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Pinball Tendons Crack Closure Technology

Concrete is a popular construction material due to its unyielding nature. Although concrete is resistant to erosion, rotting, and rusting, due to its low tensile strength, reinforced concrete is prone to cracking. Also, because the cracks expand and become bigger over time, they can be a potential risk for concrete elements and lead to the failure of structures. Consequently, effective and early crack-closing and concrete healing can greatly enhance and improve concrete structures' lifespan. Mechanical closing of the cracks by tendons has been one of the successful solutions. These tendons act based on a stored force in a balanced system. The new generation of tendons being investigated on a laboratory scale is Pinball Tendons (PBT). In addition to the simple activation phase, these tendons can store much more force due to their sleeve being made from steel. The significant feature of PBTs is that they do not need to receive any energy or recharge after the casting in concrete, so their service life lasts until they are activated to close the crack and release the prestressed force. According to the recorded CMOD data in this study, the tendons managed to close more than 65% of the crack aperture. The speed of the crack closure is another positive aspect of PBTs, 90% of crack closure has been done within the first 8 seconds. Because of this performance, in addition to the self-healing during the life span of structures, tendons can be a helpful alternative for repairing and enhancing concrete in sudden events like earthquakes and explosions.

Keywords:
Self-Healing, crack closure, durability, concrete.

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S. Sharifi and B. Balzano, 'Pinball Tendons Crack Closure Technology', *Proceedings of the Cardiff University Engineering Research Conference 2023*, Cardiff, UK, pp. 34-38.

doi.org/10.18573/conf1.i

INTRODUCTION

Concrete is the most frequently used engineering material in the modern world due to its high performance and low cost. It is regarded as one of the global consumption's most valuable construction materials [1,2]. However, despite concrete's many advantages, such as good strength and durability, cracks can easily damage it. Cracks can threaten concrete elements and decrease their toughness and life span [3]. Cracks allow moisture and corrosive chemicals to access the steel reinforcement, speeding up the deterioration process [4]. This has led to high maintenance and repair costs for concrete, which comprise a significant portion of the overall cost of concrete structures [5].

Self-healing concrete is an effective solution for reducing concrete degradation by automatically repairing cracks [6]. One of the most recent concrete self-healing methods presenting acceptable results is using tendons to close cracks [7]. Initially, these tendons could close the crack based on the generated force by the shrinkage of a particular type of polymer known as a shape memory polymer (SMP)[8]. But later, with changes in the design of the tendons, the new tendons (Hybrid SMP) were able to close the crack with a prestressed force as the main force, which was a significant improvement in the ability to close cracks [9].

In the Hybrid SMP, a core of aramid fibres (made from Kevlar) is put into the Polyethylene terephthalate (PET) tube, then the Kevlar is tensioned, which causes the compression on orientated PET tube. Anchors are used to holding the aramid fibres in this position. So, this tendon will be in an equilibrium condition until the activation. The Pre-stressed aramid fibre (Kevlar) offers the needed force to close the concrete crack. The Hybrid SMP employed the prestressed force in the core for closing cracks which depended on the PET's strength; despite initial success, the prestresses in the tendon were relatively limited because the compressive strength of the PET sleeve was low and limited [9].

This paper describes the preliminary research on a new tendon with the aim of increasing the prestressed capacity by removing the PET and trying to make a more accessible activation phase. The new system is made of three parts; the first is a stainless steel tube, the second is a hybrid prestressed element (Kevlar) and another stainless steel tube that forms the core of the tendon, and the third is a metal ball that holds the system in equilibrium and acts as an activator. The tendon is in equilibrium until the activation phase. The prestressed force is released at this point, and the load is applied as a compressive force to cracks.

The initial findings demonstrate an ability to increase the prestressed load, which improves crack-closure ability significantly.

GENERAL CONCEPT

Heide and Schlangen demonstrated in 2007 that they could minimise the size of cracks in concrete by applying compressive forces to the samples. By emerging the shape memory alloys (SMAs), this finding took concrete self-healing systems in a new direction[10]. Due to the high cost of using the SMAs, Jefferson et al. (2010) suggested using Shape Memory Polymers (SMPs). The polyethylene terephthalate (PET) was considered a good shape memory polymer for the manufacturing of crack-closure technology. PET has the characteristic of shortening when heated. When constrained, its shape memory action develops stress which can be used to close cracks within the concrete element. Balzano et al. (2021) suggested an improved design for the SMP Tendons. The improved Hybrid Tendons were characterized by a pre-stressed Kevlar inner core constrained by an outer PET sleeve. When activated, the PET would shrink hence releasing the pre-stress stored in the inner core [9,7].

