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Article

Test and Analysis of Reinforced Concrete Beams Reinforced by Polyurethane Concrete-Prestressed Steel Wire (PUC-PSW)

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Abstract: In this paper, polyurethane concrete (PUC) is used as wire embedding material to form a new polyurethane concrete- prestressed steel wire (PUC-PSW) reinforcement method. The lightweight and high-strength PUC materials not only bond and anchor the prestressed steel wire (PSW), but also passively participate in the structural force. The problems caused by using mortar or composite mortar as the embedding material are avoided. Twelve reinforced concrete T-beams were tested for PUC-PSW flexural reinforcement. It consists of 1 unreinforced beam, 4 PSW reinforced beams, and 7 PUC-PSW reinforced beams. The wire embedding material, wire anchorage form, PUC material depth, amount of wire, and loading type were used as variables. The test results show that PUC-PSW reinforcement can obviously enhance the flexural load and ultimate load of the reinforced beams compared with PSW reinforcement. The ability of PUC-PSW reinforcement to limit crack development is better than that of PSW reinforcement beam, especially after the main beam steel yield. The strength, stiffness and crack limiting ability of the reinforced beam increase with the PUC thickness of the reinforced layer.

Keywords: Polyurethane concrete-prestressed steel wire (PUC-PSW); Polyurethane concrete (PUC); Reinforcing beam; Bending test

1. Introduction

Bridges play a critical role in road traffic and are vital to the overall transport system. With socio-economic progress, the transport sector is booming and the volume and load capacity of vehicles has increased remarkably, changing dramatically from what it was in the past. Due to the rapidly increasing vehicle load, acid rain, temperature and other natural factors, a series of diseases occur in the normal service period of the bridge. For example, structural cracks, deterioration of concrete materials, corrosion of steel bars [1–3]. Diseases of bridges will have different degrees of impact on their security, suitability and sustainability of the structure, which will reduce the carrying capacity of the bridge and may even threaten the normal functioning of the bridge [4]. Appropriate bridge strengthening methods can improve the bearing capacity of Bridges and extend the service life of Bridges [5–7].

The bonding steel plate reinforcement method can limit the development of cracks and improve the flexural performance of Bridges [8–10]. However, steel plates are difficult to accommodate when faced with irregular concrete surfaces and are prone to rusting problems in the natural surroundings. The method of attaching fiber materials is to attach high-strength fiber materials to the surface of the reinforced members with epoxy resin to exert the high strength and good durability of the composite materials [11–13]. However, carbon fiber cloth/plates are weaker and not as effective in improving structural stiffness, as well as having a greater material cost.

The prestressed steel wire (PSW) reinforcement method is to anchor the PSW to the reinforced beam body, and spray composite mortar to bond it to the reinforced beam body as a whole [14–16]. Compared with the reinforcement method of steel wire mesh and composite mortar [17,18], the ability to exploit the maximum tensile strength of the wire, thus dramatically increasing the efficiency of material utilization, and will not fail due to the peel and damage of thin layer of mortar. The PSW reinforcement method is an active reinforcement method, which can significantly improve the stiffness and bearing capacity of the main beam. However, the polymer mortar (PM) sprayed outside the steel wire has low tensile strength, and a large number of cracks appear in the cracks of the original beam before reinforcement, which affects the durability of both the PSW and the steel bars of the original structure.

Polyurethane concrete (PUC) materials are designed to be extremely flexible and lightweight, with excellent bond strength and resistance to acid and caustic attacks [19–21]. In this paper, polyurethane concrete-prestressed steel wire (PUC-PSW) is proposed to strengthen reinforced concrete structures. The steel wire is tensional and anchored on the surface of the reinforced beam body, and then the steel wire is embedded in the PUC composite material by pouring PUC composite material, which is a composite reinforcement method combining the active force of the steel wire and the passive force of the PUC. For the experimental study on the flexural reinforcement of PUC-PSW, the reinforcement effect of PUC material was explored with the embedding material, anchoring form of wire, thickness of PUC material, number of wire and loading method as variables.

2. Materials

2.1. Concrete and Steel Bar

All specimens were made of the same concrete mix, and the compressive strength of the concrete cube was 40MPa. The main beam longitudinal use of 18mm diameter grade III rebar, the yield strength of 418MPa was measured. The vertical steel bar is a two-threaded steel bar with a diameter of 10mm, and the measured yield strength is 250MPa. The measured yield strength of the first grade light round steel bar with a diameter of 8mm is 320MPa.

2.2. Polyurethane Concrete

PUC is a polymer material, which is mainly composed of polyurethane raw materials, ordinary Portland cement and molecular sieve. The PUC coordination is shown in Table 1. Polyurethane is a kind of polymer with excellent properties, which is mainly formed by polymerization of isocyanate and polyether.

Table 1. Composition of polyurethane concrete.

Chemical composition	Percent (%)
Polyether	25
Isocyanate	25
Portland cement	45
Molecular sieve	5

PUC material density is 1550kg/m3. The compressive strength test adopts a cube test mold with a size of 70 mm×70 mm ×70 mm, and the bending strength adopts a cuboid test mold with a size of 450 mm×100 mm ×100 mm. The compact resistance of the PUC material reached 59.3 MPa, while the fracture strength had an average value of 41.5 MPa. These strength properties were verified by tests, and the specific data can be understood by looking at Figures 1 and 2.

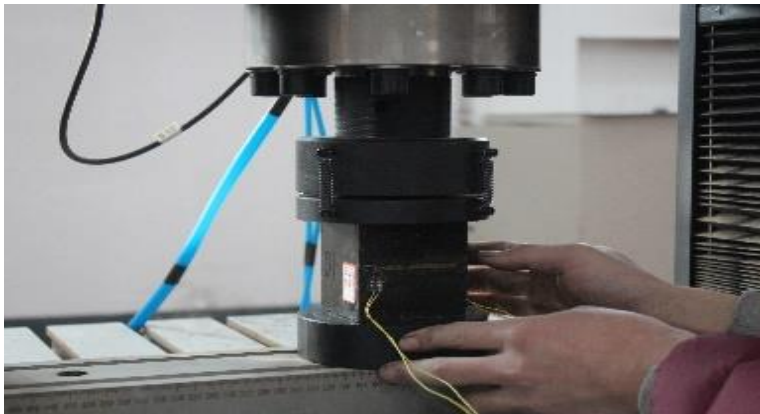


Figure 1. Compressive test diagram of polyurethane concrete material.



Figure 2. Flexural test diagram of polyurethane concrete material.

2.3. Steel Wire

The stress-strain curve of the steel wire with a diameter of 4 mm, when performing the stretch test, is detailed in Figure 3. The average ultimate tensile strength of the wire was 1255.6MPa and the average elastic modulus was 138.3GPa. The ultimate tensile strain of each specimen was greater than 2.5%, and the average value was 2.68%. The stress at 0.2% residual strain is defined as the nominal yield strength, which is approximately 85% of the ultimate tensile strength and takes the value 1067MPa.

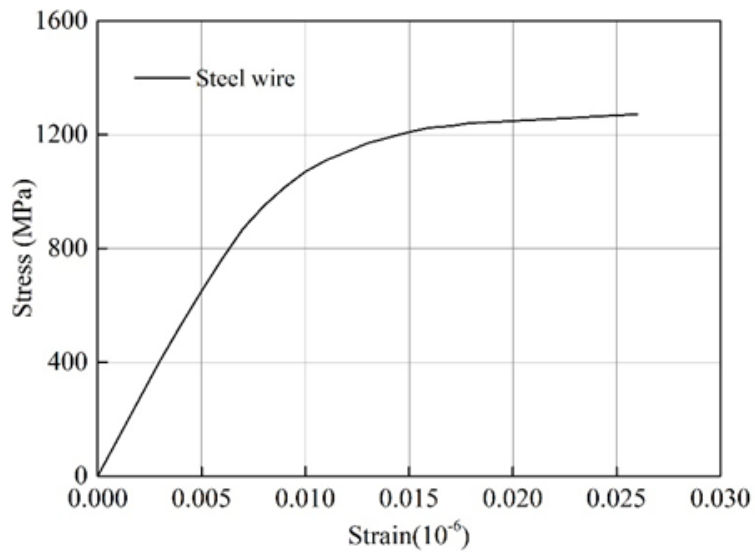


Figure 3. Tensile stress-strain curve of steel wire.

3. Test Beam Design

3.1. Design of Test Beam

In this paper, the flexural tests of 12 T-section simply supported beams are carried out. Uniform specimen dimension, total distance 3000mm, clear width 2700mm, of which the duration of pure flexural section is 900mm. The longitudinal tensile steel bar is 2, and the longitudinal reinforcement ratio is 0.91%. The diameter of the standing steel bar is 10mm. In order to prevent insufficient shear strength, a first-order optical round bar with a diameter of 8mm was configured along the length direction of the specimen, and the spacing between the pure bending sections was 150mm and the shear bending sections was 80mm. The specific parameters of the section are shown in Figure 4.

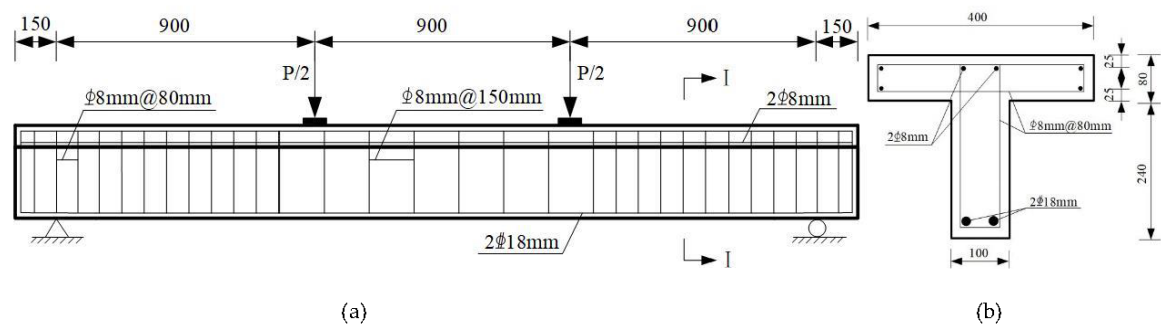


Figure 4. Specimen size and reinforcement: (a) Longitudinal section; (b) horizontal section.

