Review

Research Status of Structural Optimization Design, Materials, and Prestressing Techniques for PC Small Box Beams: A Review of Research Progress

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Abstract: Based on recent research findings and an analysis of the literature on Precast concrete (PC) small box girders, this paper presents a systematic discussion of the optimization design, materials, and prestressing techniques for PC small box girder structures. The study analyzes and summarizes the optimization design of PC small box girders in terms of diaphragms, prestressing tendons, cross-sectional dimensions, and materials. It synthesizes the impact of these optimization methods on the mechanical performance of PC small box girders. Furthermore, the current research status of retard-bonded and external prestressing technologies is discussed in detail, along with a summary of the mechanical properties of small box girders utilizing these techniques. Finally, several future research directions are proposed on the basis of the current state of research.

Keywords: PC small box girders; optimization designs; prestressing technology; mechanical performance

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1 Introduction

Precast concrete (PC) small box beams [1] have developed rapidly because of their economic and technical advantages, as well as their fast construction speed and low structural cross-sectional height. They are widely used in highways, railways, and municipal road bridges with spans ranging from 20 to 40 meters. Compared with other cross-sectional forms, such as hollow slabs and T-beams, small box beams are the most commonly used, as they exhibit excellent performance in terms of structural load-bearing capacity, economy, and applicability.

The advantages of small box girders in terms of structural performance include the following: [2-4]

(1) The cross section is a closed thin-walled type, which provides greater stiffness than other girder cross section types do, particularly featuring a larger torsional moment of inertia;
(2) It exhibits excellent dynamic characteristics, effectively resisting torsional deformation caused by vehicle loads and seismic forces; and
(3) This demonstrates favorable overall structural performance, with a more uniform cross-section and better integrity under the action of transverse distributed eccentric loads on the bridge.

The advantages of small box girder bridges in terms of economic efficiency and applicability include the following:

(1) Currently, both domestic and international structural design methods for simply supported bridges or continuous bridges with spans of 20–40 m are relatively well established, resulting in bridges with excellent economic performance;

(2) The precast process of PC small box girders is characterized by a high degree of mechanization. Additionally, the maturity of construction techniques enhances the convenience and reliability of the overall construction process; and
(3) Small box beam bridges have relatively low bridge heights, which reduces obstructions to the landscape and results in a simple and aesthetically pleasing appearance. They are often selected for urban bridge designs where landscape considerations are important.

However, during small box beams construction, the component size, volume, and self-weight often face limitations due to hoisting and transportation conditions. Additionally, during operation, issues [5] such as beam cracking, excessive creep deflection, and other defects may arise due to discrepancies between the design calculation model and actual conditions, excessive focus on economic factors, poor construction quality, inadequate maintenance, traffic volumes exceeding expectations, and the prevalence of overloaded vehicles. Investigations have revealed that defects primarily occur in areas such as the web's diagonal cracks, longitudinal cracks in the web, longitudinal cracks in the top slab, longitudinal cracks in the bottom slab, and irregular cracks in other parts, which seriously affect the durability of small box beams. In response, both domestic and international researchers have conducted extensive studies on small box beams, driving their optimized design and performing mechanical property tests to further enhance their performance.

This paper focuses on PC small box girders, compiling and summarizing research achievements in terms of structural design and materials from the past five years. On the basis of this foundation, advancements in new prestressing techniques, such as retard-bonded prestressing and external prestressing, have been analyzed. Additionally, the paper outlines potential directions for future research in this field.

2 Current State of Research on the Optimization Design of PC Small Box Girder Structures

2.1 Research on the Optimization Design of Diaphragms in PC Small Box Girders

The diaphragm is a critical load-bearing component in small box girders. Its incorporation significantly enhances the overall integrity and stability of the box girder, increases its torsional rigidity, and improves the distribution of internal stresses. According to the literature [6-8], the introduction of diaphragms effectively increases the transverse stiffness of the section, reduces the distortion deformation of the box girder, and mitigates the distorted transverse bending moment. However, it also leads to substantial changes in the magnitude and distribution of the distorted double moments and distortion moments within the girder, resulting in a notable increase in the warping stresses within the cross section. When a middle diaphragm is introduced, it increases the self-weight of the structure and amplifies the mid-span deflection but exerts minimal influence on the mid-span bending moment in the small box girder ultimate limit state [9]. Regardless of whether the girder is situated on a straight or curved bridge, eccentric loading is typically present. The addition of transverse diaphragms facilitates the dissipation and transmission of torsion and shear forces, thereby improving the stress state of the main girder. Diaphragms located at both ends and the center of the box girder contribute to the enhancement of its overall lateral performance, thereby increasing its capacity to resist transverse horizontal loads [10]. Furthermore, the box girder end diaphragms play a crucial role in transferring support reactions and serve as bearing points for the structural support of the box girder.

The diaphragm, as an important component of small box girder bridges, plays a crucial role in ensuring the collaborative load-bearing behavior of individual box girders. Parameters such as the thickness, number, and layout of diaphragms significantly affect the mechanical performance of the main girder structure. As a result, many scholars have conducted extensive research into the optimization design of diaphragms in PC small box girders.

Zhu [11] used Midas software to establish a computational model and quantified the impact of diaphragm quantity on the overall load-bearing behavior of precast, assembled small box girders. Xie et al.[12] studied an 8-span, 35-meter prestressed simply supported small box girder bridge, using Midas software to create a beam grid model and perform a comparative analysis of the mechanical behavior of the bridge under different diaphragm configurations. Xu et al.[13] conducted transverse static load tests on small box girders with varying numbers of middle diaphragms and combined these results with finite element modeling to study the influence of diaphragm quantity on the lateral stress variation in multicell small box girders, followed by a comparative analysis. These studies suggest that for precast, assembled small box girders, setting a single diaphragm at the midspan can ensure cooperative load-bearing behavior of the main girder and effectively reduce the midspan live load bending moment. However, excessive installation of diaphragms can lead to excessive dead loads on the bridge, which is detrimental to the bridge structure.

Mai [14] employed a combination of numerical simulations and experimental comparisons to investigate the impact of middle diaphragms on the small box girder load-bearing performance, with the results presented in Figure 1. The study revealed that, under compliance with the prescribed structural requirements, the transverse stress in the lower flange of the middle diaphragm decreased as the height of the diaphragm increased.

