Research Article

Failure Mechanism and Mechanical Properties of a Retard-Bonded Prestressed Concrete Girder While Curing

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Received 28 February 2019; Accepted 15 April 2019; Published 23 May 2019

Academic Editor: Flavio Stochino

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The mechanical performance and failure mechanism of a retard-bonded (RB) type prestressed concrete (PC) girder in different curing periods are investigated through four-point loading experiments. Six RB-type PC girder specimens with three RB prestressed tendons (PTs) along the longitudinal direction were fabricated. The measurements include the following: the retard-bonded agent ages versus the load-carrying capacity of the girder, the deflection of girder, the strain distribution at key cross sections through the girder, the pressure at PT tensile and anchoring ends, crack distribution, and so on. The experimental results indicate that when stretching the PT within proper tensile period, the retarder curing ages have less impact on the cracking load and a greater impact on the ultimate bending strength; the ultimate bending strength of the RB-type PC girder increased with increased retarder curing. Nonetheless, stretching the PT after excessive retarder curing (after the retarder had solidified completely), the cracks in the PC girder's pure bending segment are wider and less numerous, the ultimate bending strength of the girder is lower, and its ductility is poor.

1. Introduction

Retard-bonded (RB) prestressed concrete (PC) structures, as a new type of PC structure, at different retarder curing stages, offer advantages of convenience in construction akin to unbonded (UB) PC structures and a force transfer mechanism similar to that acting in a bonded PC structure [1].

The retard-bonded prestressed tendon (RBPT), which is made of prestressed tendons (PT), a certain thickness of retarder material, and a high density polyethylene (HDPE) protective pipe with internal screw-threading, is shown in Figure 1. The retarder material layer permits movement of the PT under tension and also provides bond strength between the PT and HDPE protective pipe when the retarder material layer has fully cured: the RBPT will then rely on the same force transmission mechanism as a bonded PT.

It usually takes one or two years from manufacture for the complete solidification of the retarder of the RBPT [2]. The curing process (of the retarder) can be divided into two

stages from an engineering perspective: a proper tensile period and a curing period (Figure 2). The period when the viscosity of the retarder is less than 30,000 Pa·s and the viscous resistance on the RBPT provided by the retarder material layer is equivalent to that in the unbonded condition is the proper tensile period. After this, the retarder evolves into a malleable solid state and gradually solidifies. The degree of retarder curing can be expressed by its Shore D hardness. When this reaches 80, the retarder is considered to have undergone complete solidification, and the force transfer mechanism between the PT and the concrete in the RBPC structure is same as that in a bonded PC structure [3].

In recent years, the RBPC has been widely used in the field of civil engineering due to extensive research and development work carried out by Asian researchers. In the 1990s, Japanese scholars explored the curing properties of different types of retarder materials and methods of measurement of the friction coefficient of stretched PT, pointing out that the RBPC girder has a similar load-carrying capacity and mode of failure to the UB-type PC girder [4–6]. The

FIGURE 1: Retard-bonded prestressed steel tendons (RBPT).

FIGURE 2: The retarder curing process.

research results indicated that stretching the PT when the viscosity of the retard-bonded agent is less than 30000 Pa·s, the coefficient of friction caused by the local deviation per meter of the prestressed duct and the coefficient of friction between the PT and the prestressed duct are less than 0.004 and 0.3, respectively. The stress loss of the PT is equivalent to the one of unbonded PT. Therefore, in Japan's concrete design specification, 30000 Pa·s is set as the critical viscosity state of the retard-bonded agent for applying tension. It is suitable to stretch RBPT when the viscosity of the retard-bonded agent is less than the critical viscosity state [7]. At the same time, it is also found that the change of the external temperature has a great influence on the curing process of the retard-bonded agent; with the increase of the external temperature, the solidification of the retard-bonded agent is accelerated, and with the decrease of the temperature, the curing of the retard-bonded agent is delayed. Since 2000, the Central Research Institute of Building and Construction, MCC Group, and other research institutions have developed a new type of RBPT structure using epoxy resin as the retarder. A series of studies thereon, including RBPT manufacturing techniques, physical property testing of the cured retarder, and measurement of the friction coefficient of RBPT, have been conducted and laid a foundation for the system's engineering applications [8–12]. The retard-bonded agent has good flow properties before the proper tensile period; after the retard-bonded agent was fully cured, the compressive strength, flexural strength of the retard-bonded agent, and the bond strength between the RB and the PT can reach to 50 MPa, 20 MPa, and 4 MPa, respectively, which can meet the engineering requirements [13].

