationship between the load and the mid-span deflection of specimen L1 and specimen L2, respectively. In the beam reinforced with SMA wires, an abrupt decrease was observed immediately after a crack was generated, because the concrete had no more resistance to tensile stress; the load then constantly increased until load removal. On unloading after incurring an extremely large deflection in the beam with SMA, the deflection recovered almost completely through the superelasticity of the SMA wires, as shown in figure 5.

In specimen L2, reinforced with steel wires, when the mid-span deflection exceeded 2 mm, the load was relatively constant, as shown in figure 6. After the mid-span defection exceeded 8 mm, the load decreased and the main reinforcements finally failed. On unloading after incurring an extremely large deflection in specimen L2, the deflection hardly recovered, compared with specimen L1 with SMA wires.



a) At maximum deflection b) After unloading: the crack almost disappeared

Figure 7. Crack behavior of specimen L1.

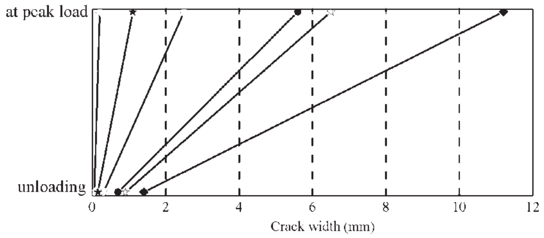


Figure 8. Crack width at center of specimen L1.

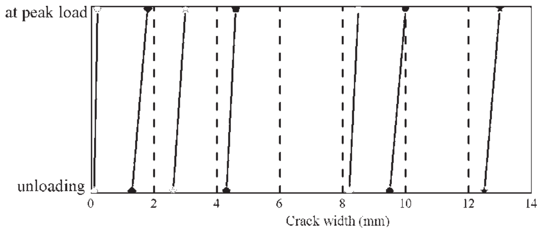


Figure 9. Crack width at center of specimen L2.

Because a vertical force was applied to the center of the simply supported beam, the crack width around the critical section only increased with an increase in deflection. Figures 7(a) and (b) show the crack behavior of specimen L1 at maximum deflection and unloading, respectively. These figures clearly show that the crack under maximum deflection almost closed after unloading.

Figures 8 and 9 show the variation in crack width for specimens L1 and specimens L2, respectively, at peak load and unloading for several cycles after the crack was generated. After unloading, the residual crack width in specimen L1 was about the same value, but it tended to rapidly increase in specimen L2 with the crack width increasing at hysteresis peaks.

Figure 10 shows the relationship between the load and the mid-span deflection of specimen L3. The curve of the relationship of load versus mid-span deflection in specimen L3 was similar with that in specimen L1. In other words, the tendencies of deformation during both loading and unloading were similar in specimen L3 and specimen L1. The residual crack width after unloading was about same value for specimens L3 and L1, without any influence of the number of SMA bars. However, specimen L3 can carry more load than specimen L1 at identical deflection because there are more main bars of SMA in specimen L3 than in specimen L1. This indicates that increasing the number or areas of SMA wires can effectively increase the bearing capacity and stiffness.

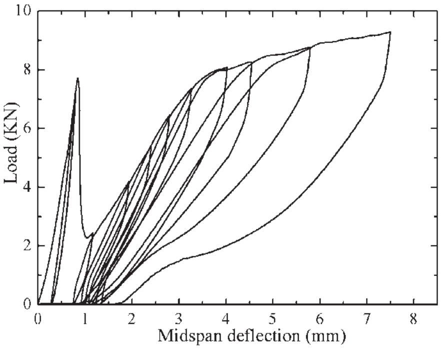
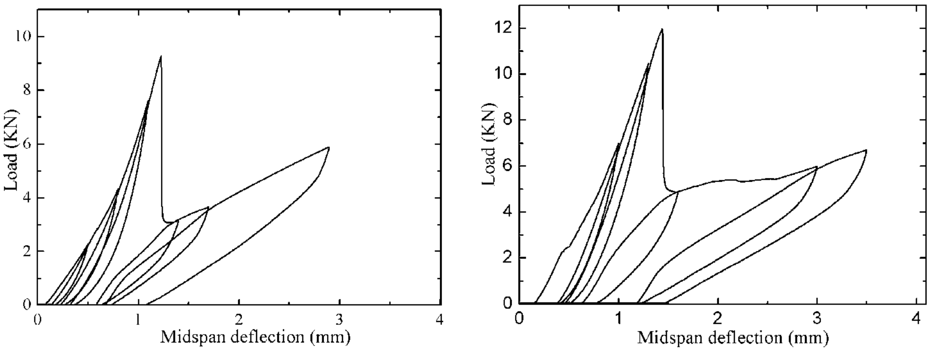


Figure 10. Load versus mid-span deflection in specimen L3.

