Experimental study on the effect of the Prestressed Concrete Cylinder Pipe strengthened by external prestressed strengthening strands

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ABSTRACT: To evaluate the reinforcement effect of prestressed concrete cylinder pipe(PCCP) with external prestressed strands, a prototype test of PCCP was performed. The maximum width of the cracks in the outer concrete core at spring-line reduced from 1.2 mm to 0.1 mm after strengthening. The strains of the core concrete changed slightly and the width of cracks in the outer concrete core was maintained at 0.1mm when the internal water pressure gradually increased to the design pressure of 0.9 MPa. The strengthened pipe was capable of sustaining the design internal water pressure and the water tightness property was in a good state. The strains of the steel strands were all below the tensile strain level. The reinforcement of PCCP with external prestressed steel strands is able to meet the strengthen requirement of the test and the strengthening effect is evident.
KEYWORDS: prestressed concrete cylinder pipe; external prestressed steel strands; wires breakage; strengthening effect

1 INTRODUCTION

Prestressed concrete cylinder pipe (PCCP) is a composite structure composed of a concrete core, a steel cylinder, prestressing wires and a mortar coating. It has several merits, such as a high capacity for withstanding loading, strong impermeability, strong durability, and cost-effectiveness (S. Ge et al., 2014). PCCPs have been adopted for more than 70 years(J.J. Roller et al., 2013) since their invention in 1942, and have been widely utilized in long-distance pressured water transportation system in the United States, Mexico, Canada, China and other countries. PCCP failures may lead to a catastrophic loss without warning due to the pipes' dimension and high internal water pressure (S. Ge et al., 2015).
To strengthen the deteriorating pipe, a series of studies involving the replacement, internal reinforcement (steel cylinder relining, steel cylinder slip-lining, carbon fiber reinforced polymer (CFRP) reinforcement), external reinforcement (CFRP tendons, prestressed steel strands) and other methods were conducted by R. Timothy Ball(2012), S. Rahman(2012), Michael K. Kenny(2014), Michael Ambroziak(2010), Mehdi S. Zarghamee(2013,2014), Dou Tiesheng(2017) and Raafat EL-Hacha(2006). Compared with other reinforcement methods, the significant advantage of the external reinforcement is that it actively compensating for the prestress loss caused by the broken prestressing wires[5] and it is unnecessary to take the deteriorating pipes out of service, which is especially suitable for pipes that cannot be dewatered. The well-known large-scale application of the external prestressed strands is the Great Man-

Made River pipelines in Libya (H. Elnakhat et al., 2006). However, little progress has been made in the strengthening effect of the external prestressed strands on PCCP.

To evaluate the strengthening effect of external prestressed steel strands on PCCP, a prototype test under variable internal water pressure was conducted for a prototype PCCP. The strains of the concrete core, prestressing wires and strands before and after the reinforcement were monitored in real time and then analyzed. The structural behaviors of the pipe and the strengthening effect of the method are discussed in this paper.

2 TEST SCHEME

2.1 Test material

(1) PCCP The structure of the embedded prestressed concrete cylinder pipe (PCCPE) adopted in this test is depicted in Fig. 1. Tab. 1 provides several key parameters of the PCCP. The design value is 0.6 MPa +0.276 MPa = 0.876 MPa ≈ 0.9 MPa (Refer to ANSI/AWWA C304, *Standard for Design of Prestressed Concrete Cylinder Pipe*).