For the mechanical properties after the retarder reaches complete solidification, scholars studied the tension-friction performance of the PT of the RB PCB and conducted trials to assess the bending capacity of the beam: the results indicate that after a certain period under tension, the working performance of RBPC structures is the same as that of bonded PC structures [9, 14]. Comparison of the concrete crack calculations between the RB PCB and UB prestressed concrete girders revealed that the cracking of the RB PCB matched that of the bonded PC girder [15–18]. For RBPC structures, research under a given retarder formulation, which considered the local deviation per-meter κ of the prestressed duct and the coefficient of friction μ between the PT and the prestressed duct, has been conducted [7, 19, 20]. A special retarding adhesive material had been developed which meets technical requirements: physical and chemical property tests were conducted on the unique properties of this retarding adhesive material. The results indicate that the retarding adhesive offers excellent performance, and combined with the performance characteristics of the retarding adhesive, the curing process and the anti-interference performance are analysed [3]. The effect of temperature on curing period and filler anti-interference performance is clarified. In addition, a series of studies examining the mechanical properties of the retard-bonded agent were also completed. The tensile strength and the flexural strength in the cured state were measured, and Young's modulus of elasticity and Poisson's ratio of the retard-bonding agent material were obtained. The results show that the retard-bonded agent has excellent mechanical properties comparable to those of bonded prestressed concrete. Such research mainly focuses on the influence of tensile factor and deviation coefficient of the RBPT in the tensile period and the mechanical properties of the RBPC structure after the retarder completely solidified. However, retarder curing will take 1 or 2 years; there are few reports on the influence of degree of curing on the mechanical properties of the structure, which affects its application and development.

In summary, in the tensile period, there are few reports on the effect of degree of curing on the structural force transfer mechanism during the gradual curing of the retarder over 1-2 years. Here, at a given degree of curing in the proper tensile period, after stretching the prestressed tendons, a bending performance comparison test is conducted. A qualitative assessment of the influence of retarder curing on the prestressed girder load-carrying capacity is discussed; in contrast, stretching the PT of girder specimens after different curing times allowed measurement of girder carrying capacity to verify the influence of the tensile period of PT on the mechanical properties of this type of structure. These provided the theoretical basis for the engineering application.

2. Experimental Work

2.1. Test Survey. To study the influence of degree of retarder curing on the mechanical properties of the PCBs, six retard-bonded PCBs were designed. The girders are 3300 mm in length and 300 mm and 400 mm in width and height, respectively. The concrete grade is C50 (with a compressive

strength of 23.1 MPa), and $\Phi 12$ HRB400 (yield strength, 400 MPa) steel bars were used as longitudinal reinforcement, with $\Phi 8$ HPB300 (tensile strength, 270 MPa) used as stirrups. The spacing of stirrups in the pure bending girder segments is 250 mm and in the girder bending shear segments is 80 mm. Three 12.7 Φ 15.2PTs, with strength f_{ptk} of 1860 MPa, are arranged on each girder along the longitudinal direction [21]. Both the stretched end and the fixed end are fitted with a YM15-1J clip anchor. PC girder specimen reinforcement and the arrangement of the tensioning device are shown in Figure 3.

The tensile period of the retard-bonded agent used for the girder experiment is 8 months, and the curing period is 2 years. To assess the influence of stretching period of prestressed tendons on the mechanical properties of the structure, the prestressed tendons were stretched according to the dates shown in Table 1 (on 2017.7.18, 2017.10.25, and 2017.12.15). Firstly, on 2017.7.18, in the tensile period, we stretched the prestressed tendons of the four test specimens to their design load. Then, the prestressed tendons of Sep. PC 5-6-8 and Sep. PC 6-8-8 were stretched on 2017.10.25 and 2017.12.15, respectively. The Shore hardness values are 60.8 and 80.5 for Sep. PC 5-6-8 and Sep. PC 6-8-8, corresponding to a given retarder curing period and a fully cured period. To obtain the effect of retarder curing process on the mechanical properties of the girder specimens, with the curing of the retarder, the flexural capacity of the prestressed girders was measured every 3 months. The properties and states of the retarder, at different degrees of curing, are summarized in Table 1.

2.2. Test Setup and Loading Protocol. The loading jack is shown in Figure 4: the prestressed tendons are anchored, and a 500 kN loading sensor is installed between the anchor tool and the girder. The same type of sensor is installed in the same place at the other end, and a jack is used to apply load till the stress reached the design tension value. When the prestress was stabilized, the anchorage was clamped, and the stretching process completed.

