Experimental Study on the Self-Repair Properties of Shape Memory Alloy Concrete Beam

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Abstract The one-way memory composite super-elastic shape memory alloy wires were laid on the bottom of the reinforced concrete beam to make the intelligent concrete beam. The paper compares the self-repair properties of each test beam, and analyzes the influence of different memory filament ratio and different damage degree on the self-repair properties of SMA reinforced concrete beams. The test results suggest that the shape memory alloy can improve the self-repair ability of the concrete beam, the best when the damage degree is 70 and 50%.

Keywords Reinforced concrete beam · Shape memory alloy (SMA) · Self-repair

1 Introduction

Reinforced concrete structures are the most widely used and most abundant structural form in the world of construction today and will remain an essential structure in engineering for some time to come. However, during the long-term use of engineering structures, concrete in reinforced concrete structures often undergoes different degrees and types of cracks, which may lead to corrosion of reinforcement, thus causing permanent damage to the structure and seriously affecting the normal use and durability of the structure. Therefore, the study of the cracking and deformation resistance of structures is of great practical importance. At present, with the development and continuous progress of modern materials, concrete structure has achieved a new breakthrough in the process of moving towards intelligence and complexity, i.e., intelligent structures are used to solve the above problems.

At present, the main materials that can be used as driving materials in smart structures are current variant materials, magneto rheological materials, shape memory

The original version of this chapter was revised: The author Xian Cui now has been changed as corresponding author. The correction to this chapter is available at https://doi.org/10.1007/978-981-19-8657-4_48

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Y. Yang (ed.), *Advances in Frontier Research on Engineering Structures*, Lecture Notes in Civil Engineering 286, https://doi.org/10.1007/978-981-19-8657-4_36

materials, etc. [4], among which shape memory alloys, as typical smart materials, are one of the best shape memory materials in terms of shape memory performance. Shape-memory alloy has two important properties: shape memory effect and super-elasticity, and can recover to the state before deformation after plastic deformation by heating them above a certain temperature [3]. At the same time, if the recovery process is limited, the material will produce a large recovery stress, that is, the SMA wire to produce a large recovery drive characteristics. Also, shape memory alloys are easy to combine with concrete and steel materials. In the repair and enhancement of concrete beam structure, the shape memory effect and super elasticity of shape memory alloy can effectively improve the mechanical properties of concrete structure, the shape memory effect has the advantage of easy application of prestress, and its super elasticity can control and recover the deformation and deflection of structural members, reduce the impact of typhoon and earthquake, and more effectively ensure the safety and reliability of the structure. It is because of these advantages that shape memory alloys have great application prospects and broad development space in various fields [1, 2, 5, 6].

In this paper, super-elastic SMA wires and unidirectional memory SMA memory wires were buried in the tensile zone of reinforced concrete beams to make smart concrete beams, and the self-healing ability of SMA concrete beams were studied by using the method of single-point loading test in the span. 15 SMA concrete beams were tested for their mechanical properties, and the effects of different unidirectional memory SMA wire and super-elastic SMA wire contents, degree of damage and other factors on their recovery.

2 Experimental Programme

2.1 Experimental Materials

Ni–Ti shape memory alloys were used for the test, and the diameter of both super-elastic SMA wire and unidirectional memory SMA wire was 1 mm. The parameters of the shape memory alloy used are shown in Table 1. The specimens were made of C20 concrete as the matrix material with the ratio of water:cement:sand:stone = 0.54:1:1.51:2.60, where the cement strength grade was 32.5 MPa. The average measured compressive strength of the concrete cubes measured by the test was 20.64 MPa.

Table 1 Chemical composition of SMA wire

Ni	Ti	C	Co	Cr	Nb	Fe	Cu	N	O	Unit
55.8	44.1	0.007	0.003	0.03	0.003	0.004	0.003	0.0015	0.043	%

2.2 Experimental Design

In order to investigate the mechanical properties of SMA smart concrete beams and to obtain a better design solution for the content of super-elastic SMA wires and unidirectional memory SMA wires, 15 reinforced concrete beam specimens with SMA wires were designed and fabricated for comparative analysis, numbered L1–L15, and the basic characteristics of the specimens are shown in Table 2. The geometry of the concrete base beam is 400 × 100 × 100 mm. Six SMA wires were preembedded in the tensile zone and the upper part was equipped with two 8 mm diameter reinforcement bars as erection bars. The longitudinal reinforcement of the beam was 2φ8 in the compression zone, 2φ8 in the tension zone, and the hoop reinforcement was taken as φ6@100, and the thickness of the concrete protective layer was 25 mm. The main variation parameters of the specimen were the content of super-elastic SMA wire and one-way memory SMA wire and the damage degree of the specimen. The specimens were formed in the mold by layered casting method, and after removing, they were maintained under standard maintenance conditions until the age of 28d, and single-point loading test was carried out in the span on the electronic material testing machine (Fig. 1).