In order to study the influence of PUC-PSW reinforcement technology on the flexural performance of the member, the test variables used are: PSW embedment material, PSW anchorage form, PUC material thickness, PSW quantity, and whether the beam is pre-cracked. The beam parameters are shown in Table 2, where beam CB is a control beam and is not reinforced. In order to study the effect of PSW embedding material on the performance of the reinforced beam, the reinforced beam is divided into two parts, one is PSW reinforced beam with a total of 4 pieces, and the other is PUC-PSW reinforced beam with a total of 7 pieces. The diagram of the reinforced beam is shown in Figure 5. The cross-sectional diagram of reinforced beams I-I is shown in Table 3.

Table 2. Parameters of beam reinforcement.

Group	Beam number	The number of steel wire	Prestress (MPa)	Embedded material	Material thickness (mm)	Anchorage form	Preload	Reinforcement under load
Control beam	CB	-	-	-	-	-	-	-
	A1	5	700	-	-	Anchor gear	-	-
	A2	5	700	Mortar	20	Anchor gear + Mortar	-	-
PSW	A2-1	7	700	Mortar	20	Anchor gear + Mortar	-	-
	A3	5	700	Mortar	20	Anchor gear + Mortar	Preload	-
	A4	0	700	PUC	20	-	-	-
PUC-PSW	A5	5	700	PUC	20	Anchor gear +PUC	-	-
	A6	5	700	PUC	20	PUC	-	-
	A7	5	700	PUC	20	Anchor gear +PUC	Preload	-

A8	5	700	PUC	30	Anchor gear +PUC	-	-
A9	2	700	PUC	20	Anchor gear +PUC	-	-
A9-1	2	700	PUC	25	Anchor gear +PUC	-	-

Beam A1, Beam A2, Beam A2-1 and Beam A3 are the four girders that have been strengthened with PSW, and these wires were all tensioned at a contained stress of 700 MPa. Among them, the steel wire of beam A1 has no embedding material and is non-bonded PSW reinforcement. Beam A2-1 adopts 7 PSW, and the other 2 beams are reinforced with 5 steel wires. In order to study the reinforcement effect of cracked beams, the beam A3 was preloaded to 50kN, and the cracks in the beam body were ensured to be no more than 0.2mm, and then the load was removed for reinforcement. The thickness of all the reinforced beam mortar is 20mm. Except for beam A1, which is anchored by a single anchorage device, the other 3 beams are anchored by a combination of mechanical anchorage of the anchorage device and bonded anchorage of composite mortar.

Beams A4 to A9-1 are 7 PC-PSW reinforced beams. Among them, there is no PSW in beam A4, which is a simple PUC reinforced beam. To investigate the effect of PUC bonded anchorage, beam A6 was sheared at the anchorage at the end of the beam after the PUC was poured, allowing the wire to be bonded and anchored only through the PUC. Beam A7 is pre-loaded to 50kN, while ensuring that the beam cracks do not exceed 0.2mm, and then the load is removed for reinforcement. In order to study the influence of different PUC thickness on the performance of reinforced beams, the thickness of PSW embedded PUC material in beam A8 was set to 30mm. In order to study the effect of the number of PSW on the performance of reinforced beams, the number of wires in beams A9 and A9-1 is set to 2, and the thickness of PUC material embedded in the wires of beams A9-1 is 25mm.

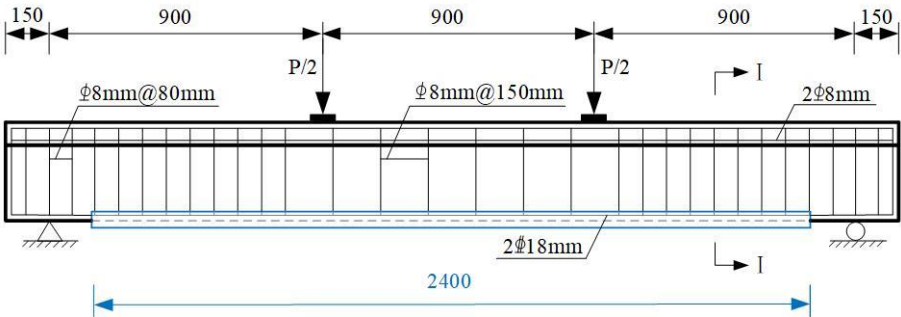
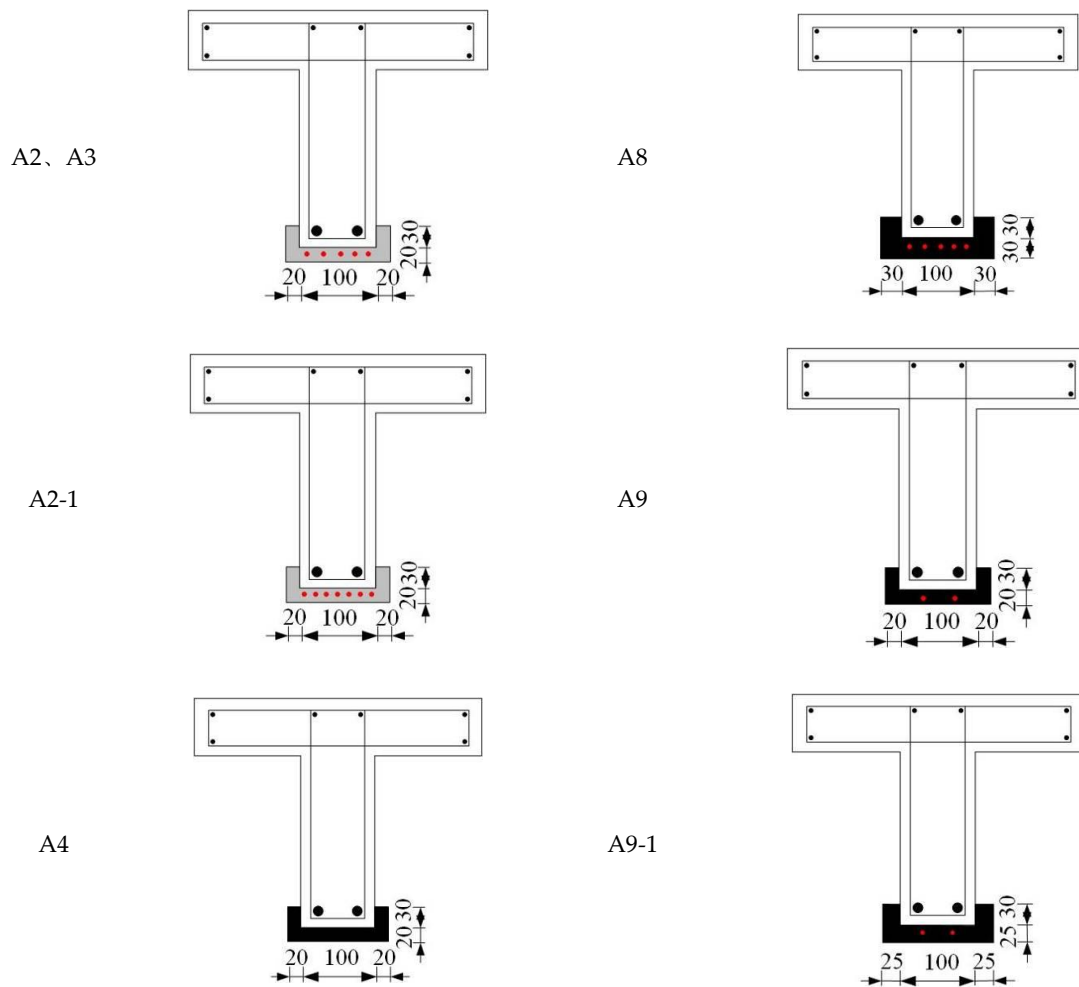


Figure 5. Profile of the reinforced beam.

Table 3. Cross-sectional diagram of reinforced beams I-I.

Beam number	Cross section	Beam number	Cross section
A1		A5、A6、 A7、A9	



3.2. Hardening Procedure

First, the beam end is slotted and installed with the PSW anchorage, as shown in Figure 6 (a) and Figure 6 (b). Notch about 100mm wide along the width direction at the end of the beam to expose the main steel bar inside the main beam. Weld the prepared anchor to the exposed steel bar of the main beam, and remove rust on the surface of the steel bar in order to ensure the welding quality. When welding, pay attention to adjusting the relative position of the main bar, anchor and beam bottom.

Secondly, the concrete surface of the beam bottom is treated, as shown in Figure 6 (c) and Figure 6 (d). In order to strengthen the material and concrete have a better bonding effect, the use of concrete hammer to chisel the concrete surface paste and loose concrete parts, so that it exposed the coarse aggregate, and then air compressor to blow away the floating ash on the concrete surface.

Thirdly, extruded anchor head fabrication, steel wire feeding and tension anchorage, as shown in Figure 6 (e) and Figure 6 (f). Since the anchorage used is similar to pier anchorage, the cutting length of the wire should be controlled according to the designed tension control stress. The aluminum alloy sleeve is extruded with a hydraulic tool, and the steel wire and aluminum alloy sleeve become a whole after extruding. Aluminum alloy casing is selected as the extrusion anchor head, the steel wire is stacked into two wires into the casing, and then the press is extruded to form the extrusion anchor head, so that the steel wire and aluminum sleeve form a whole. One side of the steel wire is directly inserted into the anchor, and the other end is tensioned with a hand hoist or a wire tensioner. The steel wire is extended and the extruded anchor head exceeds the anchor.

Finally, the PUC material is poured, as shown in Figure 6 (g) and Figure 6 (h). Fix the pre-made U-shaped wooden formwork at the bottom of the beam, and close the two end parts of the wooden

formwork at the contact position with the concrete, so as to prevent the PUC material from flowing out during the casting procedure. In the early stages of PUC material pouring, the material has similar characteristics to self-compacting concrete and has good fluidity. The formwork will be removed 24h after pouring. PUC material has the function of protecting and co-anchoring the steel wire.