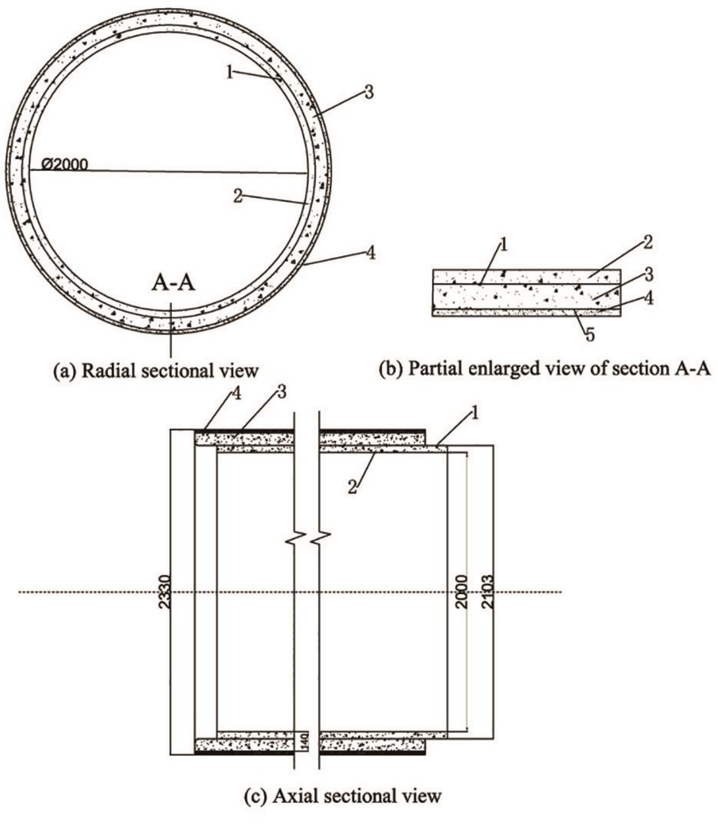

Fig. 1 The structural drawing of PCCPE (1-Cylinder, 2-Inner concrete core, 3-Outer concrete core, 4-Mortar, 5-Prestressing wires, Dimension: mm)

Tab. 1 Key parameters of the tested PCCP

Key Parameters	**Values**	**Key Parameters**	**Values**

Inner Diameter of PCCP/mm	2000	Compressive Strength of concrete /MPa	55
Thickness of core concrete/mm	140	Modulus of concrete/(N/mm^2)	2.786×10^5
Inner Diameter of cylinder/mm	2100	Compressive Strength of mortar /MPa	45
Thickness of cylinder/mm	1.5	Modulus of wire/(N/mm^2)	1.93×10^5
Diameter of wires/mm	6	Spacing between each wire/mm	22.1

(2)Steel Strand The strand adopted in the test is 1×7-15.20-1860 (Refer to ISO 6934-4:1991, Steel for the prestressing of concrete-Part 4: Strand, NEQ). Tab. 2 gives the key parameters of steel strands. In general, each strand is protected by three anti-corrosion barriers. The strands were wrapped externally outside the pipe with the 62 mm spacing between each strand according to the service water pressure and experience gained from Libya's work (H. Elnakhat et al., 2006 and R. Ojdrovi et al., 2008).

Tab. 2 Key parameters of the adopted strands

Key Parameters	Values
Nominal diameter without PE /mm	15.2
Nominal section area without PE/mm^2	140
Nominal tensile strength /(N/mm^2)	1860
Modulus /(N/mm^2)	1.95×10^5
Coefficient of linear expansion/ (1/°C)	1.2×10^{-5}
Outer diameter with PE/mm	22

2.2 Apparatus and procedures

A prototype test was conducted in an assembled apparatus (Fig. 2) and the apparatus was mainly constituted by two PCCPs and a fitting made of steel.

Fig. 2 The schematic diagram of the test apparatus

The entire test process contains five load stages and these five stages were divided into twenty-four steps, as shown in Tab. 3. Furthermore, in most of the actual pipe failures modes, most pipes fail at 4 or 8 o'clock, not at invert, crown, or spring-lines (S. Ge et al., 2015). The position of 8 o'clock was chosen in this test for convenience.
The design of tensile strength factor for strands is 0.63 (Y. Zeng, 2012 and M. Zhe, 2017). To prevent a prestress loss due to the retraction of clips and the stress relaxation of strands, excessive stretching is essential. The tensioning process is divided into six stages, which are 20%, 25 %, 50%, 75%, 100% and 115%. Tensioning is performed simultaneously from both sides and in a symmetrical manner along the pipeline axis.

Tab. 3 The entire procedure and load steps

Load Stage	Load Step	Details	Internal water pressure/MPa
	1	Preparation	0
	2		0.1
	3		0.2
I	4	Increase internal water pressre, hold for 5 minutes	0.3
	5		0.4
	6		0.5
	7		0.6
	8		0.6
II	9	Break prestressing wires manually until visible cracks propagate.	0.6
	10		0.6
	11		0.5
III	12	Decrease internal water pressre, hold for 5 minutes	0.4
	13		0.3
	14		0.2
	15		0.2
IV	16	Tensioning operation of steel strands	0.2
	17		0.2
	18		0.3
	19		0.4
	20		0.5
V	21	Increase internal water pressre after tensioning, hold for 5 minute	0.6
	22		0.7
	23		0.8
	24		0.9