Prestressed concrete girder loading devices and monitoring instrument devices are shown in Figure 5. The four-point loading method was used in monotonic static loading experiments [22]. The loading protocol involved the following processes: the load was monotonically increased before the concrete cracked, and then the girder was unloaded when the concrete cracked; after unloading, the load will be continuously reapplied to 1.1 times the cracking load; to eliminate the influence of the bond resistance of the retarder, this load was held for 5 minutes, then increased to 1.2 times the cracking load, and held for 5 minutes, and this cycle was repeated until the specimen reached its ultimate strength capacity, after which it was unloaded; the residual deflection was measured and then the test was stopped.

2.3. Test Monitoring Content. The tensile stress at both ends of the prestressed tendons would be mainly monitored in prestressed stretching tests. In the four-point monotonic static loading experiments, the instrument mainly monitored

the following: the load-carrying capacity of the girder, vertical deformation, the strain in the concrete in pure bending segments, the stress at both ends of the prestressed tendon, and the concrete crack condition [23].

The design load on the girder was collected by the pressure sensor on the jack. The strain in the concrete was measured by uniaxial strain gauges pasted onto the girder surface. The development of concrete cracking was measured by a crack tester. The arrangement of measuring points is shown in Figure 6. Prestressed tendon stresses were measured via the pressure sensor installed at both ends of the girder. The hydraulic actuator displacement transducers are used to measure the deflection of the girder [24].

2.4. Retarder Curing Properties. To assess the curing state of the retarder inside the RB PCB, when stretching PT in the RB PCB, we stripped the plastic sleeve at the end of the PT, collecting the retarder attached on the surface of RT with beakers and other containers, then putting the retarder in similar environmental conditions to the other PCB specimens, and then using an LX-A Shore hardness tester to measure the degree of curing of the retarder at regular intervals while observing the apparent characteristics of the retarder (Figure 7 and Table 1).

2.5. Finite Element Analysis Model. The finite element model of the RBPC girder is established using ABAQUS package [25]. Owing to the mechanical properties of the retard-bonded agent changing gradually with time during the curing period, it is difficult to simulate the six experimental specimens. Only two specimens, unbonded and bonded PC girder, are simulated. The FE model is shown in Figure 8.

Eight-node linear brick elements (the C3D8R element) are used for simulating the concrete and the retard-bonded agent. The truss elements (the T3D2 element) are used for simulating the reinforcement and the prestressed tendons.

For the unbonded PC girder, the contact relationship between the PT and the concrete is coupling (Figure 8(b); for the bonded PC girder, the PT is embedded in the concrete (Figure 8(c)) [26, 27].

Young's modulus of elasticity and Poisson's ratio of the concrete are measured by material test, and an elastoplastic damage constitutive model has been used. Stress-strain diagram of the reinforcement and prestressed tendons is considered elastic perfectly plastic. The boundary condition and loading protocol are the same with the experimental ones.

3. Bending Test Results and Discussion

To investigate the influence of the stretching of PT at different retarder curing stages and retarder hardness on the mechanical properties of the girders, when the Shore hardness of the retarder is 0, 60.8, 81.3, and 93.0, a series of girder bending tests were conducted. Through the comparison and discussion of the girder bending test results, including girder deflection curves, concrete strain distributions at the midspan along the girder height, the

FIGURE 3: Test specimen.

TABLE 1: Properties and states of retard-bonded agent at different degrees of curing.

Specimen	Date	Prestressed tensile test		Date	Girder load-carrying capacity test	
		Shore hardness value of RB	Curing state of the retarder		Shore hardness value of RB	Curing state of the retarder
PC 1-0-0	2017.07.18	0	Dark grey viscous liquid	2017.07.19	0	Dark grey viscous liquid
PC 2-0-6	2017.07.18	0	Dark grey viscous liquid	2017.10.28	64.8	Grey solid, extremely hard
PC 3-0-8	2017.07.18	0	Dark grey viscous liquid	2017.12.17	81.3	Grey solid, extremely hard
PC 4-0-9	2017.07.18	0	Dark grey viscous liquid	2018.03.17	93.0	Grey solid, extremely hard
PC 5-6-8	2017.10.25	60.8	Grey-yellow solid, harder	2017.12.18	81.3	Grey solid, extremely hard
PC 6-8-8	2017.12.15	80.5	Grey solid, extremely hard	2017.12.18	81.3	Grey solid, extremely hard

Note. The specimen was named PC *-*-* , where the first asterisk represents specimen number, the second asterisk indicates the hardness of the retard-bonded agent when the PT is stretched, and the last asterisk indicates the Shore hardness of the retard-bonded agent.