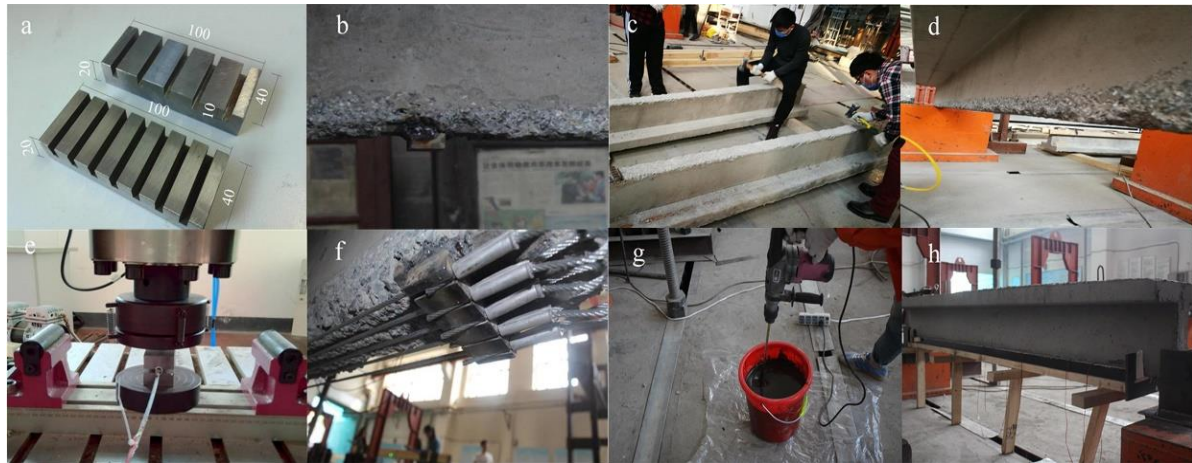


Figure 6. Reinforcement steps: (a) anchorage; (b) beam end anchorage; (c) beam surface chisel; (d) main beam erection; (e) anchor head extrusion; (f) beam end anchorage; (g) polyurethane concrete mixing; (h) polyurethane concrete pouring.

4. Load and Measure

Mechanical jack was used for test loading, and the maximum pressure of the jack was 500kN. Resistive pressure sensor and data acquisition system were used for pressure measurement during loading. Forward loading was used for test, and the component was damaged by 5kN/ grade loading, as shown in Figure 7.

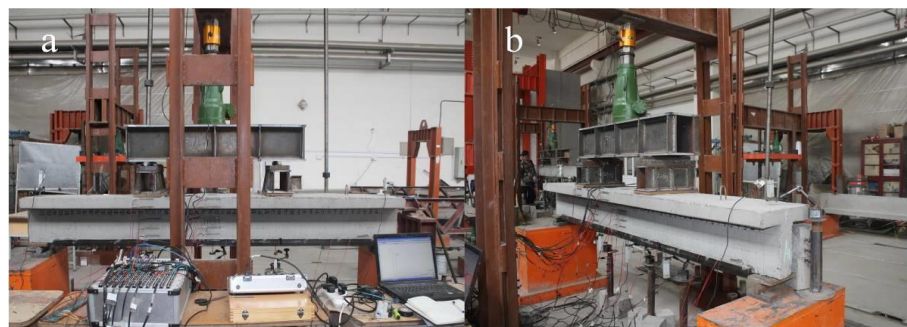


Figure 7. Static load test diagram.

During the tests, resistance strain gauges were installed on the surface of concrete, steel reinforcement, steel wire, PUC and composite mortar in order to measure the strain in each of these materials. The concrete strain gauges are arranged on the middle side of the span of the specimen. Six strain gauges of 100mm×3mm are uniformly pasted along the height of the section. Four strain gauges with dimensions of 5 mm × 3 mm were pasted on the two loaded principal bars and placed in the cross section at the loading point and the cross section at the center of the span, as depicted in Figure 8.

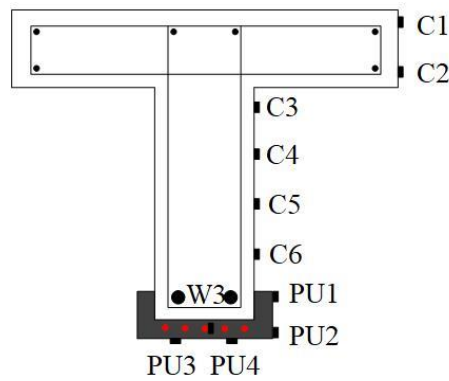


Figure 8. Cross section layout of strain gauge.

5. Test Results And Analysis

5.1. Load Displacement Curve

The damage mode of the beam is shown in Figure 9 and Figure 10 illustrates the load-contraction curves of beam CB, beam A1, beam A2 and beam A5. Beam A1 is an unbonded PSW reinforced beam, and the stiffness of the reinforced beam is obviously higher than that of the CB beam. When the load attains 135kN, the reinforced beam yields and its rigidity decreases rapidly until the load attains the ultimate load of 144kN. Because the steel wire is not bonded to the concrete, the stress on the steel wire is evenly distributed with the increase of load, so the reinforced beam has good ductility on the load-deflection curve. Failure modes of beams CB and A1 are shown in Figure. 9 (a) and Figure. 9 (b). Beam A2 was reinforced with bonded PSW, these wires were inserted into the composite mortar material. At the beginning of the loading, the stiffness of beam A2 increased slightly compared to beam A1, but as the load increased, the composite mortar cracked, resulting in the difference in stiffness between the two beams becoming inconspicuous. When the load reaches 141.3kN, the steel wire breaks, the deflection reaches 24.6mm, and the load decreases rapidly. The remaining steel wire without breaking also breaks one after another with the increase of the load, and finally remains at a relatively stable load of 105kN. The damage diagram of the beam is shown in Figure 9 (c). The load deflection curves of beams A2, A2-1 and CB are shown in Figure 11. Beam A2-1 and beam A2 have the same wire embedment material, but beam A2-1 has more wire embedment than beam A2. According to the information shown in the figure, beam A2-1 has a slightly higher stiffness compared to beam A2 and therefore exhibits a smaller deflection value for the same load. When the steel wire reaches 160.4kN, the steel wire in the mortar emits a sound of "touching" and breaks, and the deflection is 23.0mm. The failure mode of the beam A2-1 is shown in Figure 9 (d).

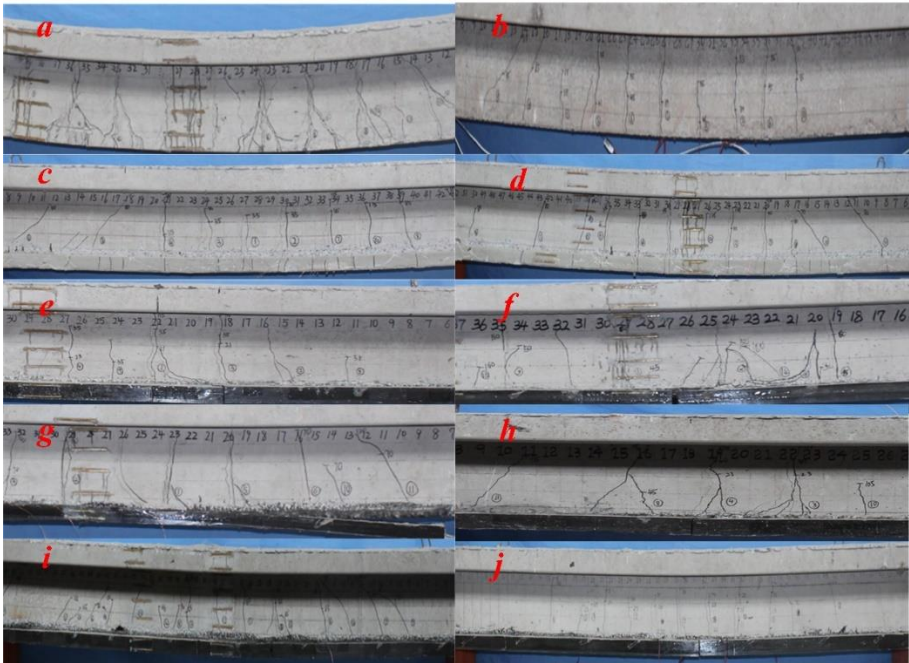


Figure 9. Failure mode diagram of beam: (a) beam CB, (b) beam A1, (c) beam A2, (d) beam A2-1, (e) beam A4, (f) beam A5, (g) beam A6, (h) beam A8, (i) beam A9, (j) beam A9-1.

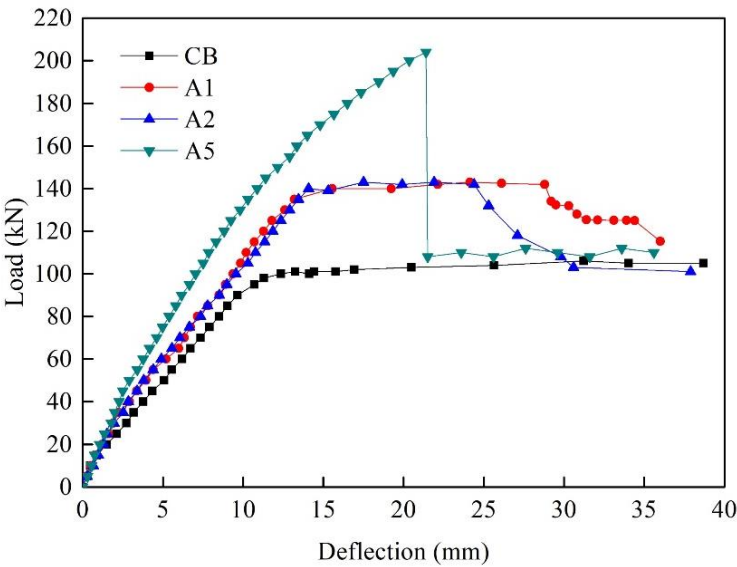


Figure 10. Load-deflection curves of beams CB, A1, A2 and A5.