3 TEST RESULTS AND DISCUSSION

3.1 Results Revised

Hoop compressive strains were produced in the core concrete owning to the contribution of the prestress applied by prestressing wires. Therefore, the hoop tensile strain caused by internal water pressure in each component of the PCCP will be balanced by the compressive prestrain. In other words, only when the tensile strain is larger than the compressive prestrain will the real tensile strain be measured. Therefore, the real strain state of the core concrete and prestressing wires should be revised by the following equation:

$$\varepsilon_r = \varepsilon_i + \varepsilon_m$$

where ε_r is the real strain of the component, ε_i is the initial prestrain caused by prestress, ε_m is the strain measured by strain gauges. Moreover, positive values represent the tensile strain and negative values represent the compressive strain.

To assess the state of PCCP, the onset of micro-cracking in the concrete core is when the strain of core concrete reaches $1.5\varepsilon_t' = 1.5 \times \frac{0.52\sqrt{f_{cu,k}}}{E_c} = 207\mu\varepsilon$, where ε_t' represents the elastic strain when the stress of the core concrete reaches the design value of tensile strength. Once the strain reaches $11\varepsilon_t' = 1522\mu\varepsilon$, visible cracks are likely to appear.

3.2 Results and discussion

Fig. 3 exhibits the hoop strain in the prestressing wires of section 1(Fig. 3 (a)), section 2 (Fig. 3 (b)) and section 3(Fig. 3 (c)) with continuous load steps. The strains of section 1 and section 2 changed obviously with the wires breaking, while the strains of the prestressing wires away from the wires breakage area (S3) did not show evident variation.

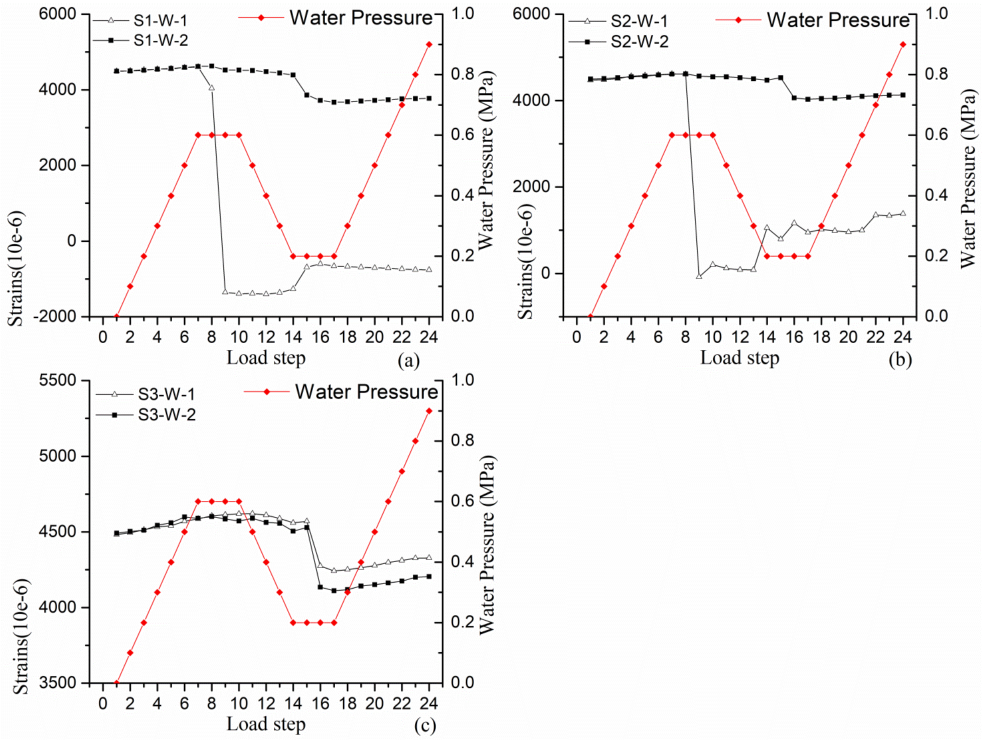

Fig. 3 The strain curves of prestressing wires((a) Section1, (b) Section2, (c) Section3

Fig. 4 presents corresponding strains in the inner core concrete of section 1(Fig. 4 (a)), section 2(Fig.4 (b)), the outer core concrete of section 1(Fig. 4 (c)), section 2(Fig. 4 (d)) and section 3(Fig.4 (e)).

