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RC beam with variable stiffness and strength

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Abstract

Shape memory alloys (SMA) show a temperature depending stiffness and strength. A reinforced concrete (RC) beam with SMA wires was tested and compared with a conventional RC beam. Furthermore, tensile and pull-out tests with the SMA wires are presented. By using the constrained recovery effect, it was possible to produce a changeable prestress in the RC beam.
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1. Introduction

Civil structures like bridges and buildings are designed to be passive, therefore they cannot change their static and dynamic behaviour as a reaction, e.g., to changing loads. An adaptive structural system reacting to changing influences on the structure would need sensors, active or semi-active elements and a control system. Active elements apply energy into the system, in contrast semi-active elements dissipate the system energy or change the system properties, e.g., by changing the stiffness of the element. One possible smart material to be used as active or semi-active elements are shape memory alloys.

Shape memory alloys (SMA) have been known for many decades. They are mainly used in medicine, electronics, air and space industry and in the consumer goods industry. Examples are medical implants and instruments, cell phone antennas, frames for glasses, pipe couplings etc. The most usual SMA material on the market is nickel–titanium (Ni–Ti).

SMA have remarkable properties, such as memory effect (free recovery effect), super-elastic effect, changes of the mechanical and electrical properties due to temperature changes and the constrained recovery effect. Shape memory effect (free recovery effect) means that a large (pseudo-) plastic deformation can be reversed by heating. If the going back is prevented by, e.g., concrete, a stress in the SMA results (constrained recovery effect). The background of these effects is the fact that the crystal lattice structure of SMA consists either of martensite phases in low temperatures or of austenite phases at high temperatures. The described remarkable effects are caused by these two phases and their special transformations. The phase transformations are triggered by temperature changes or mechanical action. Extensive information about the material itself and its behaviour can be found in the literature, see, e.g. [1–4].

Until today, SMAs have found very limited applications in civil engineering probably due to their cost and to limited knowledge of the material in the civil engineering industry. A further disadvantage is the very low young's modulus. Nowadays, the main application

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of SMA in the building industry is for seismic retrofitting [5–11]. To reduce damaging effects of earthquake vibrations, the super-elastic effect is used to dissipate energy and to change the stiffness from stiff to weak on a certain load and back to stiff if the load decreases again. Furthermore, the property of the high stiffness at high loads is used. In addition, the 'yielding' plateau is used to keep prestresses constant during vibrations.

By using the constrained recovery effect, Soroushian et al. [12] used iron-based shape memory alloys to transfer corrective forces to a reinforced concrete bridge with beams lacking sufficient shear strength. Other researchers included SMA wires in matrices such as plastic, plaster or mortar. The aim of Parlinska et al. [13] was to develop adaptive plastic composites which are able to change their dynamic properties. In [14], SMA wires were used to generate a compressive residual stress in plaster specimens to achieve higher bending strength and [15,16] showed that it was possible to induce prestress in small plates and beams made of cement-based matrices.

With controlled tendons like 'muscles' in our civil structures, which produce stresses only when needed, it would become possible to design more slender and lighter structures. The undesirable stresses from the today usual permanent prestress could be avoided. This idea of controlled tendons like 'muscles' for reinforced concrete structures by using conventional servo-hydraulic jacks was described in Pacheco [17].

One purpose of the presented study was to figure out if it is possible to combine reinforced concrete with SMA wires to reach a changeable structure which has the potential to react to changing environment. A further aim was to get valuable experiences about the behaviour of the material SMA and its handling.

In the presented experiments, SMA wires of over 4 mm diameter were used to reinforce a concrete beam with a span of 1.14 m. Several deformation cycles were performed on the beam, to show its variable load–deformation behaviour. The temperature in the SMA wires was increased by a circulating current. Tensile and pull-out tests with SMA wires of the same type were carried out.

2. Method

2.1. Materials

The SMA wires were supplied by Memory-Metalle GmbH, Germany. According to the supplier, the chemical composition of the wires was 55.32% nickel and 44.64% titanium. The diameter was about 4.3 mm. These SMA wires were used in the above described tests.

The composition of the concrete for the pull-out tests and the test beams is shown in Table 1. It was produced by Empa. The aggregate was tunnel excavation material. After 28 days, the concrete for the test beams had a cube strength of 44.3 MPa, a tensile strength of 3.1 MPa and an elastic modulus of 24,200 MPa. The tests were performed 40 days (beam KS) and 56–91 days (beam SMA) after concreting. To investigate the influence of heat on the concrete, heating tests on concrete with the same composition were carried out. They showed that the heating causes a reduction of the elastic modulus, while the compression strength stays constant, see Fig. 1.

Table 1
Formulation of the concrete used for the pull-out tests and the test beams

Grain size	Size distribution	kg/m^3
0...4 mm	50%	950
4...8 mm	30%	570
8...11.2 mm	20%	380
Cement	CEM I 42.5	325
Water	Water–cement ratio = 0.56	182
Additive	Sikament-10 PLUS (1.4% of cement mass)	4.55
Apparent density		2412

Test results of the properties of the steel bending reinforcement in beam KS are given in Table 2.

2.2. Tensile and pull-out tests

Firstly, tensile tests on the SMA wires were performed to determine the stress–strain behaviour at different temperatures. Furthermore, to investigate the bond behaviour of the wires in the concrete, pull-out tests were executed. To improve the bond behaviour, the surface of the SMA wires was sand-blasted and then coated with quartz sand in an epoxy adhesive. Pre-tests showed that cold mechanical treatment for better bonding was not possible, because it changed the mechanical properties of the SMA.

A total of six pull-out tests were performed, varying the anchor length and the surface treatment. See Fig. 2. The test set-up of the pull-out tests can be seen in Fig. 3.

2.3. Four point bending tests

Two reinforced concrete beams were tested. One was a reference beam with conventional bending steel reinforcement (test beam KS). The other test beam (test beam SMA) included SMA bending reinforcement with the same surface treatment as for the pull-out tests. See Fig. 4. The longitudinal view of the beam SMA and the location of the measurements presented later in this paper are shown in Fig. 5. See also the photo in Fig. 6.

In the first test, beam KS was loaded to failure. In a second phase, several deformation cycles were per-

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