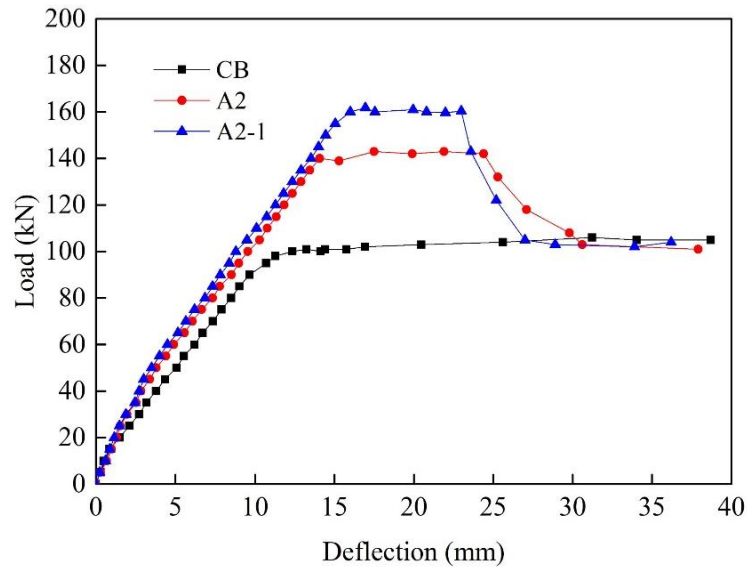


Figure 11. Load-deflection curves of beams CB, A2 and A2-1.

The load-contortion curves of beam CB, beam A2, beam A4 and beam A5 are shown in Figure. 12. Beam A5 is a PUC-PSW steel wire reinforced beam with a PUC thickness of 20mm. When the load achieves 150kN, the curve's slope starts to become smaller, which indicates that the stiffness of the primary girder starts to degrade. The strain in the PUC in the reinforced beam rises as the load progresses. When the test load attained the ultimate load of 204.3kN, the PUC and the wire fractured simultaneously with a "bang" sound. This phenomenon indicates that the consolidated beam has been damaged, and the greatest deflection of beam A5 at this time is 21.8mm. The load-contortion curve at this stage is almost horizontal, and the reinforced beam has been undergoing damage, and the damage pattern of the reinforced beam is shown in Figure. 9(f).

The load-deflection curves of beam CB, beam A2, beam A3, beam A5 and beam A7 are shown in Figure 13. Beams A3 and A7 are preloaded to 50kN and then reinforced after unloading. Beam A3 is a PSW reinforced beam, and beam A7 is a PUC-PSW reinforced beam. The failure mode of the pre-cracked reinforced beam A3 is similar to that of the directly reinforced beam A2, and the failure mode of the pre-cracked reinforced beam A7 is similar to that of the directly reinforced beam A5. At the initial stage of loading, the rigidity of beam A2 is slightly smaller than that of beam A7, and the discrepancy between the rigidities of these two beams gradually decreases with the growth of loading. However, at the very initial loading stage, the difference in rigidity between beam A5 and beam A7 is not apparent. Because PM cracks at the cracks formed during the concrete precracking, the limiting cracks are completely borne by the steel wire, and the preformed cracks are rapidly developed, resulting in the stiffness of the preloaded reinforced beam A3 being significantly lower than that of the directly reinforced beam A2. In the case of PUC-PSW reinforced beams, the PUC and PSW jointly bear the burden of limiting crack development. The pre-stress force effect of the wires closes the cracks in the preloaded beams and generates a certain pre-stress force. Subsequently, the PUC material has a good ability to limit crack development, so that the crack of the pre-cracked reinforced beam A7 does not develop significantly in the initial stage of loading. Therefore, the stiffness of beam A5 does not change significantly compared with that of beam A7 in the initial stage of loading.

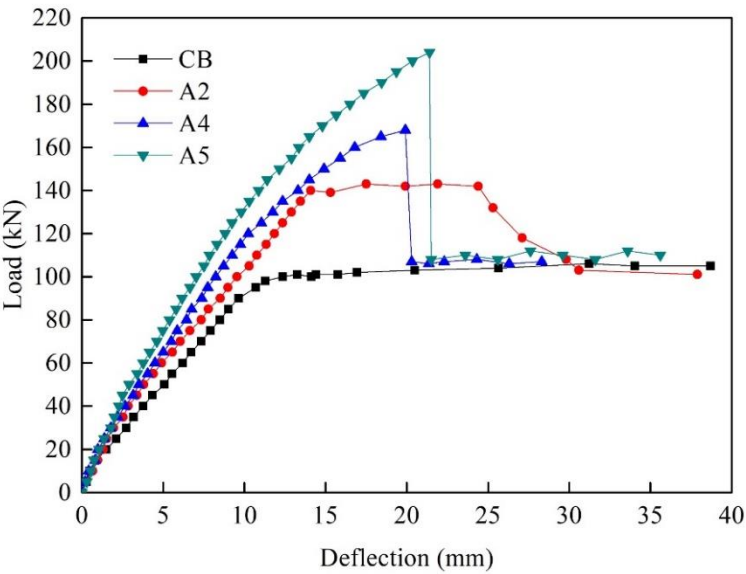


Figure 12. Load-deflection curves of beams CB, A2, A4 and A5.

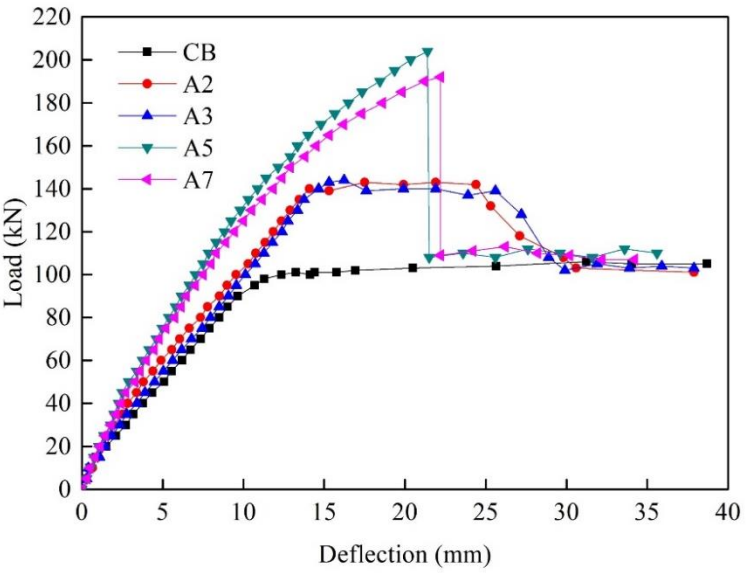


Figure 13. Load-deflection curves of beams CB, A2, A3 and A7.

The A8 beam is a PUC-PSW reinforced beam with a PUC thickness of 30mm. Compared to beam A5 with 20mm thick polyurethane concrete, beam A8 has higher structural stiffness. On the one hand, the 30mm thick PUC layer in the reinforced layer has a larger converted section moment of inertia, so it has a high section bending stiffness. On the other hand, the 30-mm-thick PUC material effectively restricted crack formation and extension during loading, thus improving the overall rigidity of the beam. Similar to beam A5, beam A8 behaved similarly in terms of cracking and disruption modes as demonstrated in Figure. 9(i).

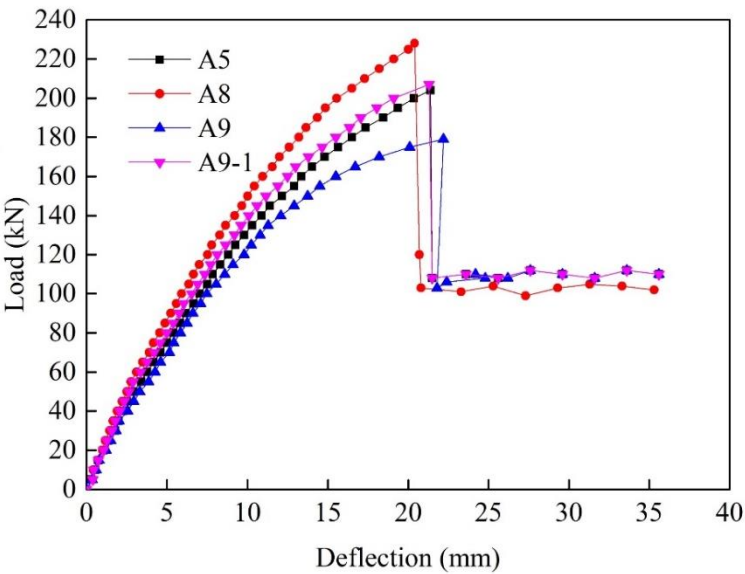


Figure 14. Load-deflection curves of beams A5, A8, A9 and A9-1.

The load-contortion curves for beam A5, beam A8, beam A9 and beam A9-1 are shown in Figure 14. Both A9 and A9-1 beams have two PSW, but the thickness of the embedded PUC material is not the same. Similar to beams A5 and A8, the stiffness of beam A9-1 is greater than that of beam A9. The PUC layer of beam A9-1 is 25mm thick and has a larger section area, so it has a larger section bending stiffness. Moreover, the PUC material is able to limit the crack unfolding well during the loading process, which in turn increases the rigidity of the beam. The load reaches 179kN. With the sound of "collision", the PUC of beam A9 and the steel wire break simultaneously, and the beam body is damaged. At this time, the deflection is 22.2mm, and the failure mode is shown in Figure.9 (i). Beams A5, A8 and A9-1 have deflection of 21.4mm, 20.4mm and 21.3mm when they fail. According to the four curves of different number of steel wires and thickness of different PUC layers, the deflection of beam A9-1 and beam A8 decreases slightly than that of beam A9 and beam A5 respectively when the beam body is damaged. Therefore, with the increase of the thickness of the PUC layer, the deflection of the beam when the failure occurs is slightly reduced.