A growth in the internal water pressure linearly increased the strains in the inner core concrete and the outer core concrete during the initial load stage (load stage I). The strains at crown, invert and spring-line orientations of core concrete, no matter inner or outer core concrete, were almost equal.

The strain in the core concrete changed nonlinearly as the percentage of broken wires increased during load stage II. The strain in the inner core concrete at crown of each section showed a greater magnitude of change than the invert and spring-line as the percentage of broken wires increased. Different from the phenomenon in inner core concrete, the strain at spring-line was larger than the crown in outer core concrete, as illustrated in Fig.4 (c) (d) and (e). In addition, as exhibited in Fig.4 (e), section 3 in the outer concrete core showed a slight variation in strain, suggesting that breaking wires manually performed no remarkable influence on the area away from wires breakage. Visible cracks on the surface of mortar coating first occurred at the pipe spring-line when the percentage of broken wires was up to 20.18% through field observation. The appearance of these cracks intensified the damage of the pipe structure and made the pipe unable to sustain any tensile stress. Interfacial debonding between the mortar coating and outer concrete core was discovered at the spring-line. The maximum width of cracks in the outer concrete core at the spring-line was 2.2 mm via field observation.

After the operation of wire breakage, the subsequent load stage (load stage III) decreased the internal water pressure to the artesian pressure (0.2MPa). The strains in the core concrete showed a decline with the water pressure decreasing. On the basis of field records, the micro-cracks in the concrete core and mortar coating displayed a slight closure. However, the maximum width of cracks in the outer concrete core at the spring-line was still 1.2 mm.

The fourth load stage was tensioning operation of strands. In general, the overall changing tendency of the strains in the core concrete was evident. The strains in the core concrete all showed a drastic drop during the process of tensioning. The maximum width of cracks in the outer concrete core at spring-line was reduced from the former 1.2 mm to 0.1 mm (Fig. 5). Most visible cracks show closure property and are eventually difficult to found.

The final load stage (load stage V) involved increasing the water pressure again until the pressure reached the design value. The strain of each measuring point when the water pressure was again up to 0.6 MPa was far lower than the strain before strengthening. Although the strain at each measuring point showed a slight growth with the continuing increase in water pressure till load step 24, the strain level was still much lower than the level when load step 10 finished. The maximum width of the cracks in the outer concrete core at spring-line almost kept invariant at approximately 0.1 mm as the pressure increased. The water tightness of test pipe was still in a good situation according to the field observation.