Although Jefferson et al. (2010) demonstrated and proved the general concept of crack closure, the ability to close cracks was limited to the force generated by PET shortening [7]. Also, Hybrid SMP tendons had some limitations because their ability remained limited to the strength of the PET sleeve [9].

This work aims to maximise the prestressed force by designing a new tendon, namely Pin-Ball Tendon (PBT). Figure 1 illustrates the concept of the new crack-closure system created for this study.

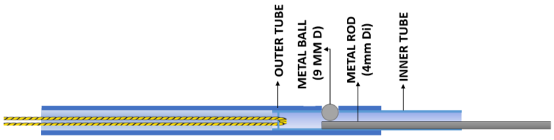

Fig. 1. Assembly of the tendon and locking of the components before the tension.

The PBT tendon is composed of three main parts:

- The inner component core (which is initially in tension),
- A steel tube (which is initially in compression),
- A metal ball that will tolerate shear force (it is the result of tension and compression forces).

The metal ball was placed into the holes in tubes by a metal rod in the first stage, and then the system was locked (Fig. 1). The second stage involved pre-tensioning the core elements (Fig. 2a), which is elastically tensioned. The entire system was "sealed" when the core achieved the desired prestress T. The system is now in an equilibrium state, and the external force has been released on the inner core. The outer element is now being compressed while the core elements are in tension. (Fig. 2b).

The prestressed PBT tendon will then be embedded into the structural element. When cracking occurs, the tendon becomes active (Fig. 3a). The ball will release upon activation, and the prestressed load in the inner core will close the crack (Fig. 3b). They do not need to receive any energy or recharge after the casting in concrete, so their service life lasts until they are activated to close the crack and release the prestressed force.

MATERIALS

The external element is a steel tube with an outer diameter of 16 MM, a wall thickness of 1.5 MM, and a drilled hole. The geometrical properties of the Outer element are illustrated in Fig. 4a.

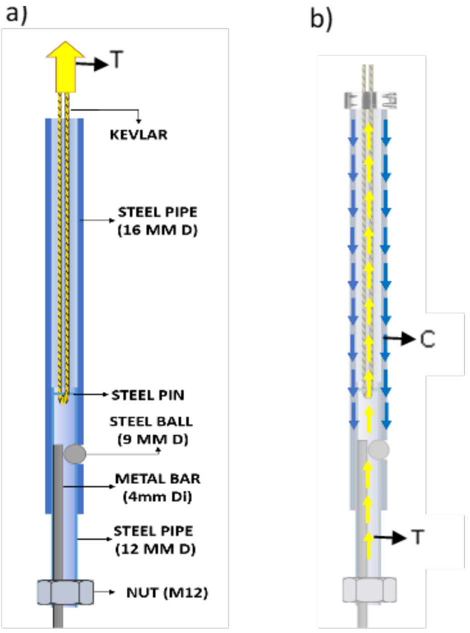

Fig. 2. General concept of PBT tendon.

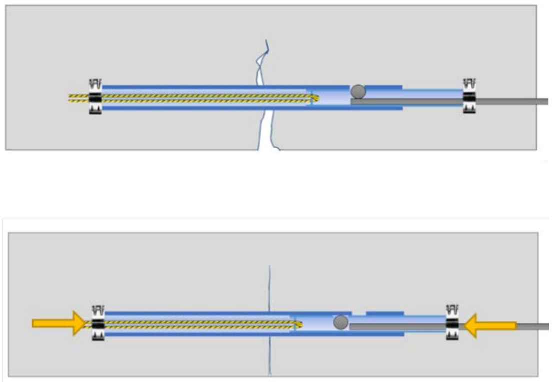

Fig. 3. Activation phase and closing cracks: the appearance of cracks in concrete (top) and closing crack by activating the tendon and releasing the prestressed force (bottom)

