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CIVIL INFRASTRUCTURE

# Smart Activation System for the Hybrid Tendons Crack Closure Technology

Cracks are a typical characteristic of a concrete structure, formed as a direct consequence of the concrete's low tensile strength. They represent a risk to the longevity of a concrete structure; over time, under the effects of loads and environmental factors, cracks tend to grow and coalesce. It is widely known that cracks reduce the mechanical properties of, and significantly increase the diffusion of deleterious materials through a concrete structure, thus shortening its service-life. The need for enhanced structural longevity and reduced maintenance costs have driven an increased demand for self-healing technologies. Smart crack-closure technologies can lead to the production of more adaptable structural elements, with reduced associated waste and CO2 emissions. The work will cover the developments of a digitally controlled system that uses smart hybrid tendons (HTs) embedded in concrete to detect and close cracks. In particular the work will focus on the digital activation system for the HTs. This technology comprises a shape memory polymer tubular sleeve hosting a pre-stressed strong core which act together to provide an effective crack-closing action and offer flexural reinforcement to the concrete element. The HTs have been the object of a lab-scale study and the digital activation system will complete their design, paving the way for their use in the real world.

*Keywords:*
*Concrete, self-healing, smart structures, resilience, reinforcement.*

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## INTRODUCTION

Concrete is the most used building material and its use is irreplaceable for countless large infrastructure developments [1]. However concrete-based buildings and infrastructure are susceptible to cracking due to the limited tensile strength of the concrete itself [2], [3].

Micro cracks are an unavoidable phenomenon in ordinary concrete[4]. Fractures in concrete structures may form as a result of temperature variations, structural difficulties, and freeze-thaw cycles. In time micro-cracks will generate macro-cracks, which facilitate the penetration of harmful ions such as chloride into concrete. These cracks may eventually cause serious challenges for concrete structures and shorten their lifespan [5].

As a solution to the challenge of cracking in concrete, self-healing concrete has been widely explored by many researchers [6]–[10].

In particular a possible solution would be to embed engineered (autonomic) self-repair mechanisms into concrete structural elements, which are able to heal cracks as they form. [11], [12].

Balzano et al 2021[12] presented a new healing system that uses pre-tensioned hybrid tendons to close cracks in cementitious structural elements. The tendons comprise an inner core, formed from aramid fibre ropes, and an outer sleeve made from a shape memory PET. During the manufacturing process, the inner core of a tendon is put into tension and the outer sleeve into compression, such that the tendon is in equilibrium. A set of tendons are then cast in a cementitious structural element and heat activated once cracking occurs. This triggers the shrinkage potential of the PET sleeve, which in turn releases the stored strain energy in the inner core. The tensile force thereby released applies a compressive force to the cementitious element, in which the tendons are embedded, that acts to close any cracks that have formed perpendicular to the axis of the tendons.

This system was proven to successfully close 0.3 mm cracks in mortar beams. Moreover, the hybrid tensons can act as effective reinforcement both before and after activation.

Although proven effective, the Hybrid tendons are still far from being ready to be used in a working infrastructure. In particular a proper activation system was still needed. Previously the tendons would be activated by placing the samples in the oven but this is not an optimal procedure especially in view of a possible use on a structure. An activation system is needed that would be embedded within the structural element and be triggered by the crack detection.

This paper describes the initial experimental work carried out to explore the use of electric heating wires as activation system for the Hybrid Tendons on structural concrete beams.

## GENERAL CONCEPT

Balzano et al. (2021) introduced a novel crack-closure technology namely hybrid tendons which proved to successfully close cracks in mortar beams. The present work follows up on the progress of this past research by applying the hybrid tendon on concrete beams of a relevant scale and exploring the viability of an activation via a heating system embedded in the beam together with the tendons.

The Hybrid tendons were activated via a system of electric wires wrapped around each tendon and externally connected to a power supply. The whole system was then connected to a computer for data collection and to control the activation.

The general scheme of the experiment setting is represented in Fig.1.