FIGURE 4: Prestressed tendon setup. (a) Anchor end. (b) Stretched end.

development of the cracks in the girder, the stress at the end of the PT tensile side and anchoring side, and so on, the effect of degree of retarder curing on the mechanical performance of the girder was evaluated.

3.1. Load-Deflection Curve. The load-deflection curves of each girder are shown in Figure 9: the horizontal coordinates express the deflection of the PCB, the vertical coordinates express the load applied to the top of the prestressed girder. Figure 9(a) shows the influence of the degree of retarder curing in the tensile period on the load-deflection relationship of the four test specimens, and Figure 9(a) also shows the analytical results of unbonded PC model and bonded PC model; Figure 9(b) shows the

load-deflection curve of the three beams when the retarder Shore hardness reached 81.3. Tensioned prestressed tendons in these three beams were stretched under different curing conditions.

In Figure 9, the RBPC girder's load-carrying capacity can be divided into the following stages: before the prestressed girder crack, the load-deflection curve changed linearly and the stiffness of the girder was constant. When the load reached the cracking load, the concrete within the tensile zone cracked, the stress is redistributed, and the pre-stressed tendons and the longitudinal reinforcement arranged within the lower flange of the girder are subjected to tensile force. At this time, the stiffness of the girder began to decrease. As the vertical load increased, the stiffness of the girder decreased but the deflection in the girder span increased.

FIGURE 5: Loading devices and monitoring instruments.

FIGURE 6: Strain gauge measuring position. (a) The side surface. (b) The bottom surface. (c) The top surface.

FIGURE 7: Apparent state and Shore hardness of retarder at different stages of curing. (a) Fluid state and 0. (b) Semifluid and 60.8. (c) Solid and 80.5. (d) Solid and 93.0.

At the moment when the concrete crushed in the pure bending segment, the girder reached its ultimate bending strength. The deflection of the girder increased by varying degrees during this process and until the beginning of the unloading process; thereafter, upon decreasing the load, the deflection of the girder decreased. After complete unloading, residual deformation was observed. The cracking load, the

ultimate bending strength, and the maximum fully unloaded residual deformation are listed in Table 2.

As seen in Figure 9(a), before concrete cracking, the initial stiffness of the experimental results is in good agreement with the analysis results of bonded and unbonded girder specimens. After cracking of concrete within the tensile zone, the bending stiffness of the experimental

FIGURE 8: FE model. (a) Mesh of concrete C3D8R element. (b) Contact between prestressed tendons and concrete of unbonded PC model. (c) Contact between prestressed tendons and concrete of bonded PC model.

FIGURE 9: Vertical load-deflection curves. (a) Influence of the degree of curing of the retarder. (b) Influence of tensile period on prestressed tendons.

TABLE 2: Cracking load, maximum bending strength, and residual deformation of PC girders.

Specimen	Shore hardness of retarder under tension (D)	Shore hardness of retarder under bending (D)	Test batch	Cracking load (kN)		Ultimate bending strength (kN)		Maximum residual deformation (mm)
				Theoretical value	Measured value	Theoretical value	Measured value	
PC 1-0-0	0	0	1	235	245	481	506	12.2
PC 2-0-6		60.8	2	229	227	481	557	7.8
PC 3-0-8		81.3	3	226	240	481	597	18.2
PC 4-0-9		93.0	4	229	250	481	609	27.2
PC 5-6-8	60.8	81.3	3	232	230	481	536	47.4
PC 6-8-8	80.5	81.3	3	219	225	481	526	24.7
Unbonded PC model	—	—	—	235	253	481	507	—
Bonded PC model	—	—	—	229	245	481	614	—

degrades gradually, and the degradation rate is faster than their simulation results. The ultimate bending strength of all of the RBPC girder experimental results is between the ultimate bending strength of the unbonded PC girder simulation result and ultimate bending strength of the bonded PC girder simulation result. It is shown that in the curing process of the RBPC girders, the retard-bonded agent has significant influence on the bearing capacity of the structure. The higher the Shore hardness is, the closer the ultimate bending strength of the RBPC girder is to the ultimate bending strength of the bonded prestressed concrete girder.