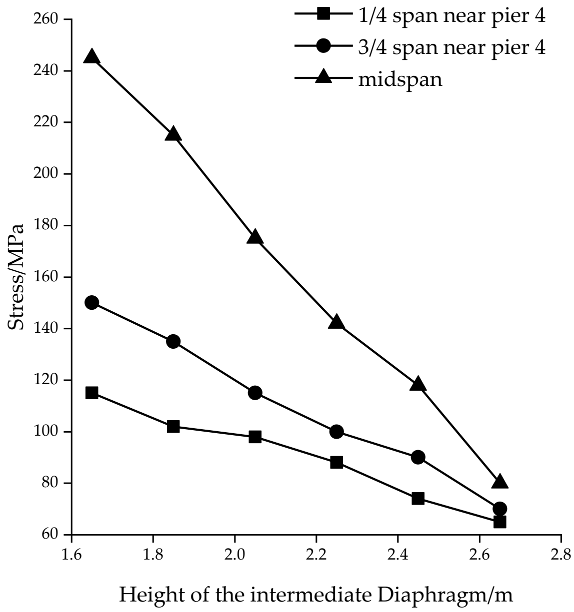

Figure 1 Effect of the midspan diaphragm height on the transverse stress in the lower flange of PC small box girders [14]

Deng et al. [15] established finite element models for continuous small box girder bridges with varying span lengths and span-to-width ratios. By altering the thickness of the diaphragms, they examined the impact on the mid-span deflection of the central girder and ultimately determined the optimal diaphragm thickness for prefabricated box girder bridges. Miao [16] conducted numerical simulations based on a 30-meter span small box girder standard design and analyzed the influence of different midspan diaphragm thicknesses on the cooperative load-bearing performance of individual girders. Through extensive virtual simulation data, increasing the diaphragm thickness from 100 mm to 200 mm significantly optimized

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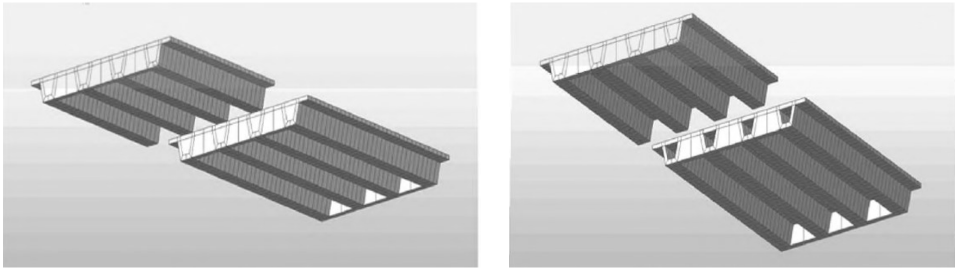
the lateral load distribution of the small box girder bridge. However, beyond this point, further increases in thickness resulted in minimal improvement in load distribution optimization. Therefore, a diaphragm thickness of 200 mm was recommended as the optimal value.

Zhou et al. [17] proposed a novel diaphragm configuration, which differs from traditional diaphragms in that the new diaphragm extends transversely through all the individual girders at both the mid-span and the support points and includes laterally continuous reinforcement. In contrast, traditional diaphragm configurations typically feature only transversely continuous diaphragms at the ends, with intermediate diaphragms generally being noncontinuous and positioned only between adjacent small box girders, thus connecting only the web plates of two adjacent girders. Large-scale model testing and finite element simulation found that the novel diaphragm configuration not only provides significantly greater lateral stiffness but also exhibits greater resistance to hinge joint defects.



a) New-type diaphragms b) Traditional diaphragms

Figure 2 Two types of diaphragm structures [17]

In summary, the configuration of diaphragms has a significant effect on the mechanical performance of small box girders. When a single diaphragm is installed at the midspan with a width of 200 mm and a height equal to or slightly less than the full height of the main girder, it is sufficient to meet the requirement for cooperative load-bearing behavior of the individual girders.

2.2 Research on the Optimization Design of Prestressing Tendons in PC Small Box Girders

The role of prestressing tendons in PC small box girders is reflected primarily in enhancing the structural integrity and load-carrying capacity of the girder [18,19]. Longitudinal prestressing tendons improve the bending resistance and bending stiffness of the box girder while also effectively counteracting tensile stresses induced by loading, reducing deformations and crack widths, and enhancing the durability of the girder. When combined with transverse and vertical prestressing tendons, longitudinal tendons work synergistically to further improve the overall performance and load-carrying capacity of the girder, ensuring the safety and stability of the bridge over its long-term service life.

Zhang et al. [20,21] investigated the optimization design of longitudinal prestressing for PC small box girder bridges. Through the adjustment of prestressing tendon parameters for small box girders, they reported that, under unchanged design conditions, increasing the eccentricity of the tendon group could enhance the precompression effect on the concrete in the compression zone of the box girder, thereby reducing the deflection of the girder under normal service conditions. ANSYS software was used to create both planar and 3D solid models of the small box girder bridge via an algorithm. The optimal topological solutions for both models were derived, and a composite structural mechanics model was established on the basis of these solutions. Furthermore, using an incremental evolutionary topology algorithm, the optimal design of longitudinal prestressing tendons for the box girder was determined. The optimized tendon parameters are shown in Table 1, and the tendon configuration is illustrated in Figure 3.

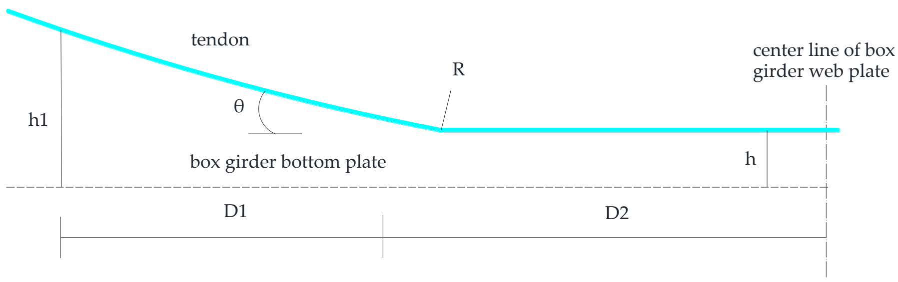


Figure 3 Tendon structure [20,21]

Table 1 Optimized design tendon parameters [20,21]

Tendon	h (mm)	H1 (mm)	R (mm)	θ (°)	D2 (mm)
N1	590	1,391	45,000	7.5	9,899
N2	465	1,111	43,000	7.5	7,771
N3	340	831	40,000	7.5	5,642
N4	215	551	31,000	7.5	3,512
N5	90	284	46,000	3	3,704

Luis Bernardo Fargier Gabaldón et al. [22] investigated an approximate method for configuring continuous prestressing tendons in box girders. The studied variables included the main span length, the length of the prestressing tendons, and the geometry of the box girder. The results indicated that as the length of the prestressing tendons decreased, the secondary bending moment induced by the tendons also decreased, which in turn reduced the secondary internal forces in the structure, thereby improving the small box girder load-carrying behavior.