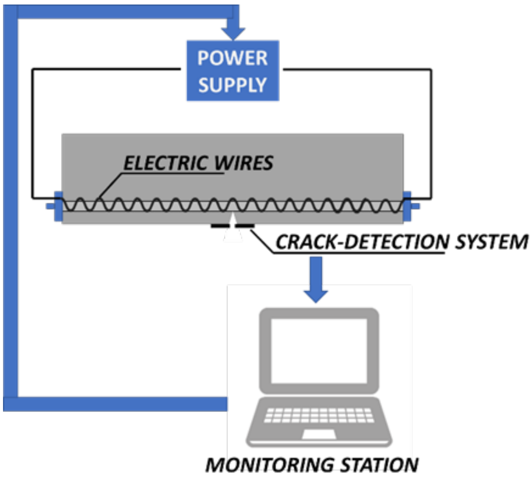

Fig. 1. General concept.

## MATERIALS

*PET*
A commercial grade of polyethylene terephthalate (PET) material (Dow Lighter C93) was used. This is an amorphous polymer, and so its shape memory behaviour is controlled by its glass transition temperature $T_g$; orientation must be imposed at around this temperature, and shape recovery is also achieved near $T_g$. For this material, $T_g$=78°C according to manufacturer's figures. This makes the triggering temperature compatible with the setting concrete environment.

*Kevlar*
Kevlar® is an organic fibres belonging to the family of the aramid fibres and is characterized by a relatively high tensile strength (ca 700 MPa).

*Electrical Equipment*
The electrical activation system is designed using high resistivity wires with excellent oxidation resistance, making it suitable to work in concrete.

The wire was wrapped around each tendon to make a coil resistance able to generate the heat for activation.

The finished tendon plus activation system is reported in Figure 2.

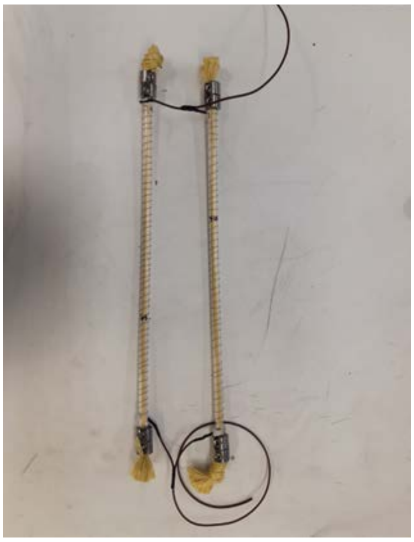

Fig. 2. Hybrid Tendons with electric wires.

*Concrete*

The concrete for the beam specimens was prepared using Portland cement CEM II A/L 32.5 R (CAS number 65997–15-1), standard quartz sand (CAS number 14808–100 60–7) as fine aggregate, 10mm aggregates and tap water. Cement (c), sand (s) and aggregates were mixed in a ratio of 1:1.55:2.1 by mass, and water (w) was added at a w/c ratio of 0.55 by mass.

Three 100x100x100mm cubes and three 100x200mm cylinders were produced in order to perform compression and splitting tests in accordance with BS EN 12350–1:2000 and BS EN 12390–6:2009 respectively, with the aim of determining the compressive cube strength (fcu) and tensile splitting strength (fcyl) of the mortar paste. All the specimens were cured for 7 days prior to being tested. The compressive and splitting test results are given below in Table 1, noting that CV denotes the coefficient of variation.

| | fcu (7days) *MPa* | fcyl (7days) *MPa* |
|---|---|---|
| **Mean** | 29.2 | 3.48 |
| **CV** | 0.02 | 0.08 |

Table 1. Mechanical Properties of the concrete mix.

## LABORATORY EXPERIMENTS

*Preparation of the specimens*

For the purpose of this preliminary study, four concrete beams with dimensions 100x100x500mm were tested. Figure 3 shows the typical cross section of the concrete specimens with the embedded hybrid tendons.

Following the stressing procedure described in Balzano et al 2021, each tendon would store an average pre-stress of 1.2kN. A number of four tendons have then been embedded in each concrete beam.