5.2. Cracks

The cracking load of the test beam is shown in Table 4. Unreinforced CB beams developed cracking at loads up to 20kN, while A1 and A2 beams had cracking loads of 40kN each, which is a 100% increase over the unreinforced beams. The pre-stressing effect makes the PSW reinforcement more effective after the initial stresses are obtained, resulting in higher opening loads for the reinforced beams. For example, the opening load of the A4 beam was 25kN, which was only 25% higher than that of the control beam. In contrast, the PUC-PSW strengthened A5 beam had a casing load of 45kN, which was 80% higher than that of A4. The ability of A5 beams to withstand higher casing loads is mainly attributed to the prestressing effect.

Table 4. Cracking load, yield load and ultimate load.

Group	Beam	Cracking	Increase	Yield load	Increase	Ultimate	Increase
number	number	load	ratio	(kN)	ratio	load	ratio
		(kN)	(%)		(%)	(kN)	(%)
Control	CB	20	-	74.3	-	101.0	-
beam							

	A1	40	100	91.4	23.0	143.1	41.7
Steel wire	A2	40	100	96.7	30.1	141.3	39.9
	A2-1	50	150	103.2	38.9	161.8	60.2
	A3	-	-	94.1	26.6	144.5	43.1
PUC- PSW	A4	25	25	98.8	33.0	168.7	67.0
	A5	45	125	120.0	61.5	204.3	102.3
	A6	50	150	112.0	50.7	133.1	31.8
	A7	-	-	118.6	59.6	192.2	90.3
	A8	55	175	137.0	84.4	228.5	126.2
	A9	30	50	110.3	48.5	179.0	77.2
	A9-1	35	75	130.2	75.2	207.8	105.7

Translated with www.DeepL.com/Translator (free version) Under the action of cracking load, the concrete at the bottom of the beam produces a small tensile strain, and the limiting force of PUC material on the crack is not stronger than that of PSW. Due to the good bonding properties of the PUC and the prestressing force effect of the wires, even though the A6 girder lacked the anchorage effect of the girder-end anchorage, the cracking load was not reduced in the case of the A5 girder in the early phase of loading compared to the A5 girder. When the wires at the end of the A6 girder were sheared, the prestressing effect still caused compressive stresses in the PUC, and these compressive stresses effectively acted on the main girder. The compressive stresses acting on the main girder were not reduced due to the good bonding properties of the PUC material. Therefore, the increase of cracking load of PC-PSW reinforced beams is mainly due to the prestressing effect of PSW.

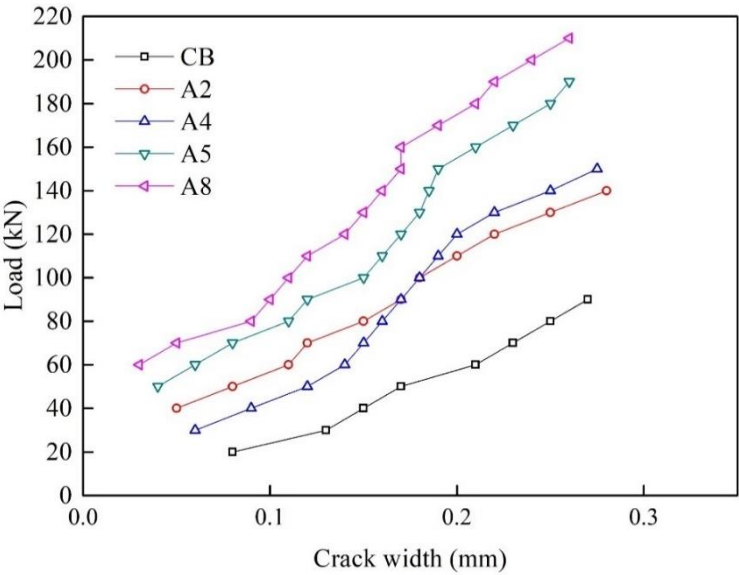


Figure 15. Load crack curves of beams CB, A2, A4, A5 and A8.

The load-crack curves of beams CB, A2, A4, A5 and A8 are shown in Figure 15. These crack values present the mean of the three dominant crack measurements in the span. When the load reaches 60kN, the crack widths of beam CB, beam A2, beam A4, beam A5 and beam A8 are 0.21mm, 0.14mm, 0.11mm, 0.07mm and 0.05mm respectively. When the load reaches 90kN, the crack widths of beam CB, beam A2, beam A4, beam A5 and beam A8 are 0.27mm, 0.17mm, 0.17mm, 0.12mm and 0.1mm respectively. The craze widths of Beam A2, Beam A4, Beam A5 and Beam A8 are smaller than the control beams under the same loading. Therefore, both PSW reinforcement and PUC-PSW reinforcement methods can effectively limit crack development, but the latter method is more effective.

In the initial stage of loading, PSW reinforced beam A2 shows better crack restraint ability than beam A4, and the prestressing effect in this stage is stronger than that of PUC. When the load exceeds 100kN, the ability of PUC to restrain the crack is very obvious. When the load exceeds 100kN, the reinforcement begins to yield and the stretching force at the crack aperture where the PUC material restricts the crack becomes greater than that of the wire.

Compared to PSW reinforcement, PUC-PSW reinforcement is considerably more successful in confining crack propagation throughout the loading procedure. The concrete cracks reinforced by PSW and the corresponding composite mortar cracks are shown in Figure 16. The composite mortar cracks and concrete cracks appear at the same time, so that the limiting cracks in the reinforcement layer are completely borne by the steel wire. However, due to the fact that PUC has a high tensile capacity, the PUC-PSW reinforced beams did not exhibit surface cracking when the concrete cracked, a condition shown in Figure 17. For PUC-PSW reinforced beam A5, the PUC and the wire in the reinforced layer work together to limit crack development. When the load exceeds 120kN, beam A5 exhibits better crack limiting ability than beam A2. Because when the load reaches 120kN, 5 beam A steel bars begin to yield, the tensile force of the PUC material at the crack opening increases rapidly, and PUC plays a dominant role in the PUC-PSW reinforcement layer after the steel bars yield. However, the ability of beam A2 to limit crack development decreases after the steel bar yields, because only the wire provides a small tensile force at the crack opening. When the load exceeds 150kN, the ability of beam A5 to limit crack development begins to decrease, probably because the stress of the wire in the PUC-PSW layer hardly increases at this time, and the limiting crack development in the reinforced layer is borne by the PUC material until the structure fails. Although the crack limiting ability is reduced after 150kN, the bearing capacity of the structure still maintains a high level.

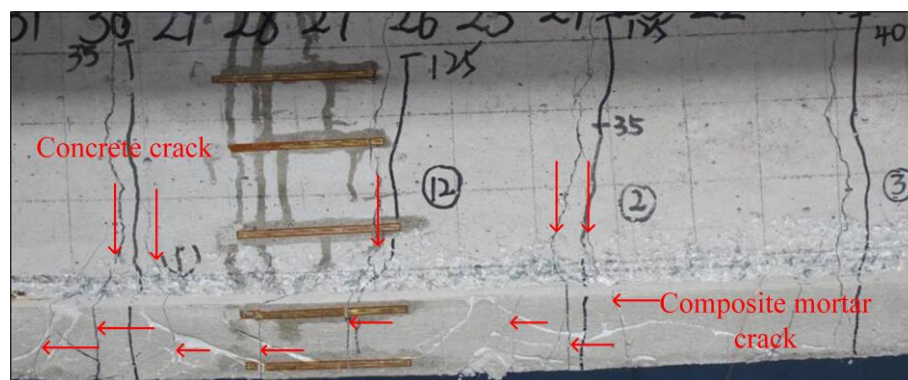


Figure 16. Cracks of concrete and corresponding composite mortar.

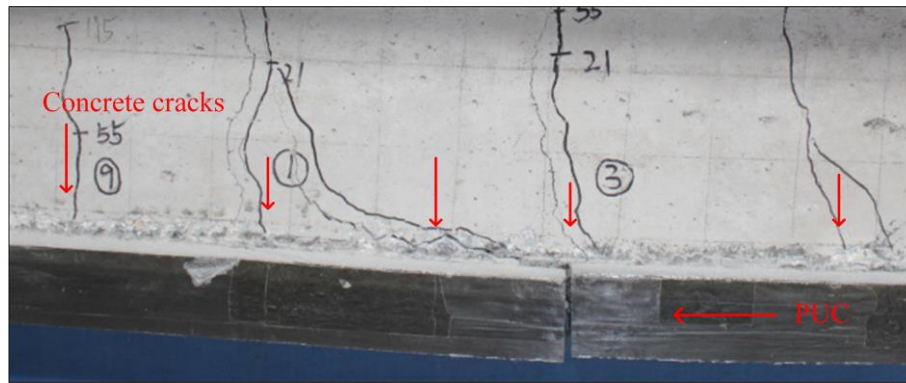


Figure 17. Concrete cracks and intact polyurethane concrete.

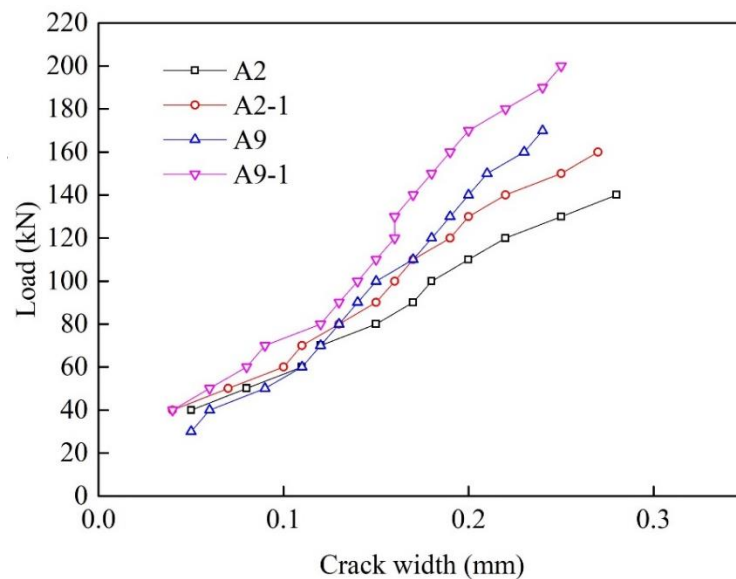


Figure 18. Load crack curves of beams A2, A2-1, A9 and A9-1.