Xiao [23] used the steel plate girder method to calculate the lateral distribution factors for the 14th and 15th spans of a certain high-speed interchange ramp bridge and reported that these factors were greater than the lateral distribution factor specified in the general design drawing for small box girders. Despite this, the same number of prestressing tendons still met the code requirements for structural stress. Xiao Yafei et al. concluded that the prestressing tendon configuration in the general design drawing is relatively conservative and that the number of tendons could be reduced appropriately. Similarly, Kou [24] conducted an optimization design study on the prestressing tendon configuration for a continuous 30-meter span small box girder, exploring three prestressing schemes, including the general design drawing. Using Midas software, Kou analyzed the ultimate limit state for the persistent load condition, the normal service limit state under persistent loading, and the structural stresses under both persistent and transient conditions. The comparative analysis further confirmed that the prestressing tendon configuration in the general design drawing is relatively conservative. While meeting the requirements for bending capacity in the positive section, it is possible to reduce the number of tendons for the positive bending moment of the web and the negative bending moment of the top slab, thus achieving a reduction in the self-weight of the main girder.

According to these studies, the parameters of the prestressing tendons are the primary factors influencing the level of prestress and constitute the focus of current optimization efforts by researchers. The key optimization trends can be summarized as follows:

(1) With other design parameters held constant, increasing the eccentricity of the tendon group effectively enhances the precompressive force applied by the

prestressing tendons to the concrete in the compression zone of the box girder, thereby mitigating deflection under normal service conditions;

(2) The optimal tendon path for the prestressing tendons is determined through topology optimization algorithms, with the goal of improving the prestressing efficiency; and

(3) By modifying the configuration of prestressing tendons, an optimized layout can be achieved, minimizing redundant tendons and reducing the self-weight of the structure.

Moreover, numerous scholars both domestically and internationally have adopted alternative approaches by focusing on the prestress tension process. By optimizing parameters during the tensioning phase, they aim to fully utilize the effectiveness of prestress.

Chen [25] investigated the impact of changing the prestressing tendon tensioning sequence on the stress, deformation, and initial prestress of a girder by establishing a finite element model. The analysis results indicated that postponing the tensioning of the prestressing tendons in the top slab until after bridge construction significantly reduced the long-term mid-span deflection of the main girder after completion, effectively improving the crack resistance of the mid-span section. Liu et al. [26] studied the influence of various construction sequences, including the pouring of cast-in-place concrete at the beam ends, the tensioning of prestressing tendons in the negative moment region, and the removal of temporary supports, on the structural behavior of a bridge. The results revealed that the optimal construction sequence, which involved pouring the concrete at the beam ends in one stage, symmetrically tensioning the prestressing tendons in the negative moment region from the center to the sides, and symmetrically removing the temporary supports from the center to the sides, resulted in minimal deflection at the midspan of the main girder.

Sheng et al. [27] studied the stress state of a new type of standard concrete box girder with a single-row prestressing anchorage configuration. The results revealed that during the tendon tensioning process, the maximum principal compressive stress in the anchorage zone of the new single-row prestressed box girder was less than the compressive ultimate strength of the concrete, with the stress primarily concentrated in the circumferential range around the bellmouth. However, the maximum principal tensile stress in the anchorage zone reached the ultimate tensile strength of the concrete, and it was distributed mainly around the anchorage plate.

In addition, a significant body of literature [28-33] has focused on optimizing the design of prestressing systems by studying the impact of prestressing ducts. Prestressing ducts are essential components for achieving internal prestressing, and the effectiveness of grouting directly affects the serviceability of internally prestressed concrete beams. Currently, the most commonly used prestressing ducts are metal or plastic corrugated pipes [34], both of which face numerous issues during their use [35]. Research has led to the development of optimized new types of prestressing ducts, which, while improving construction quality, also feature a significantly reduced diameter compared with the corrugated pipes currently in use. This reduction in diameter provides a basis for subsequent structural size optimization.

In conclusion, prestressed concrete has undergone continuous evolution and improvement; however, there is no consensus within the engineering community regarding the precise role of prestressing in the structure (such as its function, resistance, or constraint). By focusing on the tensioning of prestressing tendons, exploring rational tensioning sequences, altering the anchorage configurations of the prestressing tendons, and optimizing the prestressing ducts, efforts are being made to improve the quality of tendon tensioning and enhance the mechanical performance of small box girders.

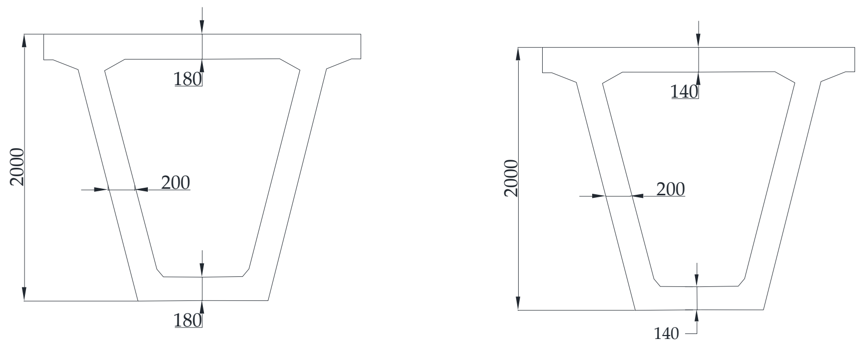
2.3 Research on the Optimization Design of Cross-Sectional Dimensions in PC Small-Box Girders

The web thickness design in small box girders must not only meet the bending and shear strength requirements of the beam but also provide sufficient torsional rigidity. While ensuring that the load-carrying capacity is met, it is also essential to guarantee adequate cover thickness for the prestressing ducts to prevent longitudinal cracks at the duct locations. The top and bottom slabs resist positive and negative bending moments, whereas together with the web, they form a closed cross section that ensures the structural stability of the girder, safeguarding the safety and durability of the bridge during operation.