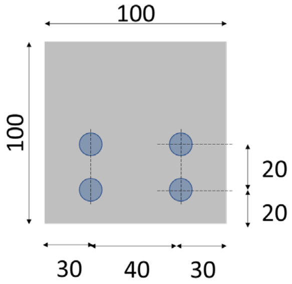

Fig. 3. Geometry of the concrete beam cross section with embedded tendons.

After 24 hours the concrete beams were then removed from the mould and covered in wet hessian and wrapped in cling film. The specimens were cured for 7 days (Figure 4).

Fig. 4. Concrete beam specimens

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*Testing*

After curing, each specimen was tested in three-point bending (Fig. 5). Prior the test, the specimen was notched in order to accommodate the knife edge plates glued to the underside of the beam. A lightweight clip gauge was located between the plates to monitor the Crack Mouth Opening Displacement (CMOD) during the experiment. The load was controlled via feedback from a machine stroke displacement transducer which allows the softening behaviour to be captured. Once the crack aperture reached the desired value the loading was stopped and the test was switched to displacement control. At this point the power supply was activated, gradually heating the embedded tendons. Two Thermocouples type K were installed in each specimen to monitor the temperature raise, hence confirming the system was capable of rising the temperature of the PET up to the activation.

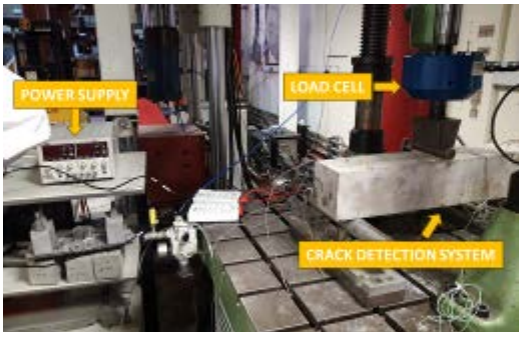

Fig. 5. Three-point bending test apparatus.

## RESULTS

Figure 6 shows the Force-CMOD graph recorded during the test. This shows that the specimen exhibited a quasi-linear behaviour until a peak (which corresponds to the point where the concrete began cracking), after which the load decayed with increasing deformation.

The test was stopped at a CMOD value ranging from 0.25 and 0.3 mm.  The tendons were then activated and the crack closure was monitored. Figure 6a  shows how the CMOD reduces after activation and this process took approximately 20 minutes. However being the machine set on Displacement-control, the load shows a rise as the crack closes.

Figure 6b shows the data from the thermocouples embedded in the concrete beam. Unfortunately the thermocouple in B1 stopped working during the experiment. However the other three show how the CMOD decrease when the temperature raises, proving the closing action of the Tendons.

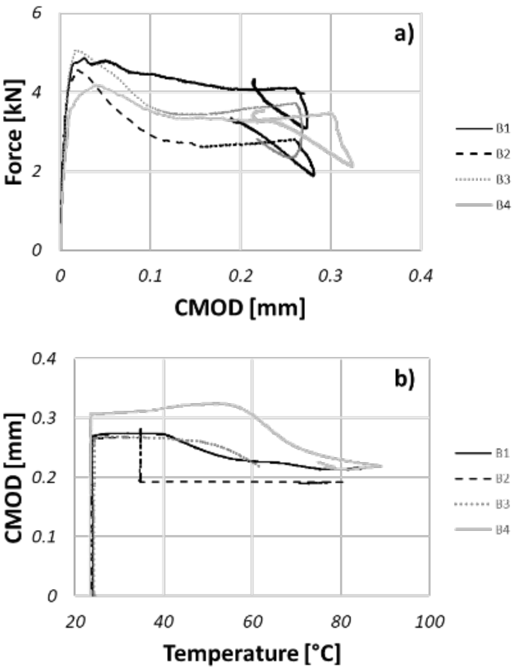

Fig. 6. Load-CMOD results.

## CONCLUSIONS

This paper presented the design of an embedded activation system for the crack-closure technology of the hybrid tendons.

The activation system consisted in electric wires wrapped around each tendon and connected to a power supply, which would activate once the crack forms.

The results of the preliminary experimental campaign are very promising, showing the potential of this system to successfully heat and activate the tendons, hence releasing the stored stress.

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