The theoretical values of the cracking load and ultimate bending strength in Table 2 were calculated according to the JTGD62-2004 2004 and (ACI318M-05 2005) [28, 29]. The assumptions are given as follows:

- (1) Strain in reinforcement and concrete shall be assumed directly proportional to the distance from the neutral axis.
- (2) Tensile strength of concrete shall be neglected in axial and flexural calculations of reinforced concrete.
- (3) Stress in reinforcement below yield strength shall be taken as Young's modulus of elasticity times steel strain. When the strain is greater than the corresponding reinforcement yield strain, the stress shall be considered independent of strain and equal to yield strength.
- (4) Maximum usable strain at extreme concrete compression fibre shall be assumed equal to 0.003. The relationship between concrete compressive stress distribution and concrete strain shall be assumed to be quadratic parabola.
- (5) An equivalent rectangular concrete stress shall be assumed to satisfy requirements of 4.

So, the rectangular cross-section flexural capacity of the girder should be calculated:

$$\gamma_0 M_{nd} = f'_c b x \left(h_0 - \frac{x}{2} \right) + f'_s A'_s (h_0 - a'_s) + (f'_{pd} - \sigma'_{p0}) A'_{ps} (h_0 - a'_p). \quad (1)$$

Concrete compression zone height x can be calculated as follows:

$$f'_s A_s + f_{pd} A_{ps} = f'_c b x + f'_s A'_s + (f'_{pd} + \sigma'_{p0}) A'_{ps}. \quad (2)$$

The section compression zone height should meet the following requirements:

$$x = \xi_b h_0. \quad (3)$$

When the stress on the concrete compression area is equal to the stress on the longitudinal reinforcement plus the prestressed longitudinal tensile stress,

$$x = 2a', \quad (4)$$

where γ_0 = importance coefficient for the bridge structure; M_{nb} = nominal flexural strength of beam; f'_c = specified compressive strength of concrete; f'_s = calculated tensile

stress in reinforcement at service loads; f'_s = stress in compression reinforcement under factored loads; f'_{pu} = specified tensile strength of prestressing steel; f'_{py} = specified yield strength of prestressing steel; A_s = area of longitudinal reinforcement; A'_s = area of non-prestressed longitudinal compression reinforcement; A_{ps} = area of prestressing steel in the flexural tensile zone; A'_{ps} = area of prestressing steel in the flexural compression zone; b = width of compression face of member; h_0 = height of effective section; a, a' = distance of tensile zone, compression area of ordinary steel, and prestressed tendons to the edge of the tensile zone, the compression zone edge; a'_s, a'_p = compression zone ordinary reinforcement points, the distance between the prestressed reinforcement centroid and the compression area edge; σ'_{p0} = compression zone prestressed reinforcement at the neutral axis; and ξ_b = the vertical compression zone and the compression zone of the concrete which simultaneously reach the design strength within the compression zone height in a balanced design paradigm.

Comparing the load-deflection curves in Figure 9 (see specimens in Table 1), although the degree of retarder curing was different, the difference between the cracking loads of each girder was small, and the results of cracking tests were similar to those predicted by theoretical calculation: this indicated that the degree of curing of the retarder had little effect on the cracking load of the girder specimen and was applicable to existing theory predicting the behaviour of prestressed concrete girder systems.

The girder initial stiffness, in addition to specimen PC 3-0-8 being slightly smaller, was essentially the same as the theoretical values; however, the ultimate bending strength of each girder specimen increased with increased degree of retarder curing: all test results were greater than the corresponding theoretical results.

After unloading, the maximum residual deformation increased with increased curing, except in PC 2-0-6 girder specimens. This was mainly due to the increased curing enhancing the adhesion performance of the retarder, thereby enhancing the load transfer capacity between the prestressed steel and the concrete, so the ultimate strength capacity increased and the ductility improved significantly: the maximum residual deformation also increased after unloading.

From the comparison of load-deflection curves of the three girder specimens (Figure 9(b)), stretching the prestressed tendons at different degrees of retarder curing has little effect on the cracking load and initial stiffness of the girder but exerts a significant influence on their ultimate bending strength and ductility. The less well cured the girder specimen, the higher the ultimate strength capacity and the better the ductility.