Through continuous development and improvement, small box girders have evolved into a more refined standard design, with the cross-sectional dimensions largely determined. However, with the advent of new materials, construction techniques, and finite element technologies, both domestic and international scholars have conducted extensive optimization design research on the cross-sectional dimensions of small box girders recommended by previous standards.

Owing to the ultrahigh material strength of ultrahigh performance concrete (UHPC), small box girders made from UHPC can have very thin walls. Ma et al. [36,37] used ABAQUS software to establish a finite element model for a 30-meter prestressed UHPC small box girder, and the results agreed well with full-scale experimental data for small box girders. Using this finite element model for structural cross-sectional optimization, they reported that reducing the bottom slab thickness at the support section from the initial 24 cm to 12 cm and the standard section bottom slab thickness from 15 cm to 8 cm led to an increase in the main compressive stress in the bottom slab from -26.76 MPa to -27.20 MPa and a rise in deflection from 16.1 mm to 19.2 mm. Despite the reduction in the wall thickness, the optimized design still met the code requirements.

Similarly, Lu et al. [38] developed a section dimension optimization design program for lightweight ultrahigh-performance concrete (LUHPC) small box girders using the optimization tool of the numerical computation software MATLAB. The program optimized the section dimensions of a specific small box girder by reducing the top slab thickness from 180 mm to 140 mm, the bottom slab thickness from 180 mm to 140 mm, and the web thickness from 200 mm to 180 mm. The optimized LUHPC small box girder resulted in a 14% reduction in self-weight compared with the original LUHPC girder dimensions and a 27.7% reduction in self-weight compared with the original dimensions of a conventional concrete small box girder. Moreover, all the mechanical performance indicators of the optimized LUHPC girder met the design code requirements.



a) Original cross-sectional dimensions b) Optimized cross-sectional dimensions

Figure 4 Comparison of cross-sectional dimensions before and after optimization [38]

Guan et al. [39] proposed a design approach that replaces a portion of the mid-span ordinary concrete segment of the girder with UHPC material. The design parameters were optimized using the response surface method, with two key parameters, $A \cdot \rho/EI$ and section bending efficiency, selected as the optimization criteria. Through response surface analysis, the optimal design parameters were determined, which resulted in a reduction in the top slab thickness from 28 cm to 22 cm and the web thickness from 40 cm to 25 cm, whereas the bottom slab thickness remained unchanged at 32 cm. Based on this parameter combination, a finite element model was established and compared with the original design model. The results revealed that the bending moment at each pier top decreased by more than 12%, the total bending strain energy of the entire bridge decreased by 34.7%, the upper and lower edge stresses at key cross-sections generally decreased by 12%, and the maximum deflection was reduced by 23.3%. In addition, Wu et al. [40] established different representations of the bending moment for box-shaped cross-sections and, by considering material nonlinearity, derived a section optimization theory and analytical expressions aimed at full-stress optimization. They also provided an analytical expression for the optimal stiffness distribution of the structure, offering a theoretical foundation for practical engineering applications.

In contrast to this research approach, many scholars have reported that, during the operational phase of small box girder bridges, cracking often occurs in areas such as the web and bottom slab to varying degrees [41-43]. Consequently, optimizing a small box girder design with a focus on crack resistance has led to different cross-sectional optimization results. Sun et al. [44], through numerous engineering examples, combined the standard design of a 4×25 m simply supported and then continuous small box girder and proposed corresponding optimization measures to address cracking issues. These measures included increasing the top slab thickness from 18 cm (as per the general design) to 19 cm and improving the prestress anchorage structure in the negative moment region. The results revealed that the bending capacity of the mid-span positive section increased by 7.1%, whereas the bending capacity of the slant section near the middle pier improved by 8.3%.

Wang et al. [45] used the finite element software ANSYS to establish a finite element model of a PC small box girder to investigate the causes of longitudinal cracks in the web and preventive measures. They proposed an optimized solution and conducted a comparative analysis under equivalent conditions. The results indicated that increasing the cross-sectional dimensions and wall thickness of the box girder significantly reduced the tensile stresses caused by construction deviations, thereby increasing the crack resistance of the web.

The cross-sectional dimension is a critical parameter that significantly influences the mechanical performance of box girders. As evidenced by these studies, optimizing the small box girder for various objectives leads to different design outcomes. The high-strength properties of emerging materials can be utilized to reduce the cross-sectional dimensions, thereby reducing the self-weight and construction costs while fulfilling the structural performance requirements. To mitigate potential issues such as cracking and other forms of deterioration during the operational phase of the girder, slightly increasing certain cross-sectional dimensions, particularly the web thickness, may be beneficial. This adjustment can substantially reduce the risk of damage, such as cracks, which may arise from construction tolerances, material inconsistencies, or other factors, thereby increasing the durability and serviceability of the box girder.

3 Research on the Optimization Design of Materials in PC Small Box Girders

In recent years, the development of prestressed concrete structures has been significantly driven by advancements in materials, particularly in concrete and steel strands. On the one hand, concrete has evolved from ordinary concrete to high-performance concrete and UHPC. UHPC [46-48], a cement-based composite material characterized by ultrahigh strength, exceptional toughness, and superior durability, is composed of cement, mineral admixtures, fine aggregates, high-strength short fibers, and superplasticizers, mixed with water and hardened through hydration. This material has been increasingly adopted in engineering applications because of its outstanding mechanical and durability properties.

On the other hand, prestressed steel strands evolve toward higher strength, lower relaxation, larger diameters, and better corrosion resistance [49,50]. Currently, the most commonly used prestressed steel strands in bridge engineering are 7-wire strands with a nominal diameter of 15.2 mm. Research results indicate that large-diameter (17.8 mm) steel strands [51-53] exhibit superior mechanical properties and more efficient material utilization. At the same tensile strength, large-diameter steel strands can achieve prestress efficiency improvements of 35% and 92% compared with traditional 15.2 mm and 12.7 mm strands, respectively. This demonstrates that while maintaining structural mechanical performance, large-diameter steel strands significantly increase the bending capacity of the main beam, reduce the beam height, and decrease the number of steel strands in specific cross-sectional beams. Therefore, compared with concrete small box beams with conventional prestressing tendons, concrete small box beams with large-diameter prestressing tendons can further improve the span capacity and mechanical performance while reducing the self-weight of the beam.