The load-crack curves of beam A2, beam A2-1, beam A9 and beam A9-1 are shown in Figure 18. The steel wires of beams A2, A2-1 and A9 are embedded in a material with a thickness of 20mm. Beams A2 and A2-1 are composite mortar, and beams A9 are PUC material. When the load is less than 70kN, although beam A2-1 and beam A2 are arranged with 5 and 3 PSW more than beam A9, the crack width of the three beams under the same load is not much different in the early stage of crack formation. With the increase of load, after the load exceeds 70kN, the split widths of beams A9 and A2-1 remain approximately the same, but the split width of beam A2 quickly increases with the growth of load, which is noticeably larger than that of the other two beams. Because beam A2 is less than beam A2-1 with two PSW, with the increase of load, steel wire tensile stress, a larger number of steel wire under the same conditions, the total tensile stress is larger, so the ability to restrict crack development is strong. Compared with beam A2-1, although beam A9 has 5 fewer steel wires than beam A2-1, PUC material and PSW jointly participate in the force, PUC material will not crack with the cracking of concrete, and can produce tensile force at the crack to limit the cracking, so even if the PUC lacks 5 steel wires, it still has a good ability to limit the crack development. When the load exceeds 110kN, the crack of beam A2-1 develops faster than that of beam A9. With the continuous increase of load, the gap between the crack width of two beams gradually increases. Since both beams A2-1 and A9 began to enter the yield stage at 110kN, for beams A2-1 reinforced with PSW, the limiting crack development work in the reinforced layer was fully undertaken by the steel wire, while for beams A9 reinforced with PUC-PSW, the limiting crack development work in the reinforced layer was jointly undertaken by the steel wire and PUC. With the increase of the strain of the reinforced layer in the reinforced beam, PSW begins to enter the nominal yield stage, and the stress increases

slowly, while the stress of PUC material continues to increase with the increase of strain until the reinforced beam fails. Beam A9-1 has the same wire arrangement as beam A9, but is 5mm thicker than the PUC material of beam A9. Since the magnitude of the tensile stress in the PUC material continues to escalate with rising strain, an initial gap between the split widths of these two beams occurs during the inception of the initial phase of loading. This gap in crack width gradually widened as the loading value increased until it eventually led to the damage of both the beams.

5.3. Yield Load and Ultimate Load

The bearing capacity of the test beam is shown in Table 3. The load comparison diagram of beams CB, A1, A2 and A2-1 is shown in Figure 19. The buckling load of beam A1 is 94kN, which is 23% greater than that of the control beam. The yield loads of beams A2 and A3 are 96.7kN and 94.1kN respectively, which are 30% and 27% greater compared to the control beam. Numerically, the buckling loads of beams A2 and A3 are not considerably elevated compared to beam A1. Due to the premature cracking of the composite mortar, the mortar does not increase the yield load of beams. As there are two more steel wires in beam A2-1 than beam A1 and beam A2-1, the yield load of beam A2-1 has been significantly increased. Under normal circumstances, directly increasing the amount of prestressed tendons can effectively increase the yield load. Beam A4 is a single polyurethane concrete reinforced beam with a yield load of 98.8kN, a slight increase over the PSW reinforced beam. Although there is no PSW in the PUC material, a single PUC material can still greatly increase the yield load of the beam.

The ultimate strength of beams CB, A1, A2 and A2-1 is shown in Figure. 19. The ultimate loads of PSW-reinforced beams A2 and A3 were 141.3kN and 144.5kN, respectively, which were 40% and 43% greater than that of the control beams, and both beams suffered wire fracture damage. Beam A2-1 has two more steel wires than beam A1 and beam A2, resulting in a 13.1% and 14.5% increase in ultimate load compared with beam A1 and beam A2, respectively. By increasing the amount of wire configuration, the ultimate load carrying capacity of the concrete beams can be effectively enhanced and this enhancement is greater than the corresponding increment in yield load. Beam A4, with an ultimate load of 168.7 kN, shows a significant ultimate strength enhancement compared to beams A2 and A3 despite the absence of PSW in its PUC. In the PSW-reinforced beams, the wires yielded before the beams were damaged, whereas the tentative strength of the PUC-reinforced beams continued to increase until the final destruction of the structure.

The load comparison diagram of beam CB, beam A2, beam A3, beam A5 and beam A7 is shown in Figure 20. The yield loads of beams A5 and A7 are 120kN and 118.6kN respectively, which is a significant improvement over the PSW strengthened beams A2 and A3. Due to the good mechanical properties of PUC material, the embedded PUC material has a great influence on the yield strength of the structure. Compared with the beam A2-1 with the increase of the number of steel wires, the amplitude of the yield load increased by embedding PUC material is more obvious.

The ultimate load comparison of beams CB, A2, A3, A5 and A7 is shown in Figure 20. The load carrying capacities of beams A5 and A7 were 204.3kN and 192.2kN, respectively, which were increased by 44.6% and 36.0% compared to beam A2. With the same wire configuration, embedding the wires in the PUC can significantly increase the load carrying capacity of the reinforced beams, and the improvement is very considerable. The failure mode of both A5 and A7 beams is that the wire and PUC break at the same time. Therefore, the thicker PUC layer can further improve the load carrying capacity of the beam.

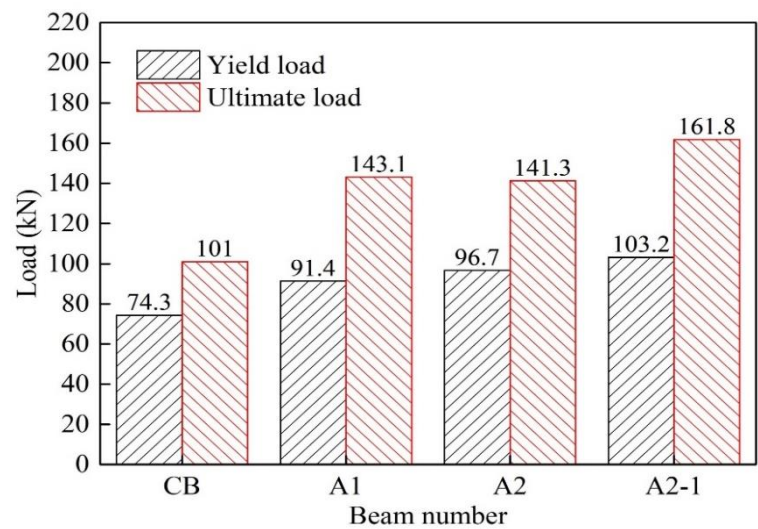


Figure 19. Load comparison diagram of beams CB, A1, A2 and A2-1.

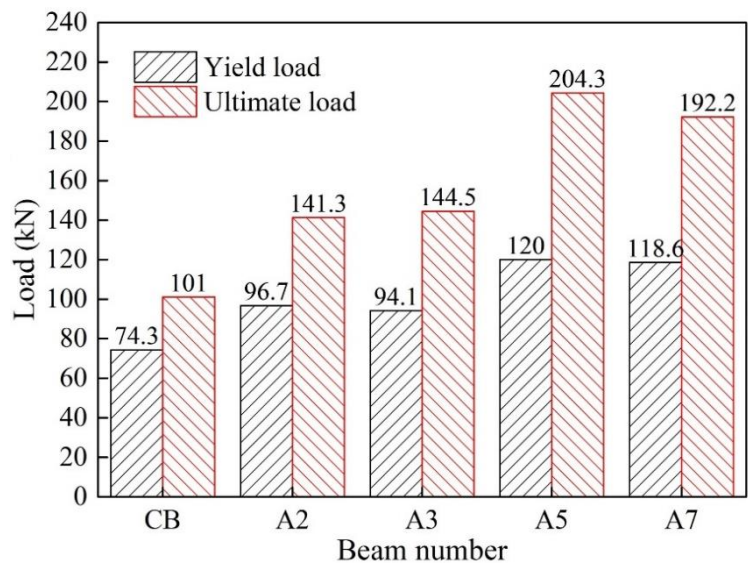


Figure 20. Load comparison diagram of beams CB, A2, A3, A5 and A7.

The load comparison diagram of beam A5, beam A6 and beam A8 is shown in Figure 21. The yield load of beam A8 increased by 137% over the control beam and 14.2% over beam A5, indicating that the yield load of the reinforced beams increases with the increase in the depth of the PUC. Beam A6 yield load only 51% greater than control, while that of beam A5 with beam end anchorage is 61.5% higher. Compared with beam A5, the yield load of beam A6 decreased by 6.7%. Therefore, only relying on PUC can not be stable anchoring steel wire, when the yield load reached, the concrete at both ends of the small oblique cracks, PUC material has a small slip.

As shown in Figure 21, the ultimate carrying capacity of A8 beam is 228kN, which is 11.8% higher than that of A5 beam due to the addition of 10mm PUC layer. Because the concrete at the end of the PUC-PSW reinforced layer of A6 beam has a small oblique crack at yield, the deflection increases rapidly with the continuous increase of load, but the load increases slowly. As the end of the reinforced layer suddenly peeled off from the concrete, the ultimate strength was 133.1kN, 53.5% lower than that of the A5 beam.