Table 2 Experimental protocol

Specimen number	Super elastic ratio (%)	One-way memory ratio (%)	Degree of damage (%)
L1	100	0	30
L2	100	0	50
L3	100	0	70
L4	70	30	30
L5	70	30	50
L6	70	30	70
L7	50	50	30
L8	50	50	50
L9	50	50	70
L10	30	70	30
L11	30	70	50
L12	30	70	70
L13	0	100	30
L14	0	100	50
L15	0	100	70

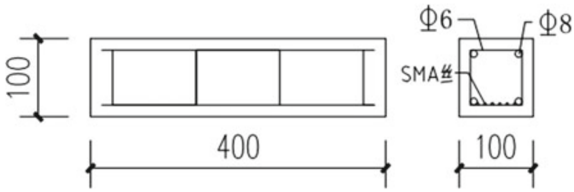

Fig. 1 Reinforcement diagram of the test beam

Fig. 2 Test equipment and instruments

2.3 Test Equipment, Instruments and Devices

Figure 2 shows the actual photo of the test beam when it was loaded. The test beam was loaded at a single point in the span and the test equipment used was PWS-500 hydraulic servo fatigue tester. The actuator of the tester has its own force sensor and displacement sensor. The strain gauges were pasted on both sides of the reinforcement in the tensile zone and on the top surface of the concrete compression zone at the mid-span position of the test beam to monitor the strain changes in the concrete beam.

2.4 Test Methods

(1) Test loading

Single point loading test at mid-span on beam specimens after maintenance. The displacement loading control mode was used with a loading rate of 0.1 kN/s. The loading method used for the test was single cycle loading, and the unloading was carried out on the basis of 30, 50 and 70% of the ultimate load.

(2) Self-repair test

The self-repair test mainly used a small sun heater to heat the deformed specimens after loading, and the temperature was observed by a thermometer placed on the concrete beam specimens, and the specimens were heated until they reach about 20°. After stopping the heating, the self-repaired specimens were loaded again and loaded until the specimens were damaged or the maximum displacement of the loading was 20 mm.

3 Test Results and Observations

3.1 Test Results

During the loading process, the mid-span deflection of the specimen gradually increased with the increase of the load; tiny cracks appeared at the bottom of the specimen, after which the cracks widened and rapidly expanded along the height of the beam toward the top of the beam. When unloading, it can be seen that the cracks of the specimen have obvious recovery, which is due to the effect of SMA one-way memory and super-elastic.

3.2 Recovery Effect Analysis

Figure 3 gives the strain of the reinforcement in each specimen during the heating process, from which the repair effect of SMA wire in each specimen can be analyzed. From Fig. 3, it can be seen that.

The strains of reinforcement at different levels of damage were reduced for different contents of super-elastic memory wire and unidirectional memory wire, indicating that SMA wire can improve the self-repair ability of reinforced concrete beams regardless of the material content percentage.

At 30% damage, the material percentage did not have a significant effect on the strain value of the reinforcement. At 50 and 70% damage, the difference in recovery strains was not significant. During unloading, the recovered strains were significantly higher in the 30 and 50% unidirectional memory wire specimens than in the 70 and 100% unidirectional memory wire specimens, but with increasing heating time, the recovered strains in the latter were significantly higher than those in the former. This is due to the fact that during unloading, the super-elastic memory wire can significantly improve the recovery of the beam, so the recovery of the specimen with higher content of super-elastic wire is more obvious; while with the increase of heating time, the unidirectional memory wire gradually plays the main role and makes the reinforcement of the specimen with higher content of unidirectional memory wire have higher recovery strain. The analysis of Fig. 3 shows that the recovery effect of the reinforced concrete beam with 70% unidirectional memory wire and 30% super-elastic wire is optimal.