3.2. Concrete Strain Distribution along the Girder Height. During the load testing of each girder, when increasing load until the concrete showed the onset of cracking, the concrete strain distribution along the girder height direction at midspan was as shown in Figure 10: the

FIGURE 10: Concrete strain distributions through the girder height at a midspan cross section. (a) PC 1-0-0. (b) PC 2-0-6. (c) PC 3-0-8. (d) PC 4-0-9. (e) PC 5-6-8. (f) PC 6-8-8.

horizontal axis represents the distance from the measure point of the strain gauge to the girder's lower boundary, and the vertical axis represents the measured strain (tension positive). From Figure 10, it can be seen that the strain

distribution through the concrete was similar, and the further from the neutral axis of the concrete girder, the larger the measured strain. With increasing load, the measured strains increased.

3.3. Concrete Strain Distribution. During loading process, the concrete strains at the upper and lower edges of the midspan cross section and at the lower edge of the $\frac{1}{3}$ -span girder cross section are as shown in Figure 11. The horizontal axis represents the measured strain (tension positive), and the vertical axis represents the applied vertical load.

When the load was less than the load causing the onset of cracking, whether compressive or tensile, the strain in the concrete measured at any cross section increased, and the load-strain relationship was linear. After the applied load exceeded that required for the onset of cracking, the compressive strain, at the upper edge of girder midspan cross section, increased rapidly until the concrete was crushed; in contrast, the tensile strain in the concrete, at the lower edge at midspan and $\frac{1}{3}$ -span, except at a few measurement points, increased rapidly. Elsewhere, after reaching peak strain, it decreased to about $300\mu\epsilon$, remaining constant thereafter. The main reason for there being no further increase in the tensile strain is, after the onset of concrete cracking in the lower edge under tension, the cracks expanded gradually and the concrete maintained a certain tensile stress. The main reason for the rapid increase in the strain at some measurement points was the fact that the strain gauges were affixed at the crack edges, whereas the cracks were gradually extended under load.

3.4. Stress Variation in Prestressed Tendons under Loading. The monitored stresses on RBPT at both ends of each girder are shown in Figure 12. Figure 12(a) shows prestressed tendon stress at both ends of the four test specimens versus retarder curing degree test: in this case, data arising from stretching of the prestressed tendons in each girder specimen in the tensile period are shown. Figure 12(b) shows the test results of the other three girder specimens in terms of the relationship between vertical load and end stress on the steel bar, obtained when the retarder Shore hardness was 81.3. The horizontal axis represents the vertical load applied to top of the girder, and the vertical axis represents the stress variation at both ends of the RBPT.

The load-carrying capacities of four test specimens in the same tensile period, but under different degrees of curing, are contrasted with the stress changes in prestressed tendons (Figure 12(a)). At the initial stage of loading, the stress on the end PT of the three beams, PC 1-0-0, PC 2-0-6, and PC 3-0-8, did not change with an increase in vertical load. When the vertical load reached that required for the onset of cracking, the stress on the end of the prestressed tendon increased significantly. When test specimen PC 1-0-0 reached its ultimate bending strength, the stress on the end prestressed steel bar reached 1600 MPa. After unloading, the stress rapidly decreased from 1600 MPa to less than 1000 MPa. The main reason for this is that the retarded-bonded agent does not solidify during loading, and there is no effective bond between the prestressed steel and the concrete, so they can undergo relative sliding motion; therefore, when the beam cracks, the stress on the prestressed tendon changes

rapidly with changing load. For specimen PC 2-0-6, after vertical load reach the ultimate load of 557 kN, the stress on the end of the beam remained almost unchanged. The test specimen PC2-0-6 reached its ultimate load, and until the vertical load decreased to the cracking load, the stress on the end of the beam remained almost unchanged. When decreasing the vertical load from the cracking load to zero, the stress on the end of prestressed tendon decreased rapidly. This is due to the fact that the retard-bonded agent starts to cure during loading, and a certain bond develops between the prestressing tendons and the concrete, resulting in no significant change in the internal force on the prestressing tendons in the initial unloading stage. For the test specimen PC 3-0-8, when the vertical load reached 240 kN, the rate of increase of stress remained slow; as the vertical load was increased from 240 kN to 450 kN, the stress on the prestressed tendons increased by only 16 MPa, and then, under increased vertical load, the stress increased rapidly to 1200 MPa. When the vertical load was decreased from the ultimate load to around 150 kN, the stress on the end of the prestressed tendons remained almost unchanged, and then decreased slowly with the vertical load.