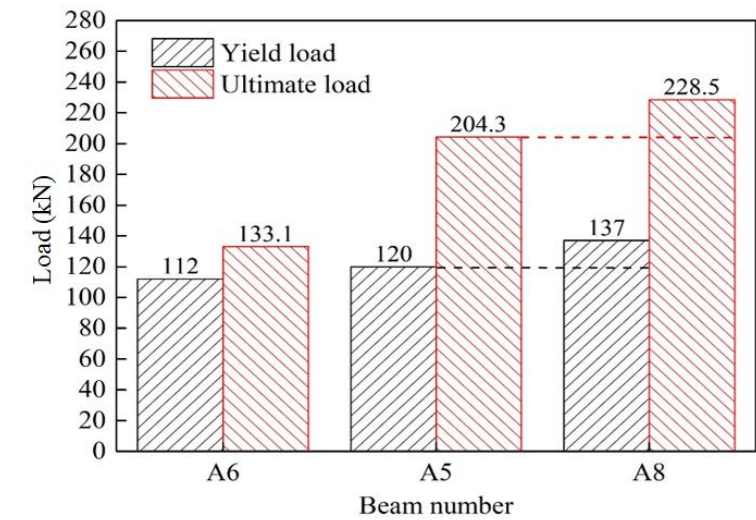


Figure 21. Load comparison diagram of beam A5, beam A6 and beam A8.

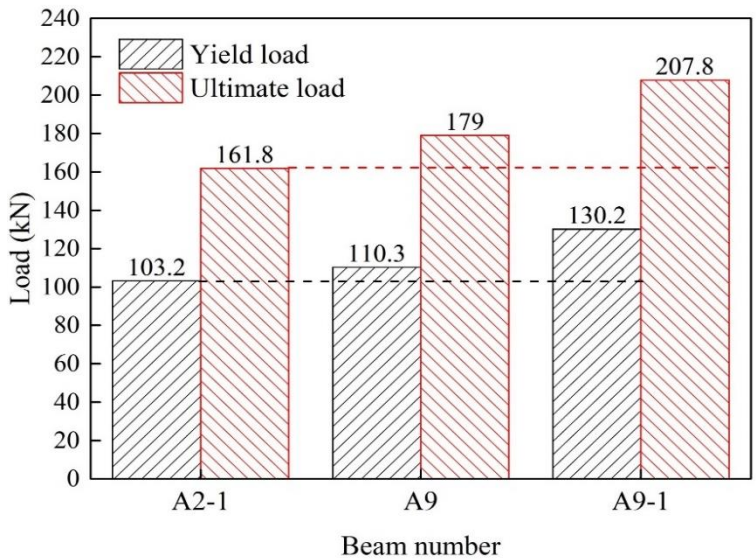


Figure 22. Load comparison diagram of beams A2-1, A9 and A9-1.

The comparison of yield loads of beam A2-1, beam A9 and beam A9-1 is shown in Figure 22. Although beam A9 has 5 fewer steel wires than beam A2-1, and they are all embedded in the material with a thickness of 20mm, the yield load of beam A9 is 6.9% higher than that of beam A2-1 because the two beams are embedded in different materials. Beam A9-1 is embedded in a 25mm thick PUC material, and also has 5 fewer steel wires than beam A2-1, and the yield load is 130.2kN, 26.2% higher than beam A2-1. It is shown that if the number of steel wires is reduced under necessary conditions, the requirement of yield strength can be satisfied by embedding steel wires into PUC materials.

The comparison of ultimate loads of beam A2-1, beam A9 and beam A9-1 is shown in Figure 22. Although beam A9 has 5 fewer steel wires than beam A2-1, the ultimate strength of beam A9 is 10.6% higher than beam A2-1 because of the different embedding materials. Beam A9-1 has 5 fewer steel wires than beam A2-1. Because the thickness of PUC material embedded in the wire of beam A9-1 is 25mm, the ultimate load capacity of beam A9-1 reaches 207.8kN, which is 28.4% higher than beam A2-1. Therefore, in the project, if it is inevitable to reduce the number of steel wires, and ensure that the bearing capacity meets the requirements, the steel wires embedded in the PUC material can achieve the purpose.

5.4. Strain Analysis

The stress-strain curves of beam A2 and beam A5 are shown in Figure 23. When beam A2 is loaded to a yield load of 96.7kN, the strain in the wire is $7092\mu\epsilon$, resulting in a relative stiffness of 1016MPa. After subtracting the initial strain, the net increase of the wire strain is $2132\mu\epsilon$. Under the load of 96.7kN, the strain of beam A5 is $6594\mu\epsilon$ and the corresponding stress is 961MPa. The net increase in wire strain after subtracting the initial strain from the wire of beam A5 is $1580\mu\epsilon$, which is much more modest than the net increase in wire string strain of beam A2. In addition, the stretch in the reinforcement of beam A5 is much lighter than that of beam A2 under the same test load. When the tensile strain at the bottom of the beam is close to $600\mu\epsilon$, the composite mortar of the beam A2 cracks, so that the composite mortar cracks before the load reaches 96.7kN. However, when the load reaches 96.7kN, the strain value of the polyurethane concrete material at the bottom of the beam is $1873\mu\epsilon$, and the corresponding stress is about 11.3MPa. Therefore, the PSW imbedded PUC material was able to delay the yielding of the main girder reinforcement. When the yield load of 120kN was achieved in beam A5, the net strain of the wire increased by $2,155\mu\epsilon$ minus the initial opening strain. At this load, the net gain in the wire of beam A2 was $2,804\mu\epsilon$, which was much greater than the net gain in strain in the wire of beam A5. At this point, the strain in the beam A5 PUC material is $2494\mu\epsilon$, and the resulting strain is approximately 14.9 MPa. Therefore, the PUC material can effectively increase the bearing capacity of the main beam. Under the ultimate load of 228.8kN, the maximum strain of beam A5 PUC material is $7369\mu\epsilon$ and the corresponding stress is 37.0MPa.

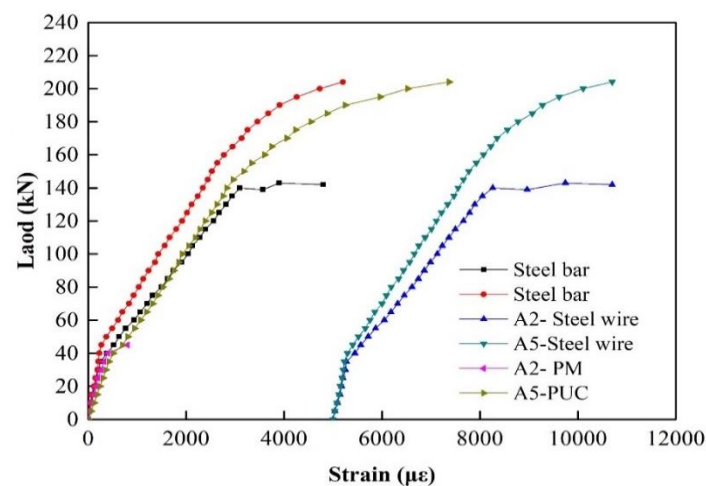


Figure 23. Load-strain diagram of beam A2 and beam A5 rebar, wire and insert material.

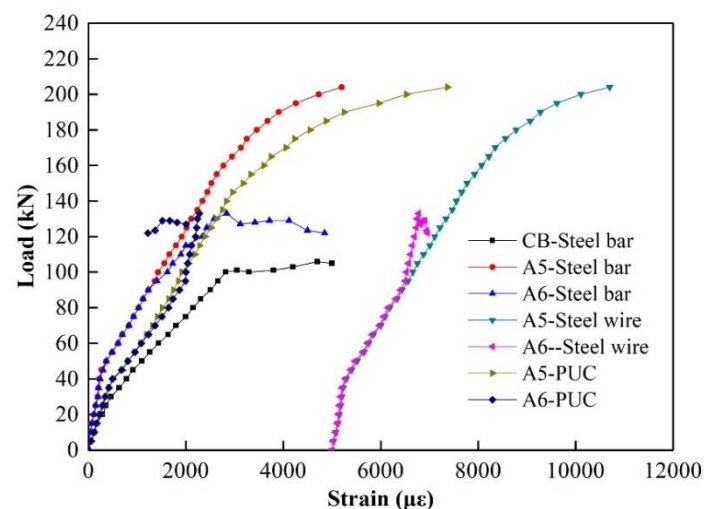


Figure 24. Load-strain diagram of beams CB, A5 and A6 rebar, steel wire and polyurethane concrete material.

The load-strain curves of rebar, wire and PUC of beams CB, A5 and A6 are shown in Figure 24. The load-strain curve of beam A6 was similar to that of beam A5 under below-yield loading. The results indicate that it is feasible for the wires to be anchored by PUC only during the initial stages of loading. With the increase of load, the strain of the reinforced layer increases, but it does not cause the slip of the wire. At 133kN, the reinforced beam fails due to anchoring failure. At this time, the strain of the steel wire is $6900\mu\epsilon$, and the strain of the PUC material is $1950\mu\epsilon$, which corresponds to the strength of about 11.9MPa under the ultimate load, which is only 30% of the ultimate strength of the material. The strength of the material is not utilized to its optimum in this case and the extreme strength improvement is not as pronounced as in beam A5. In order to make full use of PUC material without causing premature stripping damage, it is necessary to anchor the steel wire with beam end anchorage.

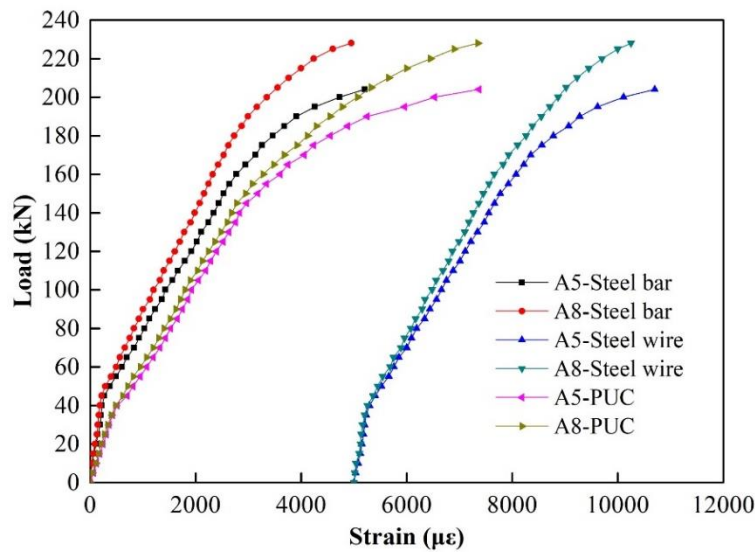


Figure 25. Load-strain diagram of beam A5 and beam A8 rebar, steel wire and polyurethane concrete material.