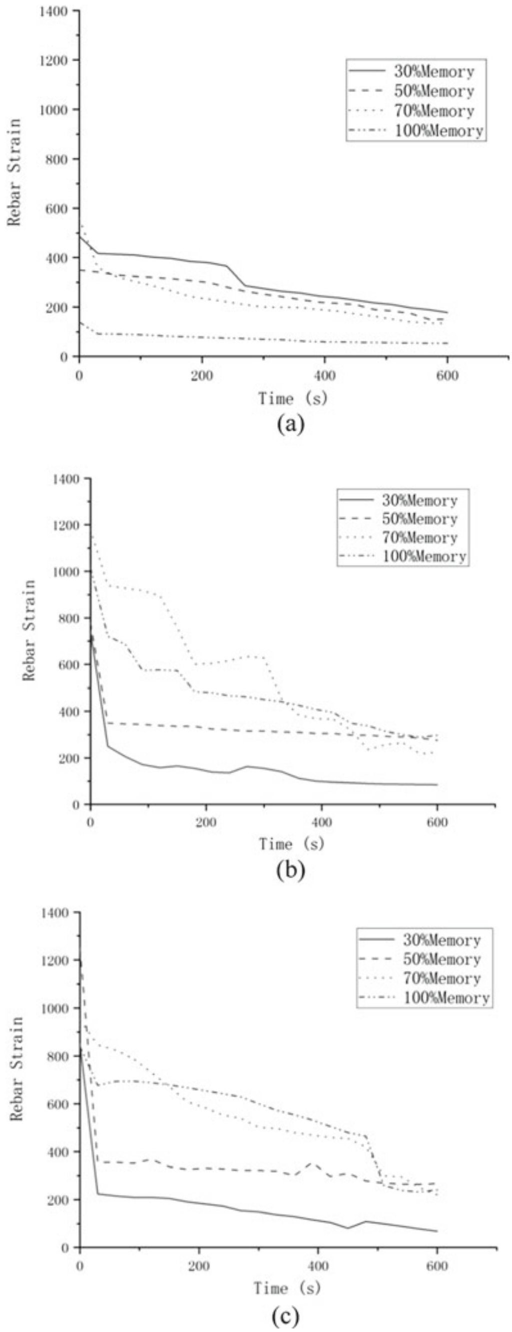

Fig. 3 Variation of recovery strain for **a** 30%, **b** 50% and **c** 70% of damaged level

3.3 Effect of Damage Level on Mechanical Properties of Test Beams

The load-displacement curves of reinforced concrete beams with 100% super-elastic memory wire (test beam L1–L3), 30% unidirectional memory wire (test beam L4–L6), 50% unidirectional memory wire (test beam L7–L9), 70% unidirectional memory wire (test beam L10–L12), and 100% unidirectional memory wire (test beam L13–L15) under different damage conditions are given in Fig. 4. Table 3 shows the test data of cracking load, ultimate load and displacement for specimens L1–L15.

As can be seen from Fig. 4, the specimens all have more obvious yield points and yield stages. When the content of super-elastic SMA wire and unidirectional memory SMA wire in the specimens is constant, in the elastic phase, with the increase of the damage degree, the bearing capacity of the specimens will subsequently increase in different degrees. As can be seen from Table 3: in the case of fully elastic memory wire reinforced concrete, the ultimate bearing capacity and ductility of the specimen with 70% damage are significantly higher than those of the other two damage levels; in the case of 30% unidirectional memory wire, the difference between the bearing capacity of 50% damage level and 70% damage level is less, but it is increased compared to the specimen with 30% damage level; in the case of unidirectional memory wire and super-elastic memory wire The ultimate bearing capacity and ductility of the 70% damage specimen are better than those of the 30 and 50% damage specimens when the content of the unidirectional memory wire is the same; while the ultimate bearing capacity of the 70% damage specimen is significantly higher than those of the 30 and 50% damage specimens in the case of 70% unidirectional memory wire, but its ductility is poor; in the case of all unidirectional memory wire reinforced concrete, the 50% damage specimen L14 The ultimate bearing capacity is higher than the other two beams, and the ductility is better than that of the specimen with 30% damage. It can be seen that the increase of damage degree can improve the mechanical properties of smart reinforced concrete beams to some extent, but the percentage of different unidirectional memory wires and super-elastic memory wires should be considered. The degree of damage required for the optimal unloading effect varies for different material occupancy ratios.