3.1 Ultra-High Performance Concrete

In response to potential splitting issues in the anchorage zones of prestressed steel strands in highway bridges, Jiang and Guo et al. [54] conducted an experimental study on the transmission performance of anchorage zones using UHPC and ordinary concrete in prestressed concrete small box beams. The results revealed that, compared with ordinary concrete, the UHPC anchorage zone presented a greater crack initiation load, slower crack development, and better crack resistance. Additionally, Feng et al. [55] studied the local compressive stress characteristics and bearing capacity of the anchorage zone in UHPC box beams with dense cross walls. Through large-tonnage tension tests and nonlinear finite element modeling, they analyzed the stress in the UHPC anchorage zone and reported that the localized compressive cracking condition was due to excessive tensile stress in the UHPC, and they qualitatively verified the local compressive bearing capacity formula for the UHPC anchorage zone.

The simple support of continuous small box beams combines the advantages of both simply supported and continuous bridges and has been widely promoted and applied both domestically and internationally. However, the complexity of the prestressed design of simply supported to continuous bridges has reduced their construction efficiency. To address this, several studies have focused on optimizing the negative bending moment region of these beams using UHPC materials. Duan and Li [56] investigated a design method for converting simply supported beams into continuous beams on the basis of the tensile and ductility properties of UHPC. By pouring UHPC into the original negative bending moment region, the structural performance of small box beams can be improved, which also enhances the construction process of simply supported to continuous small box beams.

Pan [57], Zhu et al. [58], and Li [59] also proposed the use of UHPC in the negative bending moment region at the top of bridge piers to form a stepped wet joint. Through three-point bending tests, they compared the bending mechanical properties of small box beams with those of ordinary concrete and UHPC poured in the joint area. Additionally, finite element simulations were conducted to analyze the key factors influencing crack resistance and bearing capacity. The results indicated that the contribution of the UHPC top layer to the tensile capacity is significant. The cracking moment of the beam is primarily determined by the thickness of the UHPC overlay. Compared with small box beams with ordinary concrete in the negative bending moment region, a 5 cm thick UHPC overlay increased the cracking moment of the beam by 28.9%, and a 7.5 cm thick UHPC overlay increased it by 41.6%. However, when the reinforcement ratio remains unchanged, increasing the thickness of the UHPC top layer does not significantly enhance the bearing capacity of the beam.

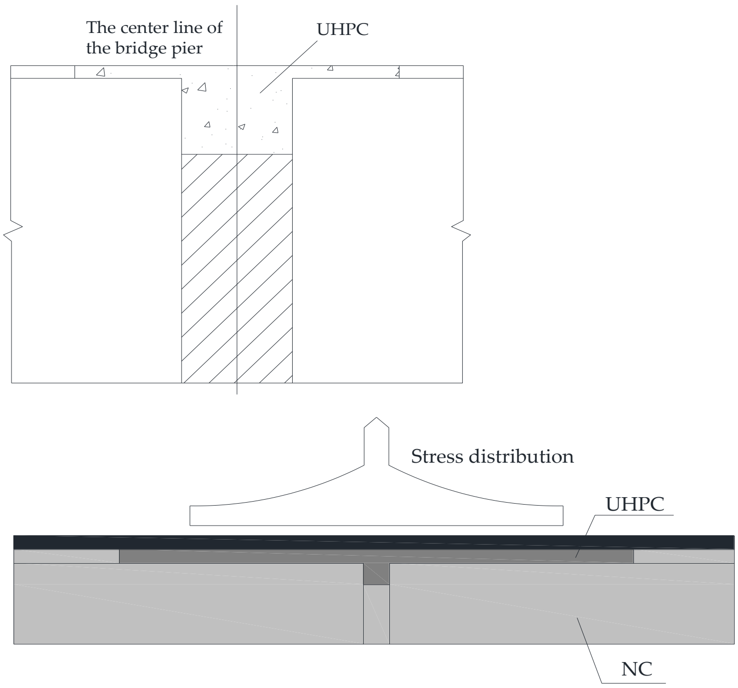


Figure 5 Structure in the negative bending moment area of UHPC [57,59]

Currently, the superstructures of precast T-beams, small box beams, and other precast assembly beams are connected mainly through joints. However, traditional joint construction methods are inefficient and prone to various defects, which severely affect the long-term performance of the structure. Using UHPC to fill joints can significantly simplify the joint structure and improve the pouring quality, and its high durability also enhances the durability of the joints. The table below summarizes the recent optimization design research on UHPC joints from various countries.

Table 2 Research Results on UHPC Joints of Small Box Girders

Ref.	Research contents	Research results
Ref. [60]	The mechanical performance of UHPC joints in bridge decks was studied based on finite element and theoretical analysis models, and design recommendations for UHPC joints were provided.	Using a rough diamond-shaped interface for the joint of UHPC bridge deck panels is recommended. The thickness of the concrete cover for the reinforcement should not be less than 2d, and the anchorage length of the reinforcement should not be less than 8d. The lateral spacing of the reinforcement (H) is suggested to be between 2d and 3d, with a minimum of 30 mm, where d is the diameter of the reinforcement.
Ref. [61]	A structural design for the UHPC joint in small box beams has been proposed to address the issues associated with traditional joints, along with an	The UHPC joint configuration with straight rebar lap splice has been clarified, with the key design factors identified as the rebar anchorage length and transverse spacing. Among these, the rebar anchorage length is the primary optimization factor for joint design. Experimental studies

Ref.	Research contents	Research results
	optimization of the joint configuration.	on the anchorage performance between rebar and UHPC have demonstrated that an anchorage length of six times the rebar diameter is sufficient to achieve full anchorage between the UHPC and rebar.
Ref. [62]	A new type of UHPC-anchor head reinforcement wet joint has been proposed. Nine box girder top slab UHPC-anchor head reinforcement wet joint tensile tests were designed and conducted.	The interface is the weak point of the wet joint. Increasing the reinforcement ratio of the joint can significantly enhance the ultimate tensile bearing capacity and effectively delay crack propagation. The staggered overlap arrangement of the anchor head reinforcement structure can notably strengthen the tensile ultimate bearing capacity of the joint interface and has a significant impact on its failure mode. UHPC wet joints can achieve high bearing capacity and ductility even at an early age of UHPC, and as the age of UHPC increases, the joint bearing capacity is greatly enhanced.
Ref. [63]	Bending tests were conducted on the template-free UHPC wet joints, focusing on the failure mode, ultimate bending bearing capacity, as well as cracking and strain behavior.	The joint width has a significant impact on the bending performance, and a joint width of at least 8 times the diameter of the transverse reinforcement is recommended. Based on the results of bending tests and numerical analysis, a design method for the template-free UHPC wet joint is proposed.
Ref. [64]	A UHPC template-free wet joint construction form with embedded corrugated steel plates as the bottom mold is proposed. Five test beams were designed, with the steel fiber content as the experimental parameter, and four-point bending tests were conducted to study the bending performance.	The main cracks of all test beams were located in the prefabricated segments, where bending failure occurred, and no significant damage was observed in the joint sections. Increasing the steel fiber content can enhance the bond at the UHPC-NC interface and improve the crack resistance of the joint, but it has a relatively small impact on the structural bending capacity. The crack resistance of the template-free joint beam with 1.0% steel fiber content is second only to that of the UHPC monolithic beam.
Ref. [65]	A four-point bending test was designed to evaluate the bending performance of the UHPC joint, and a comparison was made with joints filled with fast-setting concrete (FSC) and self-compacting concrete (SCC).	The 300 mm wide joint filled with UHPC effectively accommodates the development length of the lap splice reinforcement, exhibiting higher deformability and achieving a greater bending load capacity. The UHPC joint demonstrates superior control over interface cracking, with the cracking load being 50% higher than that of joints filled with FSC and SCC.