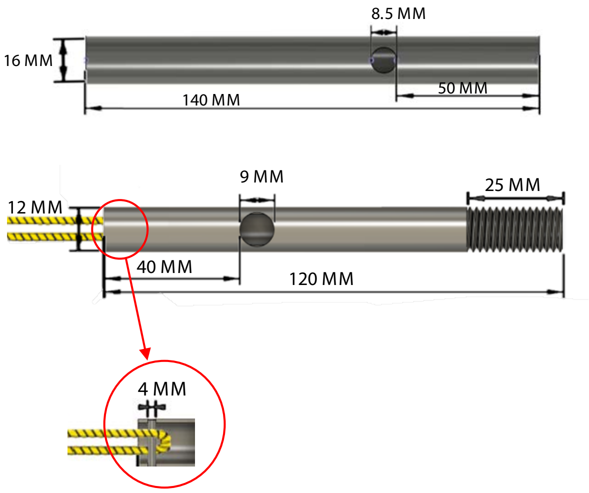

Fig. 4. The geometrical properties of the tendon: outer element (top) and inner element (bottom).

The inner element comprises a 12 MM steel tube with a 1 MM wall thickness and an aramid fibre called Kevlar, which is engaged with the 12 MM tube by a pin (Fig. 4a). A 9 MM hole has also been drilled in the inner tube. Once the Kevlar is tensioned, since the Kevlar is already engaged with the tube, the tensile stress will be distributed at the tube as well.

The inner and outer elements will be held together by a 9 MM steel ball. The steel ball was placed at the drilled hole in both elements, and then the tendons were sealed with a clamp (the total length of the tendons was 170 MM). The tubes are made of 304 stainless steel, and a 2.33 MM diameter Kevlar rope was used. Table 1 shows the mechanical properties of Kevlar.

Tensile Strength MPa	Young Modulus MPa	Density KG/M3
600	5-7 x103	1440

Table 1. Kevlar rope mechanical properties.

When the tendons are stretched, the force distribution in the tendon leads the steel ball to move towards the inside of the tubes. This situation will continue until the tubes slide on each other, and the force will be released. A piece of the iron rod was placed inside the tube to control the activation phase and prevent the ball movement. This rod will be displaced during the activation phase until it no longer obstructs the ball, and at that point, the tendon will be activated.

The tendon is hung on a load cell from the ropes side to begin the prestressing process. The inner element was then prestressed and sealed with commercially available clamps. Afterwards, the inner part was stressed to achieve a prestress of 2000 N stored in each tendon.

LABORATORY EXPERIMENTS

Preparation of the specimens

Two mortar beams with dimensions of 75x75x255 MM were tested for this preliminary study. Figure 5 depicts a typical cross-section of a mortar specimen with embedded prestressed PBTs. A tendon was embedded in the mortar beams at a distance of 15 MM from the bottom and an equal distance from the lateral sides.

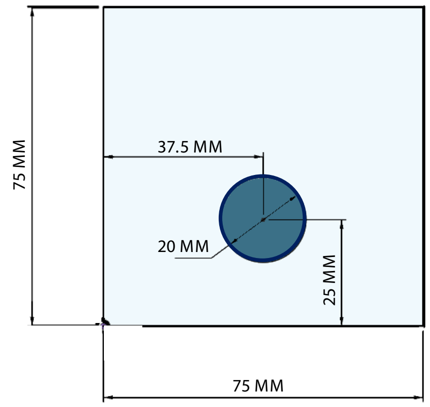

Fig. 5.Cross section of the mortar beam with embedded

The mortar paste was made using a 3:1 sand-to-cement ratio and a 0.6 water-to-cement ratio. The moulds were cast in three layers. In order to aid in the mortar's compaction, a slight vibration was imposed between each layer.

After 24 hours, the mortar beams were removed from the moulds, covered in wet hessian, and wrapped in plastic. The specimens were cured for seven days.

TESTING

A three-point bending test was carried out on the mortar beams after curing to form a crack. The bottom surface of the specimens was notched to 3 MM depth, and then the knife-edge plates adhered to the notch's sides for the purpose of attaching a monitoring gadget for recording the Crack Mouth Opening Displacement (CMOD) during the experiment.

The size of the generated crack was controlled by managing the applied force via feedback from a machine stroke displacement transducer and monitoring the CMOD.

Figure 6 depicts the relationship between the force and the CMOD and shows how the force initially rose until the first crack appeared in the samples. Then, as the deformation increased, the force reduced (due to decreasing the needed force for extending the crack). The unloading process began when the CMOD reached above 0.3 MM (Balzano et al. 2021). The final created CMOD was recorded at the end (when there was no force on the samples).