4 Conclusions

Smart concrete beams were made by using unidirectional memory composite super-elastic shape memory alloy wires laid on the bottom of reinforced concrete beams, and the mechanical properties of various test beams were investigated using mid-span single-point loading tests. The results show that the mechanical properties of concrete beams with different memory and super-elastic wire contents and different damage levels have differences, and SMA materials can significantly improve the

Fig. 4 Variation of load–displacement curve for **a** 30%, **b** 50% and **c** 70% of damaged level

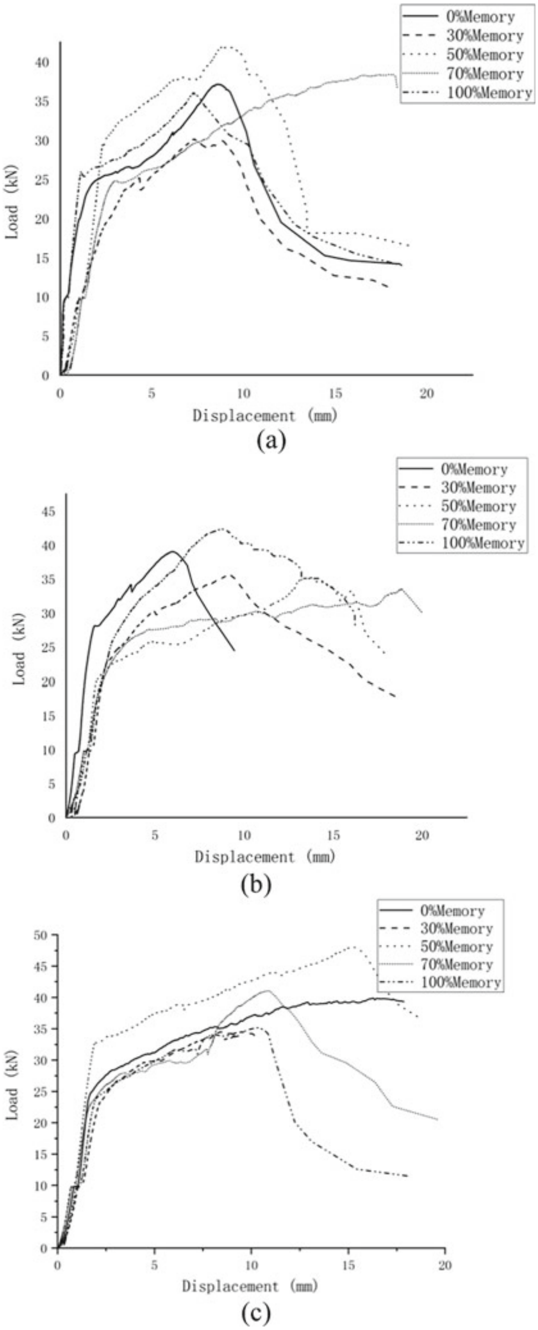

Table 3 Results of loading tests on SMA-confined concrete specimens

Specimen number	Cracking load (kN)	Ultimate load (kN)	Displacement (limit) (mm)	Displacement (steel yielding) (mm)
L1	6.1	33.6	8.7	1.6
L2	9.4	39.0	5.9	1.5
L3	9.7	39.5	17.8	1.6
L4	9.3	30.1	7.2	3.5
L5	9.7	35.4	8.9	2.3
L6	9.5	34.4	8.4	2.1
L7	9.9	41.8	9.0	2.3
L8	9.7	34.8	13.5	1.5
L9	9.8	48.1	15.4	1.9
L10	9.7	38.1	17.9	2.7
L11	9.7	33.5	18.9	3.3
L12	9.8	40.9	10.9	3.3
L13	6.1	32.3	7.3	1.2
L14	9.8	42.8	8.8	2.8
L15	9.8	34.8	10.4	2.2

mechanical properties of concrete beams and enhance their self-healing ability, with the following main conclusions:

(1) With the same degree of concrete damage, the material percentage did not have a significant effect on the strain value of the reinforcement when the degree of damage was 30%; however, when the degree of damage reached 50 and 70%, the reinforced concrete beams with 70% unidirectional memory wire and 30% super-elastic wire had better recovery results than the other contents.

(2) When the content of super-elastic SMA filaments and unidirectional memory SMA filaments in the specimen was constant, in the elastic phase, with the increase of the damage degree, the bearing capacity of the specimen would increase with it to different degrees. The mechanical properties of the smart reinforced concrete beams can be improved by appropriately increasing the degree of damage to a certain extent, but different percentages of unidirectional memory filaments and super-elastic memory filaments should be considered, which were particularly prominent at 50% of unidirectional memory filaments, where the specimen had the best self-repair effect.

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