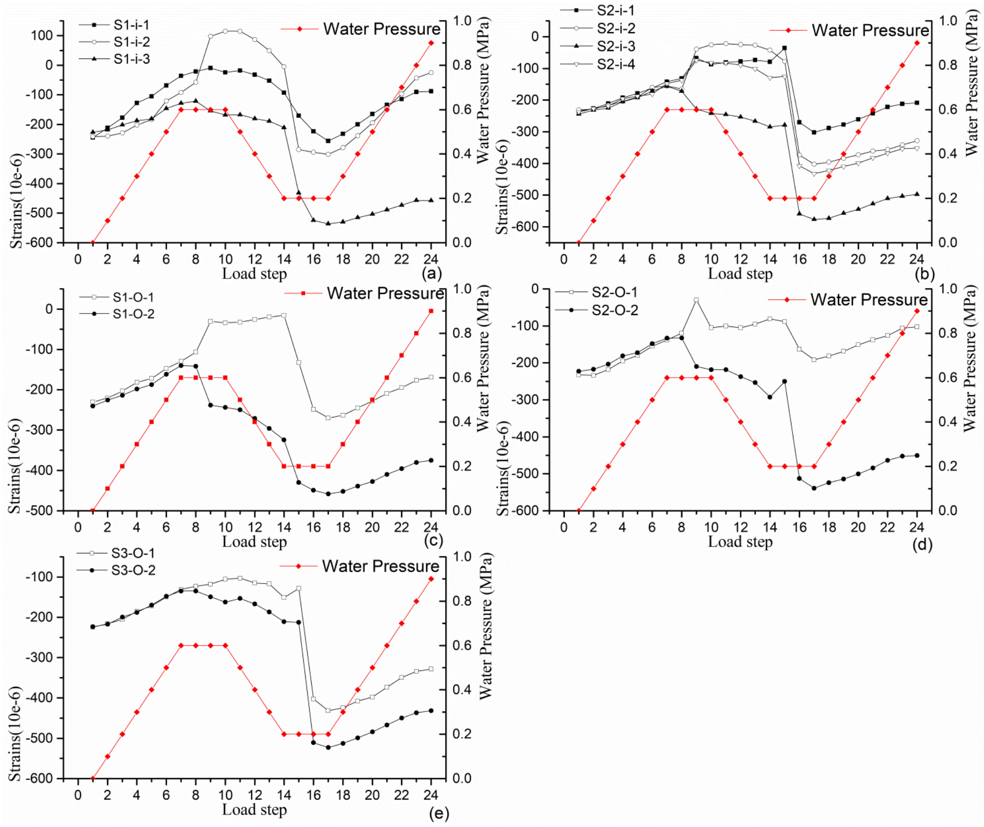

Fig. 4 The strain curves of core concrete ((a)Section1 of Inner Concrete core, (b) Section2 of Inner Concrete core, (c)Section1 of Outer Concrete core, (d) Section2 of Outer Concrete core, (e) Section3 of Outer Concrete core)

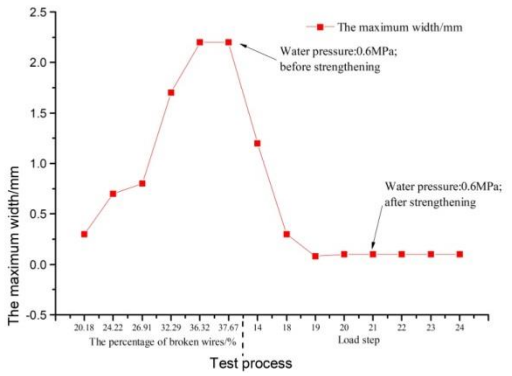

Fig. 5 The change of maximum width of cracks in outer concrete core

Fig.6 gives the strains of each measuring point in the prestressed strands. The nominal tensile strain ε_s is calculated by the following equation.

$$\varepsilon_s = \frac{\sigma_s}{E_s} = \frac{1860\text{MPa}}{1.95 \times 10^5 \text{N/m}^2} = 9538.46\ \mu\varepsilon$$

The strains of measuring points in Fig.6 were all below the tensile strain level. The hoop strand did not yield after the tensioning operation.

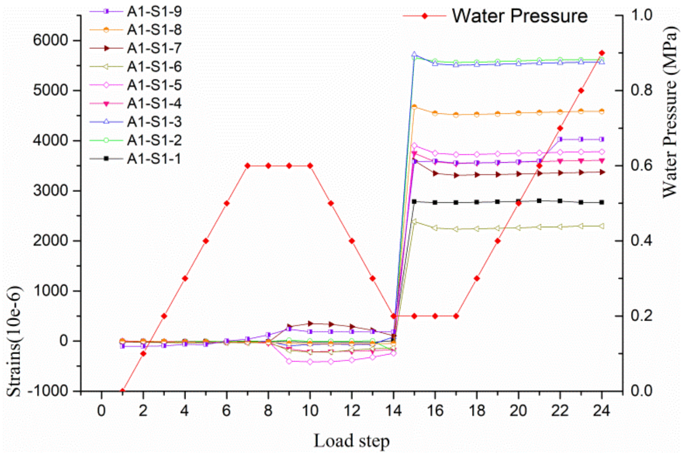

Fig. 6 The strain curves of prestressed strands

4 CONCLUSIONS

A prototype test was performed to investigate the strengthening effect of external prestressed steel strands on PCCP. Based on the test results, the following conclusions can be drawn:

(1)The strains in prestressing wires showed slight variation with the change of internal water pressure during the entire process. Breakage of the wires leads to significant prestress loss within a certain distance from the broken point. The prestress resumes partially beyond a certain length due to the bond quality of mortar coating with prestressing wires.

(2)The strands can not only constrain the crack propagation in the concrete core, but also compensate the prestress loss due to the wire breakage. The test pipe was able to sustain the design internal water pressure after strengthening and the water tightness property was in a good

condition. In addition, the maximum width of the cracks in the outer concrete core at the spring-line was reduced from the 1.2 mm to 0.1 mm because of the contribution of the strands. The effect of PCCP strengthened with external prestressed strands is evident.
(3)The strains of the steel strands were all below the tensile strain level. The method of PCCP strengthened with the external prestressed strands is able to meet the strengthening requirement of the test and is an effective method for strengthening PCCP. The study presented in this paper lays the groundwork for future research into the reinforcement of PCCP with external prestressed steel strands.

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