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Research on the Shear Resistance of Ultra-High Strength Prestressed Concrete Beams with Stirrups

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Abstract: An experimental investigation of the shear behavior of 7 bonded post-tensioned ultra-high strength prestressed concrete test beams with stirrups were tested. The effects of the shear span-depth ratio, the stirrup ratio, the grade of concrete strength and the degree of prestress on model of failure and diagonal crack-resistant capacity and shear capacity were analyzed. The shear mechanism of ultra-high strength prestressed concrete test beams was analyzed. The applicability of existing formulas for shear capacity calculation of ultra-high strength prestressed concrete beams with stirrups is investigated. The research achievements will provide an engineering application of ultra-high strength prestressed concrete test beams with stirrups.

Keywords: *the stirrup ratio; concrete strength; shear capacity; diagonal crack-resistant capacity*

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1. Introduction

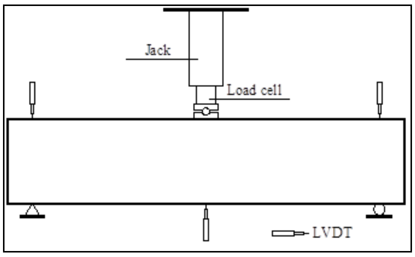
In recent years, high strength prestressed concrete structures are widely applied to high rises, large-span bridges, water conservation constructions and oceanic engineering work [1-5]. As a novel concrete, high-strength high-performance concrete surpasses regular concrete in aspects of strength, durability, performance, and volume stability, but has such shortages as high brittleness and poor ductility. The concrete strength classes that satisfy the requirements of Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts(JTG D62-2004), a recently issued code in China, merely range from C15 to C80. However, along with the development of concrete technology, high-strength concrete with higher classes than the one used in document [6] has found widespread use in practical engineering. Zhi Fei and Ye Zhiman [7] presented an experimental investigation on the shear capacity of eight simply supported and prestressed high-strength T-section concrete beams and one normal-strength concrete beam with web reinforcement. The cracking characteristics and the failure states of these beams under the condition of different parameters are studied, and a calculating formula of the shear capacity of these beams under the concentrated loading is suggested by them. Elzanaty A H.[8] studied on the mechanical performance of high-strength concrete beams. However, till now, there has been no theoretical or trial research into the shear performance of prestressed ultra-high strength concrete beams (PUSCBs, similarly hereinafter). As a result, related theories and research achievements seriously lag behind engineering practice. Therefore, the paper intends to undertake a shear bearing test to reveal the shear bearing mechanism of 7 PUSCBs. To this end, the major factors that impact on the shear bearing performance of beam specimens are systematically analyzed. What is more, for the existing formula to compute the shear bearing capacity (SBC, the same below), its applicability to the SBC calculation for PUSCBs with stirrups is discussed in the paper.

2. Test overview

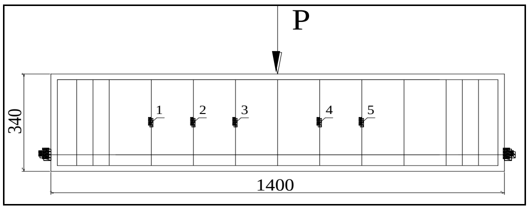
In the test, 7 simply supported PUSCBs with web reinforcement are designed; whose cross section size is 160mm×340mm. The 1400mm-long beam specimen contains a 1120mm-long shear span zone, with the shear span ratio of 2.0. The design concrete strength class of the beam specimens is C40、C70 and C100, respectively. The longitudinal bar of the beam specimens consists of three 20mm-diameter HRB335, whose yield strength is 370N/mm2. The stirrup is 6.5mm-diameter HPB235, with the yield strength of 335 N/mm2. The prestressed tendon uses steel strands in 1860 MPa, whose uniform tension control stress is 0.75 fptk (fptk represents the normal value of tension strength for prestressed tendon), diameter of 15.2mm and 12.7mm, respectively, and yield strength of 1815N/mm2 and 1798 N/mm2, respectively. Low retracting anchor is adopted as the prestressed anchor. The main test variables are stirrup ratio, concrete strength, and the degree of prestress. Table 1 is the beam specimen parameters and main test results.