RESULTS AND DISCUSSION

For a more precise presentation of the results, the CMOD data were recorded before and after activation, and the crack width was measured using a magnifying camera and CAD software. Figure 7 shows the outcome of crack closure by tendons.

According to the recorded CMOD data, the tendons were correctly activated and functioning properly. In the first sample, the tendon managed to close 67.47% of the crack aperture, and in the second tendon, the crack closing rate was 64.94%, which are both significant results. The speed tendon crack's closure is another aspect to take into consideration. 90% of crack closure has been done within the first 8 seconds. Because of this performance, tendons are a helpful alternative for repairing and enhancing concrete in sudden events like earthquakes and explosions.

Pictures by the magnifying camera from before and after the activation phase confirm the monitoring device's outcomes and the effectiveness of the tendons (Fig.8).

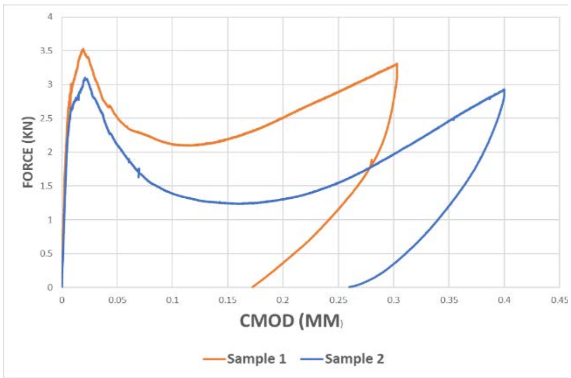

Fig. 6. Force-CMOD diagram recorded during the 3-point bending test for the mortar specimen.

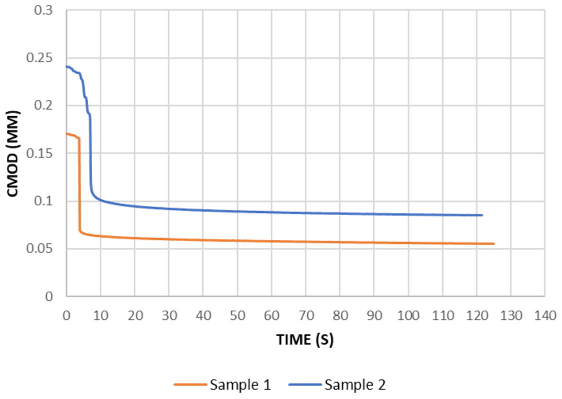

Fig. 7. The CMOD at the samples before and after the activation.

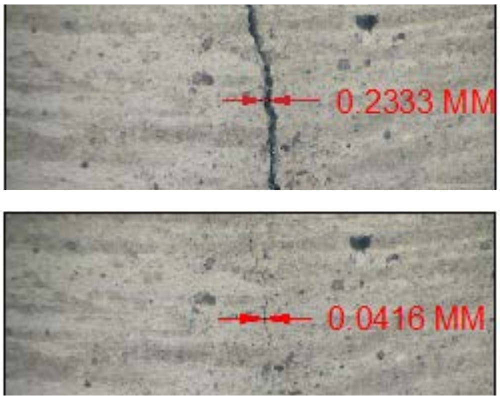

Fig. 8. Comparison of crack width before (top) and after (bottom) activation at sample 2.

CONCLUSION

The proposed PBT tendon has the capacity to store high stresses to close cracks in mortar beams successfully. In addition to showing an acceptable result in closing the cracks and providing an encouraging solution for the durability of concrete structures, the system also has the advantage of acting quickly, hence offering a potential repair mechanism in sudden accidents.

The study is still in its early stages, but the investigation into this prestressed system is ongoing.

Conflicts of interest
The authors declare no conflict of interest.

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Research Conference

E. Spezi and M. Bray (eds.) 2024. *Proceedings of the Cardiff University Engineering Research Conference 2023.* Cardiff: Cardiff University Press.
doi.org/10.18573/conf1

Cardiff University Engineering Research Conference 2023 was organised by the School of Engineering and held from 12 to 14 July 2023 at Cardiff University.

The work presented in these proceedings has been peer reviewed and approved by the conference organisers and associated scientific committee to ensure high academic standards have been met.

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First published 2024

Cardiff University Press
Cardiff University, PO Box 430
1st Floor, 30-36 Newport Road
Cardiff CF24 0DE

cardiffuniversitypress.org

Editorial design and layout by
Academic Visual Communication

ISBN: 978-1-9116-5349-3 (PDF)