In addition to the literature listed in Table 2, many other studies [66-74] have focused on using UHPC to fill joints to optimize and improve the mechanical performance of small box beams. A summary of these studies shows that UHPC joints can avoid the steel bar welding process used in traditional joints, instead employing a simple steel bar noncontact lap splice construction. Among these factors, the anchorage length of the steel bars is the most direct factor affecting the mechanical performance of the joint. The shorter the anchorage length of the steel bars is, the poorer the anchorage performance between the steel bars and the joint. To ensure the anchorage performance of the UHPC and steel bars at the joint, the anchorage length of the steel bars in actual engineering should not be less than 6-8 times the bar diameter, which is also the minimum anchorage length for the steel bars.

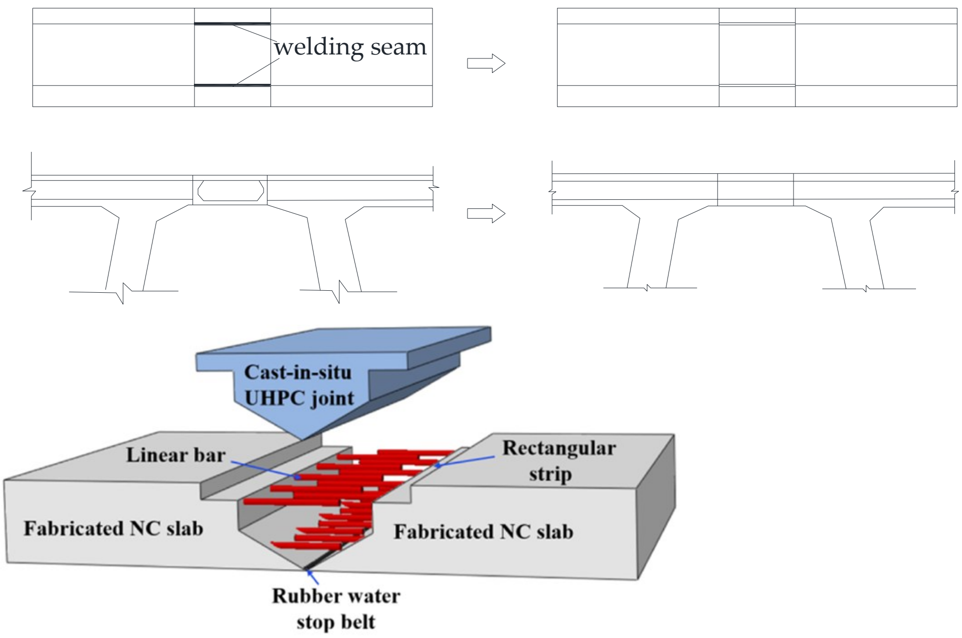


Figure 6 Structure of the UHPC joints of small box girders [61,74]

In addition to the methods previously described, which use UHPC to optimize the local structure of small box beams, scholars both domestically and internationally have also conducted research on replacing parts of ordinary concrete with UHPC to form RC-UHPC composite box beams and even using UHPC to construct entire bridges [75-82]. Compared with the original bridge, the newly designed composite small box beams reduced the usage of concrete and prestressing tendons by 49.6% and 21.1%, respectively. This was achieved without a significant increase in cost while significantly enhancing both the bearing capacity and performance of the structure.

The numerous advantages of UHPC materials enable UHPC small box beams to reduce material usage, lower structural weight, and improve the economic and social benefits over the entire life cycle of the bridge. However, owing to the high cost of UHPC materials, their application in bridge engineering is focused primarily on structural components and parts such as steel deck panels, wet joints, and anchorage zones. Bridges constructed entirely with UHPC are relatively rare.

3.2 *Large-Diameter Steel Strands*

Wang et al. [83] studied the mechanical performance of prestressed concrete beams with large-diameter high-strength steel strands. They designed and fabricated six simply supported beams with large-diameter high-strength steel strands and conducted flexural load-bearing capacity tests. The results revealed that, compared with traditional prestressed concrete beams with standard-diameter steel strands, beams with large-diameter high-strength steel strands presented significantly greater load-bearing capacity. Under the same cross-sectional dimensions, beams with a prestress reinforcement ratio of 0.844% had a 78% greater load-bearing capacity and 32% less deformation than beams with a reinforcement ratio of 0.292%.

Similarly, Amin K. Akhnoukh,[84] designed prestressed concrete beam sections using steel strands with diameters of 0.5 inches (13 mm), 0.6 inches (15 mm), and 0.7 inches (18 mm) and calculated their flexural load-bearing capacities. The results showed that, compared with smaller diameter steel strands (0.5 inches and 0.6 inches), when the same number of large-diameter steel strands (0.7 inches) was used, the flexural strength of the main beam increased by 35.5% and 92%, respectively. The structural advantages of large-diameter steel strands allow bridge designers to achieve higher beam load-bearing capacity with the same number of steel strands, resulting in smaller beam cross-sections and a higher bridge span-to-height ratio.