3. Sensor arrangement and loading scheme

To measure the stirrup strain, strain gages are stuck to each stirrup at load points or on the support. To measure the reinforcement strain, strain gages are likewise glued to each surface of longitudinal tendons and prestressed tendons in girder span. LVDT is placed in the bottom of the centroid of the girder span and on the support as well so as to measure the entire beam deformation. The hierarchical, monotonic static loading system is used for the test. The live load is exerted on the span centroid by jack, whose loading system conforms to the testing methods of concrete structure (GB 50152-92). All test data is collected automatically by IMC data collector. The test contents are: cracking load and limit (displacement) load for the beam specimen; strain for the longitudinal tendon, prestressed tendon and the tendon with stirrups; the width and development conditions of cracks; etc. Figure I is the sketch of test equipment and arrangement of sensors.



(a) loading equipment



(b)PRC–06 stirrup strain

***Fig. 1** Sketch of test equipment and arrangement of sensors*

4. Test result and its analysis

4.1 Failure mode

The failure mode of PUSCB inclined section resembles the one of prestressed normal reinforcement concrete beams (RCBs, for short). At the start of the test, the beam specimens are elastic. When the live load increases to 17%-32% of limit load, bending cracks occur below the load point in span centroid. As the live load continues to ascend, there emerge bending cracks in the shear span zone which are lower than the center of the longitudinal reinforcement, developing diagonally towards the load points. When the live load increases to 36%-44% of limit load, unexpected diagonal cracks occur in the position of the prestressed rebar in the shear span zone. As the live load exerted on the beam specimen continues to increase, the bending cracks develop slowly, while the diagonal cracks become widened. When the live load approaches the limit load, the enlargement of beam deflection degree accelerates. At the same time, the diagonal cracks extend upwards to the point of action by live load and downwards to the longitudinal rebar along which they develop towards the support. At this moment, the load acted on the inclined section of the beam specimen has reached the limit value. The diagonal crack plane for the PUSCB is smoother than that for the normal-strength concrete beam. Most of the coarse aggregates along the cracks on the failure plane are split, which shows that compared to normal-strength concrete beam, the PUSCB has poorer aggregate interlock behavior. Over the course of loading, the behavior of all beam specimens is: the stirrup yields firstly, while the longitudinal tendon fails in shear instead of yields. Table 1 shows the cracking load and the limit load for the PUSCB. Figure 2 is the corresponding failure mode.

***Table. 1:** Parameters of beam specimens and the experimental results*

#	Compress-ive Strength f_{cu}/MPa	Shear-span ratio λ	Degree of prestress λ_p	Stirrup ratio ρ_{sv}(%)	Cracking load of the inclined section V_{cr}/kN	Limit load V_T /kN
PRC–01	108.2	2.0	0.42	0.22	328.14	750.04
PRC–02	108.2	2.0	0.42	0.42	369.01	860.91
PRC–03	108.2	2.0	0.42	0.32	338.56	804.49
PRC–04	108.2	2.0	0	0.32	246.96	669.81
PRC–05	108.2	2.0	0.34	0.32	303.52	695.59
PRC–06	75.8	2.0	0.42	0.32	277.01	656.72
PRC–07	42.9	2.0	0.42	0.32	223.50	575.32

4.2 Load analysis

4.2.1 Influence of stirrup ratio

Figure 3 (a) is the influence of stirrup ratio on the cracking load of the inclined section. As can be seen from it, when the stirrup ratio increases from 0.22% to 0.32%, the cracking load of the inclined section gains by 3.18%; when the stirrup ratio increases from 0.32% to 0.42%, the cracking load of the inclined section gains by 7.91%. Therefore, the cracking load of the inclined section for beam specimens basically remain unchanged as the stirrup ratio rises up.

Despite little contribution to the cracking load of the inclined section for beam specimens, stirrup ratio increment leads to the change of shear bearing capacity of the beam specimens in an effective manner. As can be seen from Figure 3 (b), the shear bearing capacity of the beam specimens amplifies with the increment in stirrup ratio.