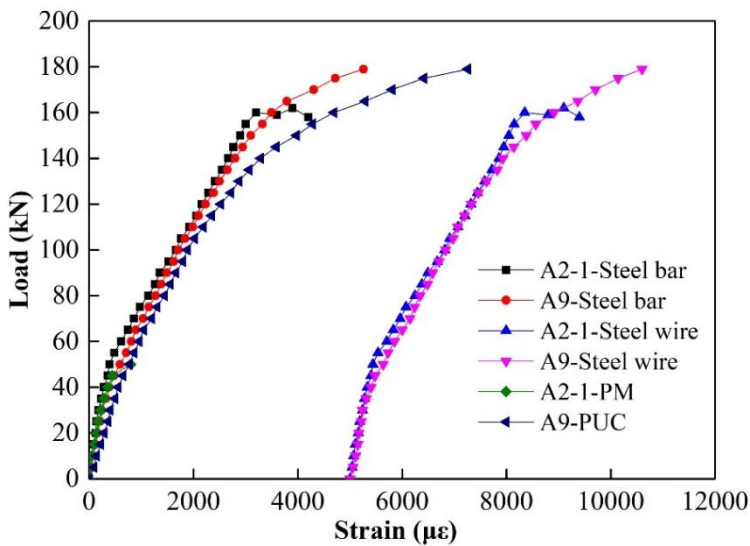


Figure 26. Load-strain diagrams of beams A2-1 and A9 rebar, steel wire, composite mortar and polyurethane concrete materials.

According to Fig. 25, the strain variation rules of steel bars, wires and PUC in beam A5 and beam A8 are similar. Since the stringers embedded in the PUC in beam A8 are 10 mm thicker than that in

beam A5, the strains of the reinforcement, wires and PUC soil in beam A8 will be smaller than that in beam A5 under the same loading.

The strains of beam A2-1 and beam A9 rebar, steel wire, composite mortar and PUC material are shown in Figure 26. When the beam A2-1 is loaded to the yield load of 103.2kN, the strain of the wire is $6905\mu\epsilon$ and the corresponding stress is 987MPa. After the initial strain is subtracted from the beam A2-1 wire, the net strain increase of the wire is $2007\mu\epsilon$. Under the action of 103.2kN load, the strain of beam A9 is $6977\mu\epsilon$ and the corresponding stress is 992MPa. After the initial strain is subtracted from the wire of beam A9, the net strain increase of wire is $2086\mu\epsilon$, which is close to the net strain increase of beam A2-1 wire. Although beam A9 is equipped with 5 fewer PSWS than beam A2-1, under the same test load, the strain value of beam A9 reinforcement is close to that of beam A2. When the tensile strain of the beam bottom is close to $700\mu\epsilon$, the composite mortar of the beam A2-1 cracks, so that the composite mortar cracks before the load reaches 103.2kN. However, when the load reaches 103.2kN, the strain value of the PUC material at the bottom of the beam is $1956\mu\epsilon$, and the corresponding stress is about 12.1MPa. Therefore, although the number of PSW used is reduced, the PUC material embedded with the PSW can guarantee the yield strength of the reinforced beam. When the load reaches 161.8kN, the beam A2-1 reaches the ultimate strength, and the steel wire has nominal yield, and the steel bar has already entered the yield stage. However, when the load reaches 161.8kN, the steel wire of beam A9 has not reached the nominal yield strength, and the PUC material has not broken. At this time, the PUC strain is $4806\mu\epsilon$ and the corresponding stress is 27.8MPa, which has not reached the PUC tensile limit strength.

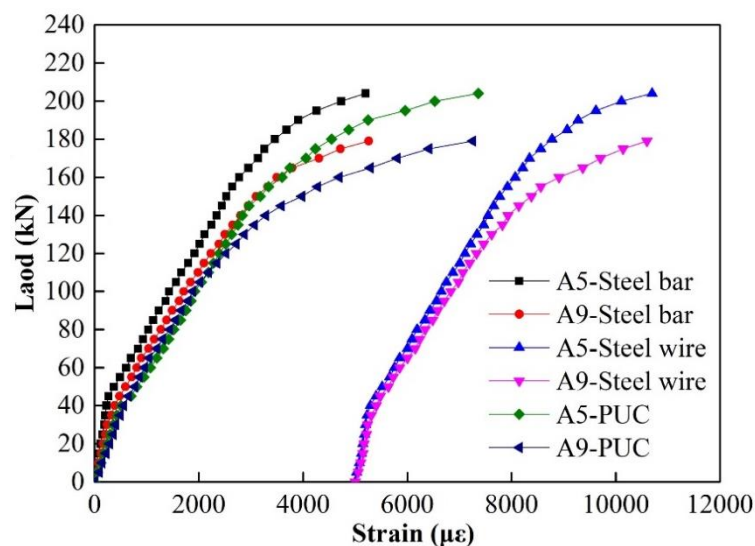


Figure 27. Load-strain diagram of beams A5 and A9 steel bars, steel wires and polyurethane concrete materials.

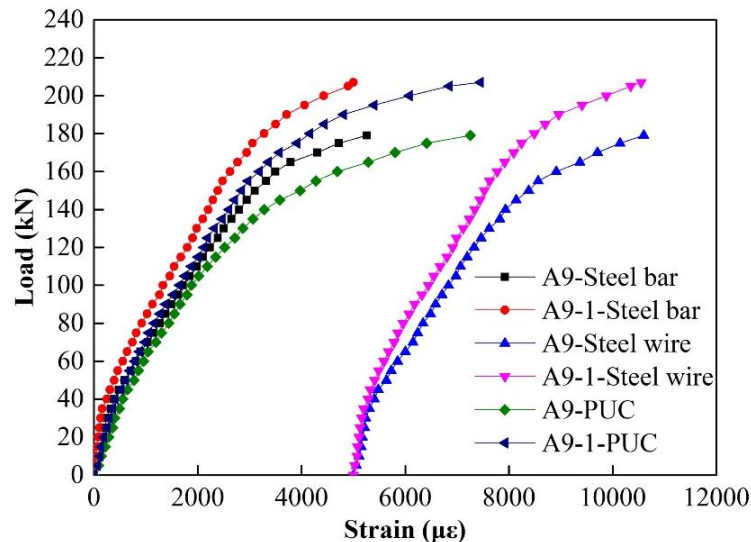


Figure 28. Load-strain diagram of beams A9 and A9-1 Rebar, steel wires and polyurethane concrete material.

The strain of beams A5 and A9 rebar, wire and PUC material is shown in Figure 27. Beam A5 and beam A9 are arranged with 5 and 2 steel wires, respectively, which are embedded in the PUC material of 20mm thickness. As can be seen from the graphs, the trends of the load-strain curves of the reinforcement, wire and PUC materials in the two beams are quite comparable. Because there are 3 more steel wires in beam A5 than beam A9, the strain of steel bars, steel wires and PUC in beam A9 is smaller than that of beam A9 under the same load. After the steel bar of beam A5 yielding, the tensile strain difference of the wire of two beams under the same load gradually increases. As the steel bar enters the yield state, the further increase of the bearing capacity of the reinforced beam is mainly borne by the steel wire and PUC in the reinforced layer. As the number of steel wires in beam A5 is more than that in beam A9, the bearing capacity of the steel wires in beam A5 increases greatly with the increase of load, resulting in the tensile strain difference of the steel wires of the two beams gradually increasing.

The strain of rebar, wire and PUC material of beam A9 and beam A9-1 is shown in Figure 28. Two PSWs are arranged in each of the two reinforced beams, and beam A9 and beam A9-1 are embedded in 20mm and 25mm PUC material, respectively. According to the graphs, the load-strain curves of reinforcement, wire and PUC in beam A9-1 and beam A9 have similar variation trends. Since the thickness of the wire inserted into the PUC in beam A9-1 is 5 mm larger than that in beam A9, the strains of the bars, wires and PUC in beam A9-1 will be lighter than those in beam A9 under the same load. As the wire enters the nominal yield state, the difference in the tensile strain of the PUC material between the two beams under the same load gradually grows, due to the fact that the reinforcement has entered the yield state. As the load grows, the load carrying capacity of the beams is increased mainly by the PUC soil material. Therefore, the difference of tensile strain of PUC material between the two beams gradually increases.

6. Conclusion

In this paper, PUC material is used as the embedded material of steel wire to form a new method of PUC-PSW reinforcement. Light and high strength PUC materials can not only bond and anchor PSW, but also passively participate in the structural force. The problems of easy cracking, easy falling off and affecting the durability of PSW are solved by using mortar or composite mortar as embedded material. In this paper, the static test of PUC-PSW reinforced beam is studied and analyzed. The test results show that:

(1) Compared to PSW strengthening, PUC-PSW strengthening can improve the yield and ultimate loads of the strengthened beams considerably. The yield load and ultimate load of the PUC-

PSW reinforced beam (20mm thick PUC) are increased by 24.1% and 44.6%, respectively, compared with the corresponding PSW reinforced beam. Even if the steel wire in the reinforced layer is removed, the yield load and ultimate load are increased by 2.2% and 19.4%, respectively.

(2) The ability of PUC-PSW reinforced to limit crack development is better than that of PSW reinforced beams, especially after the main beam steel bars yield. The PUC material does not crack during the whole loading process until the final reinforcement layer breaks, combined with the good chemical corrosion resistance of the material, this phenomenon can theoretically increase the durability of the steel wire; The stiffness of PC-PSW reinforced beam is obviously higher than that of PSW reinforced beam.

(3) Strength, stiffness, and crack-limiting capacity of reinforced beams improve with growing thickness of the PUC of the reinforcement layer and decrease with decreasing prestressing of the wires. Compared with the intact reinforced beam, the deflection of the load-reinforced beam is larger than that of the directly reinforced beam, and the structural stiffness and yield load are reduced, but the ultimate bearing capacity is not significantly reduced.

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