In all of the SMA-reinforced beams, we can observe that the deformation and the width of the crack or gap of the beams increased during loading, but the deflection recovered almost completely and the crack almost closed at unloading. This clearly indicates that the concrete beams reinforced with SMA as main bars have added a self-restoration capacity to concrete beams. Unfortunately, the cracked concrete itself was not repaired in the SMA self-repairing concrete; therefore, the cracks experienced reopening during reloading.

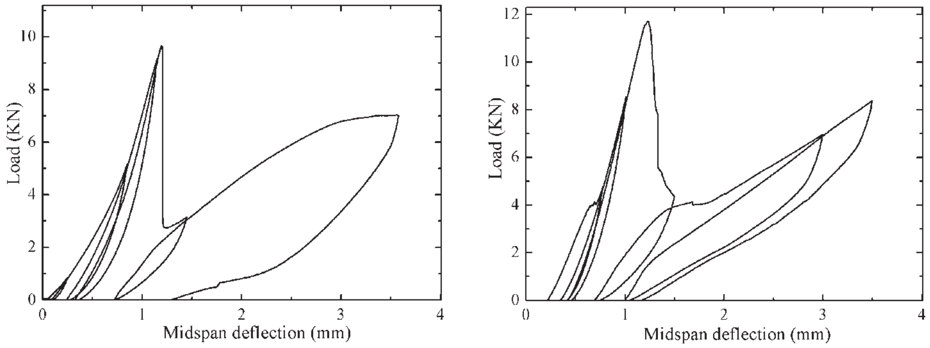
4.2. *Self-repairing performance of beams reinforced with SMA wires and adhesive-filled fibers*

Specimen L4 and specimen L5 are reinforced with main bars of SMA and adhesive-filled brittle fibers. Two specimens were first loaded to a certain deformation until an obvious crack appeared near the mid-span of the specimens and the repairing fibers in the cracked areas ruptured. Subsequently, the loading was removed and the superelasticity of SMA wires recovered the deflections of the specimens. Meanwhile, the



a) First testing b) Second testing

Figure 11. Mid-span deflection curve in specimen L4.



a) First testing b) Second testing

Figure 12. Mid-span deflection curve in specimen L5.

clamp was opened up and the adhesive flowed out from the broken-open fibers, and filled/repaired the crack. Then, the test was stopped and ten days were allotted between the first and the second tests. During this period of time, the adhesive was allowed time to set. After the predetermined time, testing resumed on the specimens, and all information was recorded.

Figures 11 and 12 show the relationship between the load and the mid-span deflection of specimen L5 in the first and the second testing, respectively. Comparing figures 11(a) and 12(a) with figures 11(b) and 12(b), respectively, we can observe that the second testing is similar to the previous reloading. These indicate that the strength of the cracked section was repaired and improved by the release of adhesive from the broken-open fibers into the crack; the cracking load in the second testing for both specimen L4 and specimen L5 increased by 28.6% and 21.2%, respectively, while in general that was not the case for a normal concrete beam reinforced by steel bars.

Figure 13 presents the crack pattern in specimen L4. Visual observations show that after the release of adhesive into the crack from the first loading, stress was redistributed to the uncracked section, where a new crack was formed, while the sealed crack remained closed. Therefore, the specimen repaired was able to derive reserve strength from the uncracked sections.

5. Conclusions

The self-repairing performance of concrete beams reinforced with SMA wires and brittle fibers containing adhesives has been investigated in experiments, and the results have been compared with those for beams reinforced with SMA wires and a beam containing steel wires. The specific conclusions are given as follows.

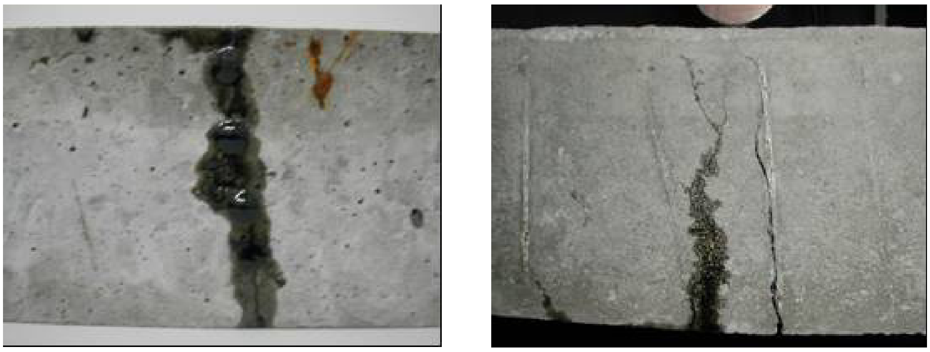
(1) Concrete beams reinforced with SMA as main bars had an added self-restoration capacity to concrete beams, and the deflection of beams reversed and the crack closed almost completely after incurring an extremely large deformation.