Zhan et al. [85-87] conducted a series of orthogonal pull-out experiments to investigate the optimal spacing and bond performance of large-diameter steel strands in UHPC beams. They also studied the bond characteristics at the interface between large-diameter steel strands and UHPC, as well as the stress distribution in the steel strands and the surrounding concrete. Data analysis found that a greater concrete cover thickness increases both the critical bond stress and the maximum bond stress. The addition of stirrups significantly enhances the maximum bond stress but has a minimal effect on the critical bond stress. An empirical formula for the maximum bond stress was proposed, and the anchorage length of the steel strands was evaluated using the approximate probability method, with the results being consistent with values from several design codes.

Fray F. Pozo-Lora, Ph.D., et al. [88] conducted pull-out tests to investigate the bond performance between prestressed steel strands with a nominal diameter of 28.6 mm and a nominal strength of 1,780 MPa and ordinary concrete. The continuous pull-out test results indicated that for 58 MPa concrete, the anchorage transfer length of the steel strand was approximately 1,200 mm, and the development length ranged from 1,800 to 2,400 mm, demonstrating good bond performance between the large-diameter steel strands and the concrete. Similarly, Carlos A. Tamayo et al. [89] and Abdullah Alabdulkarim et al. [90] performed full-scale tests on concrete beams with 17.8 mm long-diameter steel strands, investigated the anchorage length and bond performance of the strands embedded in the concrete, and obtained similar conclusions.

3.3 Conclusions

In summary, UHPC and large-diameter steel strands, as high-performance materials, exhibit exceptional mechanical properties. Since the advent of these materials, numerous scholars both domestically and internationally have investigated their mechanical behaviors, laying a solid foundation for their application in practical engineering. Owing to their superior strength, toughness, and durability, ultrahigh-performance materials can effectively reduce the cross-sectional dimensions of small box girders, thereby reducing the self-weight of the structure and offering insights into the lightweight design of small box girders. The lightweighting of small box girders, in turn, contributes to a reduction in the weight of prefabricated components, facilitating their application in rapid bridge construction techniques. This, in turn, supports the industrialization, standardization, and intelligence of bridge construction.

4 Current Research Status of PC Small Box Girder Prestressing Technology

With extensive research and experimental studies conducted both domestically and internationally on prestressing technology for small box girders, significant advancements and improvements have been made. Among these methods, retard-bonded prestressing technology and external prestressing technology represent major technological innovations in traditional prestressed components. These innovations have emerged as a result of the rapid development of engineering practices.

4.1 Retard-Bonded Prestressing Technology

Retard-bonded prestressing technology [91-93] combines the advantages of both bonded and unbonded prestressing, maximizing its economic benefits and practicality in both construction processes and structural performance.

In recent years, there has been significant research on the mechanical properties of retard-bonded prestressed concrete (RPC) beams. In terms of experimental research, Zuo et al. [94] conducted durability tests on 14 RPC beams and ordinary concrete beams under corrosive conditions and compared and analyzed the effects of the load ratio, prestressing force, and other factors on crack width and rebar corrosion. The results indicated that, under the same crack control level, the degree of rebar corrosion of retard-bonded prestressed concrete beams carrying higher load ratios was comparable to that of nonprestressed beams, demonstrating better durability.

Shang et al. [95] and Xiong et al. [96] conducted pull-out tests on RPC beams to investigate the bond performance between retard-bonded prestressed steel strands and concrete. The experiments revealed that, under the same conditions, the bond strength and peak slip of retard-bonded prestressed steel strands were greater than those of ordinary steel strands. Furthermore, the residual section of the bond–slip curve for the retard-bonded prestressed steel strands was approximately a downward-sloping sinusoidal shape.

Li et al. [97], Xiong et al. [98], and Sui et al. [99] conducted experimental investigations into the flexural performance of RPC beams. The findings revealed that the experimental values of the cracking load, yield load, and deflection for all the samples correlated well with the calculated values derived from the Code. The curing age of the retard bonding agent had a negligible effect on the cracking load when prestressing strands were tensioned within an appropriate time frame; however, it significantly influenced the ultimate flexural strength. Moreover, the ultimate flexural strength of the RPC beams increased with increasing curing time of the retard-bonding agent.

In the field of finite element simulation, Xiao et al. [100,101] employed a modified cohesive zone model (CZM) at the mesoscale to simulate the bonding interaction between retard-bonded prestressing tendons and concrete. The results demonstrated that this approach provided superior simulation accuracy in terms of macroscopic mechanical behavior and failure modes compared with traditional pullout test methods. Yin et al. [102] conducted a simulation analysis of an RPC beam during the tensioning stage and the bonding hardening stage of a retard-bonding agent using ANSYS finite element analysis software. The numerical simulation results agreed well with the experimental results. They subsequently simulated the structural behavior of the test beam during normal service conditions, analyzed the critical sections of the beam, and proactively identified potential structural failure risks.

4.2 External Prestressing Technology

External prestressing technology offers advantages such as inspectability, ease of replacement, detectable tendon force, and the ability to perform posttensioning. Combined with the relatively thin web of UHPC box girders, external prestressing tendons can replace the internal stirrups in the web, resulting in a more rational external prestressed UHPC girder structure without internal web reinforcement.

One study [103] conducted four-point bending model tests on three external prestressed UHPC beams, comprising one monolithic beam and two segmental beams. The results indicated that the failure mode of all the samples was crushing of the compressed zone of the UHPC, accompanied by yielding of the bottom prestressing tendons. This study clarified the stress variation in prestressing tendons and the calculation method for secondary effects in external prestressed UHPC segmental beams. Considering the changes in external prestressing and the effective height of the section, this study proposed an envelope range for the ultimate flexural capacity of external prestressed UHPC segmental beams.

Owing to the typically sudden and brittle nature of shear failure, shear design is often a critical aspect of structural design for box girders. Studies [104-107] conducted shear performance tests using four-point loading, and the results indicated that the shear failure mode of external prestressed UHPC girders without web reinforcement exhibited brittle failure. As the shear–span ratio increased, the failure modes of the test beams transitioned sequentially from diagonal compression failure and shear–compression failure to shear–tension failure. The higher the shear–span ratio is, the smaller the number of diagonal cracks, the smaller their inclination, and the lower the ultimate shear capacity of the test beams, with the reduction trend slowing down. A shear capacity calculation formula for external prestressed UHPC girders without web reinforcement was derived on the basis of the ultimate equilibrium method, which closely matched the experimental results.

4.3 Conclusions

Scholars both domestically and internationally have conducted extensive mechanical performance tests on PC small box girders employing retard-bonded prestressing and external prestressing technologies, providing valuable references for practical engineering applications. Both retard-bonded prestressing and external prestressing eliminate the need for prestressing ducts, reduce the girder cross-sectional dimensions, decrease self-weight, save materials, and improve construction efficiency without compromising the load-bearing capacity of the main girder. These advancements provide a pathway for further increasing the span of small box girders.