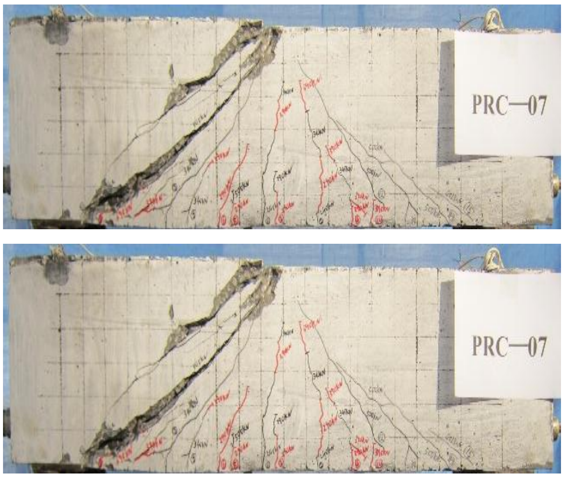


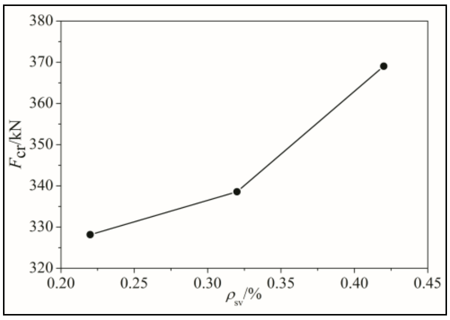
***Fig. 2** Failure mode of beam specimens*

When the stirrup ratio increases from 0.22% to 0.32% and to 0.42%, respectively, the shear bearing capacity of the beam specimens gains by respective 7.26% and 14.78%. This is because the smooth stirrup with small diameter is difficult to effectively constrain its surrounding concretes. As a result, the stirrup barely adjusts the concrete stress redistribution on the inclined section or deters cracks from developing before the formation of diagonal cracks. However, if the diagonal cracks appear, the stirrup that intersects with them will bear the action of concrete cracking and release part of shear stress accordingly. Along with the increment in live load, the stirrup yields largely. In this case, the higher the stirrup ratio is, the larger the shear stress that the stirrup can bear is.

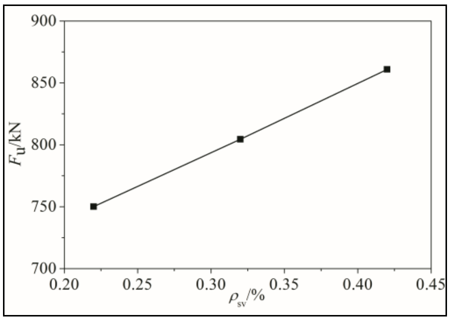
4.2.2 Influence of concrete strength

Figure 4 (a) is the influence of concrete strength on the cracking load of the inclined section. As can be seen from it, when the concrete strength increases from 42.9MPa to 75.8MPa and to 108.2MPa, respectively, the cracking load of the inclined section gains by 23.94% and 51.48%, respectively. Therefore, the cracking load of the inclined section for beam specimens ascends as the concrete compressive strength rises up. This is because the cracking load of the inclined section is directly controlled by the concrete tensile strength. In this way, as the concrete compressive strength is enlarged, the concrete tensile strength increases accordingly, which gives rise to the increment in the cracking load of the inclined section.

According to the relationship between shear bearing capacity and concrete strength (as shown in Figure 4(b)), ceteris paribus, the higher the concrete strength is, the larger the shear bearing capacity of the beam specimens is. When the concrete strength increases from 42.9MPa to 75.8MPa and to 108.2MPa, respectively, the shear bearing capacity of the beam specimens gains by 14.15% and 39.83%, respectively.

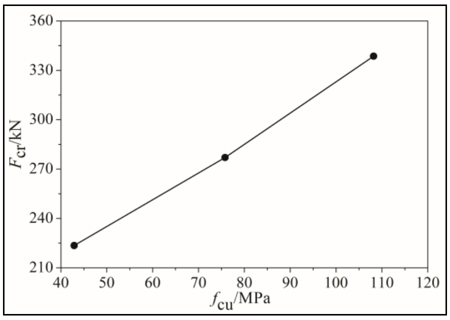


(a) Influence of stirrup ratio on the cracking load of the inclined section

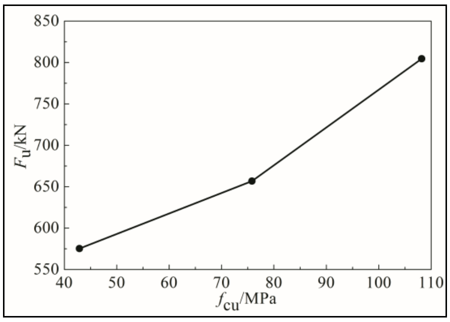


(b) Influence of stirrup ratio on the shear bearing capacity of the beam specimens