(2) For the smart beams reinforced with SMA wires, the number or areas of main SMA wires had no influence on the tendency of deformation during loading and the tendency of reversion by the superelasticity.

(3) Compared with concrete beams reinforced with SMA wires, the smart beam reinforced with SMA wires and brittle fibers containing adhesives performs better in repairing concrete after damage occurs. After the release of adhesive from the broken-open fibers into the cracks from the first loading, stress was redistributed to the uncracked section where a new crack was formed, while the sealed crack remained closed during reloading for smart concrete beams. While the original cracks experienced reopening, the load was carried directly by the wires during reloading for concrete beams reinforced with SMA wires.

a) Crack appeared near the mid-span of specimen

b) The adhesive flowed out from the broken-open fibers, filled /repaired the crack



c) Crack repaired in the bottom of Specimen

d) Original crack from the first loading did not reopen but new cracks formed

Figure 13. Crack pattern in specimen L5.
(This figure is in colour only in the electronic version)

While the potential of smart self-repairing concrete was clarified in these laboratory studies, there remain issues which require further investigation before this material can be applied in the field. For example, further research and development are needed for effective placing of the hollow fibers in large-scale applications. In addition, the economics of nitinol need to be analyzed for practical applications. Finally, due to low Young's modulus of SMA wire and the weak bonding between SMA wires and concrete, the stiffness of the smart self-repairing concrete beam remains to be improved in a future study.

Acknowledgment

The authors would like to thank the National Natural Science Foundation of China for the financial support under grant number 50538020.

References

[1] Dry C 1994 Matrix cracking repair and filling using active and passive modes for smart timed release of chemicals from fibers into cement matrices *Smart Mater. Struct.* **3** 118–23

[2] Dry C 1996 Smart earthquake-resistant materials: using time-released adhesives for damping, stiffening, and deflection control *Proc. SPIE* **2779** 958–67

[3] Dry C 2000 Three designs for the internal release of sealants, adhesive, and waterproofing chemicals into concrete to reduce permeability *Cem. Concr. Res.* **30** 1969–77

[4] Victor C L, Yum M L and Chan Y W 1998 Feasibility study of a passive smart self-healing cementitious composite *Composites* B **29** 819–27

[5] Ou J and Kuang Y 2004 Experiments and analysis of concrete material with crack self-repairing performance using embedded capsules filled with adhesive *Acta Mech. Solida Sin.* **25** 320–4

[6] Kuang Y and Ou J 2005 Experiments and analyses of the self-healing of cracks in reinforced concrete beams with embedded fibers filled with adhesive *China Civ. Eng. J.* **38** 53–9

[7] Kuang Y, Ou J and Dongsheng L I 2006 Experimental research on concrete material with crack self-repairing performance using embedded fibers filled with adhesive *Jianzhu Jiegou Xuebao* **27** (Suppl.) 107–12

[8] Yuji S *et al* 2003 Experimental study on enhancement of self-restoration of concrete beams using SMA wire *Proc. SPIE* **5057** 178–86

[9] Ma H 1998 Application of shape memory alloy to the structural deformation and control of the crevice *J. Northwest Inst. of Light Ind.* **16** 120–5

[10] Sun G *et al* 2000 A study on the thermomechanical deformation of elastic beam with embedded shape memory alloy wires *Mater. Des.* **21** 525–8

[11] Sup C and Jung J L 1998 The shape control of a composite beam with embedded shape memory alloy ire actuators *Smart Mater. Struct.* **7** 759–70

[12] Arup K M and Ihosvany N 1998 Smart prestressing with shape-memory alloy *J. Eng. Mech.* **124** 1121–8

[13] Li H, Liu Z and Ou J 2004 Study on damage emergency repair performance of a simple beam embedded with shape memory alloys *Adv. Struct. Eng.* **7** 495–502

[14] Wilde K, Gardoni P and Fujino Y 2000 Base isolation system with shape memory alloy device for highway bridges *Eng. Struct.* **22** 222–9

[15] Desroches R and Delemont M 2002 Seismic retrofit of simply supported bridges using shape memory alloys *Eng. Struct.* **24** 325–32

[16] Shiba K *et al* 1998 Active/passive vibration control systems tall building *Smart Mater. Struct.* **7** 588–98