The experimental results showed that the less well cured the material, the greater the rate of change of stress and the greater the magnitude thereof, indicating that the application of a prestressing force on the girder relied on the anchorage at one end. When the Shore hardness exceeded 80, the more well cured the material, the lower the rate of change of stress on the prestressed tendons at the end of the girder and the smaller the change therein, indicating that the retarder, in this girder, conferred strong bonding properties and had the ability to transfer stress from the prestressing tendons to the surrounding concrete.

The comparison of stresses in prestressed tendons in the three girder specimens in Figure 12(b), at different times, when the Shore D hardness reached 81.3, indicated that for PC 5-6-8 specimen, upon stretching the prestressed tendons when the retarder Shore D hardness was 64.8, under a maximum vertical load of 300 kN, the stress on tendons increased rapidly, and when the ultimate load of 536 kN was applied, the stress increased by 350 MPa, and the stress on the tendons at the end of the girder began to decrease rapidly upon unloading to about 250 kN. For PC 6-8-8 specimen, upon stretching the prestressed tendons when the retarder Shore D hardness was 80.5, under a maximum vertical load of 270 kN, the stress on the tendons increased rapidly, and when the ultimate load of 526 kN was applied, the stress increased by 457.5 MPa, and the stress on the tendons at the end of the girder began to decrease rapidly upon unloading to about 220 kN. From these results, for the girder specimens, stretching the tendons after the retarder has undergone the necessary tensile period; due to weaker bonding performance, the retarder cannot transfer the stress from the tendons to the concrete, resulting in a force transfer mechanism which was similar to that in unbonded prestressed concrete; the load-bearing capacity was low, and the ductility was poor.

FIGURE 11: Continued.

FIGURE 11: Changes in strain under load at cross sections at girder midspan and $\frac{1}{3}$ -span. (a) PC 1-0-0. (b) PC 2-0-6. (c) PC 3-0-8. (d) PC 4-0-9. (e) PC 5-6-8. (f) PC 6-8-8.

FIGURE 12: Stress changes under load in RBPC tendons (both ends). (a) Effect of different degrees of curing of retard-bonding agent on load-carrying capacity. (b) Effect of different tensile periods on load-carrying capacity.

3.5. Crack Distribution. During the test, the main cracks in the concrete in the pure bending part of each girder were as listed in Table 3: For specimen PC 1-0-0, when the load reached 245 kN, the initial crack was observed, and then, the crack grew with the increase of the load; when the load reached 420 kN, the maximum crack width, 1.21 mm, was obtained. The failure mode is similar to unbonded prestressed concrete structure, the cracks is fewer, but wider). For girder specimen PC 2-0-6, when the load reached 227 kN, an initial crack was observed on the surface of the girder; when the load

reached 425 kN, the maximum crack width reached 1.21 mm and showed similar failure characteristics to those of a unbonded prestressed concrete structure, whereas, for specimens PC 3-0-8 and PC 4-0-9, cracks were seen at 240 kN and 250 kN, respectively, and then the crack widths increased slowly under increasing vertical load. The maximum crack widths in these girders were 0.23 mm and 0.39 mm at 390 kN and 425 kN, respectively. For specimens PC 3-0-8 and PC 4-0-9, cracking began at 240 kN and 250 kN, respectively, and then the crack width increased under increasing vertical load:

TABLE 3: Crack development status.