***Fig.3** Influence of stirrup ratio on load*



(a) Influence of concrete strength on the cracking load of the inclined section

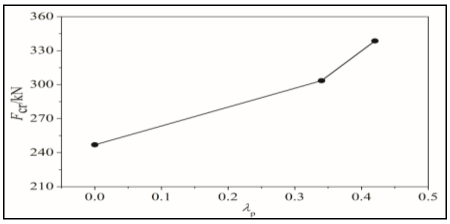


(b) Influence of concrete strength on the shear bearing capacity

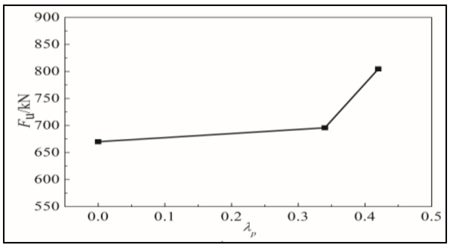
***Fig.4** Influence of concrete strength on load*

4.2.3 Influence of the degree of prestress

As can be shown in Figure 5(a) and Figure 5(b), as the degree of prestress increases, both the cracking load of the inclined section and the shear bearing capacity increase. This is because the PUSCB with web reinforcement above the neutral axis is under the double action of shear stress and compressive stress. In this case, the exertion of prestress induces a change in the state of the stress distribution for the inclined section. The neural axis as such moves down, and the shear-compression zone becomes higher. Finally, the cracking load of the inclined section and the shear bearing capacity increase.



(a) Influence of the degree of prestress on the cracking load of the inclined section



(b) Influence of the degree of prestress on the shear bearing capacity

***Fig.5** Influence of the degree of prestress on load*

5. Analysis on shear bearing capacity

Guided by Code for Design of Concrete Structures, the shear bearing capacity of 7 PUSCBs is computed, and the results are compared with the measured values (as shown in Table 2).

When the formula calculation value in document [2] and the test value of PUSCBs are compared with each other, the mean value is 1.88, and the variance is 0.28; When the formula calculation value in document [2] is used to compare with the test value of the prestressed normal concrete specimen and with the test value of 10 beam specimens in document [9], the respective mean value is 1.94 and 1.92, and the variance is as uniform as 0.05.

Therefore we can conclude that it is of the same safety to compute the value of PUSCBs and the value of prestressed normal concrete specimens by the formula in document [2]. When the shear span ratio remains unchanged, as the degree of prestress increases, the ratio of the test value to the computation value becomes greater.

According to the contrastive analysis conducted on variance, the shear bearing capacity (the concrete strength class ranges from C40 to C70) of the prestressed normal concrete specimens which is computed by the formula in document [2] is less discrete and more reliable than the shear bearing capacity of the PUSCBs computed in the same way.

***Table. 2** Results of shear bearing capacity*

#	**Shear-span ratio λ**	**Stirrup interval s/mm**	**Test value of the shear bearing capacity V/kN**	**Computation value VT1/kN**	**V/ V_{T1}**
PRC–01	2.0	180	375.020	189.79	1.98
PRC–02	2.0	100	430.455	217.18	1.98
PRC–03	2.0	130	402.245	203.66	1.98
PRC–04	2.0	130	334.905	219.23	1.53
PRC–05	2.0	130	347.795	204.00	1.70
				Mean value	1.88
				Vari	0.28
PRC–06	2.0	130	328.360	183.56	1.79
PRC–07	2.0	130	287.660	137.93	2.09
				Mean value	1.94
				Vari	0.05

Note: V denotes the test value of the shear bearing capacity; VT1 represents the shear bearing capacity computed by the Code GB50010–2010

6. Conclusion

According to the test result of the shear bearing performance of 7 PUSCBs as well as further analysis conducted on the sample load, it can be concluded that:

(1) The failure mode of PUSCBs is similar to the one of prestressed normal concrete beams, in a way that can be divided into three stages: initial crack, crack development, and failure. The beams fail in shear.

(2) The major influencing factor of the cracking load of PUSCB inclined sections contains concrete strength and the degree of prestress. The cracking load increases with the increase of concrete strength or the degree of prestress.

(3) The shear bearing capacity of PUSCB inclined sections increases with the increase of stirrup ratio, concrete strength or the degree of prestress.
(4) The shear bearing capacity of the PUSCBs computed by the formula in the Code GB50010–2010.

7. Acknowledgements

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