Vertical load (kN)	The main crack width of PC 1-0-0 in a pure bending section of the test specimen (mm)				Vertical load (kN)	The main crack width of PC 2-0-6 in a pure bending section of the test specimen (mm)				
	1	2	3	4		1	2	3	4	
245	Crack				227	Crack				
275	0.06	0.07	0.07	0.08	250	0.08	0.05	0.06	—	
300	0.07	0.07	0.07	0.10	275	0.09	0.07	0.11	0.19	
325	0.07	0.09	0.10	0.12	300	0.20	0.17	0.23	0.31	
360	0.08	0.15	0.16	0.28	325	0.20	0.16	0.19	0.25	
375	0.15	0.21	0.17	0.86	360	0.21	0.17	0.40	0.26	
400	0.15	0.21	0.17	0.86	375	0.25	0.23	0.53	0.53	
420	0.60	0.33	0.64	1.21	400	—	0.47	0.92	0.57	
506	Damage				425	—	0.61	1.21	1.01	
Average distance between cracks (mm)		256		Average distance between cracks (mm)		240		Damage		
Vertical load (kN)	The main crack width of PC 3-0-8 in a pure bending section of the specimen (mm)				Vertical load (kN)	The main crack width of PC 4-0-0 in a pure bending section of the test specimen (mm)				
	1	2	3	4		1	2	3	4	5
240	Crack				250	Crack				
270	0.08	0.08	0.09	0.09	270	0.11	0.06	0.05	0.04	—
290	0.13	0.14	0.09	0.09	290	0.20	0.06	0.07	0.05	0.15
310	0.18	0.19	0.10	0.13	330	0.22	0.09	0.13	0.09	0.16
330	0.17	0.19	0.10	0.17	350	0.29	0.05	0.11	0.17	0.17
350	0.17	0.19	0.10	0.19	375	0.32	0.11	0.11	0.19	0.15
365	0.17	0.19	0.09	0.23	400	0.37	0.18	0.14	0.25	0.19
390	0.13	0.20	0.11	0.23	425	0.39	0.20	0.18	0.32	0.25
597	Crack				609	Crack				
Average distance between cracks (mm)		233		Average distance between cracks (mm)		230				
Vertical load (kN)	The main crack width of PC 5-6-8 in a pure bending section of the test specimen (mm)				Vertical load (kN)	The main crack width of PC 6-8-8 in a pure bending section of the test specimen (mm)				
	1	2	3	4		1	2	3	4	
230	Crack				225	Crack				
265	0.12	0.06	0.12	0.06	265	0.14	0.11	0.12	0.17	
290	0.20	0.07	0.17	0.11	290	0.17	0.15	0.13	0.23	
315	0.25	0.04	0.18	0.15	315	0.18	0.19	0.25	0.25	
340	0.25	0.05	0.11	0.17	340	0.20	0.16	0.40	0.35	
365	0.29	0.04	0.20	0.21	365	0.53	0.28	0.57	1.01	
390	0.44	0.04	0.52	0.18	390	0.71	0.41	0.61	1.04	
415	0.80	0.05	0.70	0.58	415	0.93	0.53	0.75	1.07	
536	Crack				527	Crack				
Average distance between cracks (mm)		266		Average distance between cracks (mm)		250				

the maximum crack widths were 0.23 mm and 0.39 mm at 390 kN and 425 kN, respectively. The cracks were small and closely spaced, which is a failure characteristic of a typical bonded prestressed concrete structure: for specimens PC 5-6-8 and PC 6-8-8, cracking began at 230 kN and 225 kN, respectively, and then under increasing load, the crack width increased rapidly. When the vertical load reached 415 kN, the maximum crack width in specimens PC 5-6-8 and PC 6-8-8 was 0.80 mm and 1.07 mm, respectively, showing similar failure characteristics to a bonded prestressed concrete structure. Figure 13 shows the crack distribution in the specimens at the end of each test.

4. Conclusion

- (i) When stretching the prestressed tendons in the specimens during the tensile period, the degree of curing of the retarder had little effect on the cracking load of the prestressed concrete girder but exerted a significant influence on their ultimate bending strength. Using existing prestressed concrete calculation theories, the calculated cracking load matched the experimental result; however, the theoretical ultimate bending strength was conservative.

FIGURE 13: Crack distribution in PC girders. (a) PC 1-0-0. (b) PC 2-0-6. (c) PC 3-0-8. (d) PC 4-0-9. (e) PC 5-6-8. (f) PC 6-8-8.

- (ii) When stretching the tendons during the tensile period, the ultimate bending strength of the girder increased with the increase in curing of the retarder: the higher the Shore hardness is, the closer the ultimate strength capacity of the RBPC girder is to the ultimate strength capacity of the bonded prestressed concrete girder. When the Shore hardness of the retarder reached 80, the retard-bonded prestressed steel tendons and concrete worked together in a balanced fashion. The cracks in the girder were evenly distributed, and their number was relatively large: the load-carrying capacity and ductility were maximised.
- (iii) When stretching the tendons during different stages of retarder curing, the better-cured the retarder, the higher the tensile strength of the specimens and the poorer the bonding performance between the prestressed reinforced concrete and the concrete after curing. The cracks in the pure bending segment of the girder were wider and less numerous; the ultimate load able to be borne by the girder was low, and the ductility thereof was poor.

Data Availability

The data used to support the findings of this study come from the experiment conducted by the authors and are included within the article. Also, the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the project of the National Science and Technology Ministry 13th Five-Year Science and Technology (2017YFC0703805-03) and the Natural Science Foundation of Liaoning Province, China (20180550780); these supports are gratefully acknowledged.

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