5 Summary and Outlook

5.1 Summary

This paper provides a brief overview of recent research on PC small box girders and summarizes studies on the mechanical performance of concrete small box girders with rear-bonded prestressing and external prestressing.

(1) The impact of cross diaphragms on the PC small box girder mechanical performance is influenced by factors such as the number, position, thickness, and height of the diaphragms. Although different studies have focused on various mechanical properties to investigate the influencing factors, they all reached similar conclusions. For small- and medium-span small box girder structures, setting one mid-span cross diaphragm can effectively improve the transverse stiffness and crack resistance, ensuring the collaboration of the main girders. Additionally, the diaphragm thickness should not exceed 200 mm. Within a certain range, increasing the height of the diaphragm can improve the transverse load distribution, but it should not exceed the full height of the main girder.

(2) In the structural design of bridges, the PC small box girder prestressed tendon design is a crucial component of the superstructure design. By optimizing parameters such as the tendon profile and the number of tendons and improving the prestressing process of longitudinal tendons, reasonable prestress design parameters can be obtained. This approach not only enhances the load-bearing performance of the PC small box girder but also allows for the full utilization of the material properties of both the concrete and prestressed tendons, ultimately leading to material savings.

(3) UHPC is characterized by its dense microstructure, low porosity, and compressive strength exceeding 150 MPa, with a creep coefficient ranging from 0.20.8. These properties contribute to its excellent mechanical and durability performance. However, due to the high material cost, UHPC is applied primarily to specific structural components or localized areas. Under equivalent load-bearing conditions, UHPC structures have dimensions between those of ordinary concrete structures and steel structures, closely approaching the size of steel structures. The dimensions of UHPC structures are typically 1/2 to 1/3 of those of conventional structures, significantly reducing the self-weight of the

structure. For a given span, the self-weight of UHPC small box girders is generally 40% to 60% of that of conventional concrete box girders. The use of large-diameter, high-strength steel strands can effectively increase the load-bearing capacity of components, with the bearing capacity of beams using 1,720 MPa-grade steel strands increasing by 6.47%. Additionally, large-diameter, high-strength steel strands can improve the deformation performance of the components, better utilizing their serviceability, reducing steel consumption, and enhancing construction efficiency.

(4) RPC beams and external prestressed UHPC beams overcome the limitations of traditional prestressed concrete beams. They not only retain the advantages of simple construction inherent in PC small box girders but also eliminate the need for installing corrugated pipes and grouting, thus avoiding issues such as incomplete grouting common in posttensioning methods. These innovations help reduce the cross-sectional dimensions of the main girder, lower the self-weight, and save both materials and costs. All of these goals are achieved without compromising the load-bearing capacity while maintaining excellent mechanical performance.

5.2 Outlook

With the advancement of research by scholars both domestically and internationally, PC small box girders have undergone significant development. However, continuous improvement, refinement, and innovation are needed to meet the demands of future engineering applications. On the basis of the existing body of literature, this paper proposes the following considerations.

(1) Currently, the optimization design of PC small box girders is typically limited to local optimization and material topology optimization. For practical structures, smooth continuity at the regional boundaries must be maintained, and the optimized shape boundary must also be manufacturable. However, topology optimization tends to focus primarily on material distribution without fully considering the constraints imposed by real-world conditions. Additionally, the load cases considered are often relatively simple and monotonous, which weakens the engineering feasibility of such approaches. Therefore, conducting a full-stress optimization design for nonlinear structures under complex and severe loading conditions not only meets the elastic-plastic damage design requirements of actual engineering projects but also fully exploits the strength of the components, offering promising prospects for practical applications.

(2) Currently, experimental studies on PC small box girders are conducted mostly on scaled-down models, where the grades of concrete, ordinary reinforcement, and prestressed steel strands, as well as the diameter of the prestressed steel strands, are significantly lower than those used in actual engineering projects. This discrepancy highlights a gap between experimental conditions and practical applications. Additionally, destructive testing on full-scale components is lacking, with most experiments focused only on verifying the load-bearing capacity. Consequently, further research and experimental validation are needed to determine the ultimate load capacity of box girders when they completely lose their load-bearing capacity.

(3) Currently, both domestic and international studies have explored the mechanical properties of prestressed UHPC beams via the pretensioning method. Under identical bending capacities, pretensioning offers superior prestress efficiency and eliminates the need for specialized anchorage systems, thereby presenting a more cost-effective solution. For UHPC small box girders, the high material strength results in a significantly reduced girder section thickness, making the use of corrugated ducts unfeasible. Consequently,

pretensioned internal prestressed UHPC small box girders show promising application potential. This approach, while ensuring compliance with bending and shear requirements, allows for a reduction in the main girder's cross-sectional dimensions, thereby decreasing the overall self-weight.

(4) However, owing to constraints imposed by the pretensioning configuration and the construction site conditions—such as the tensioning bed—current experimental studies have focused predominantly on T-beams. Further research is needed to investigate the mechanical performance of pretensioned UHPC small box girders to fully assess their applicability and optimize their structural efficiency.

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Data availability statement: The data that support the findings of this study are available from the corresponding author, Wang, upon reasonable request.

References

1. Yang, H.; Jiang, L.; et al. Safety Evaluation for Fabricated Small Box Girder Bridges Based on Fuzzy Analytic Hierarchy Process and Monitoring Data. *Sensors (Basel, Switzerland)* **2024**, *Vol.24*, 4592, doi:10.3390/s24144592.
2. Qi, H.; Liu, Y.; et al. Evaluation and Study of Long Term Performance of the Prestressed Concrete Small Box-Girder. *Highway* **2021**, *Vol.66*, 154-158.
3. Liu, J.-t.; Zhu, W.-q.; et al. Temperature Characteristics of Prestressed Concrete Small Box-Girder with EPS Internal Formwork. *Journal of China & Foreign Highway* **2020**, *Vol.40*, 124-130, doi:10.14048/j.issn.1671-2579.2020.04.026.
4. Huang, X.; Bu, Z.; et al. Experiment Design of Precast Small Box Girder and CIP Hidden Bent Cap Structural System. *Journal of Physics: Conference Series* **2023**, *Vol.2476*, 012012, doi:10.1088/1742-6596/2476/1/012012.
5. Li, K.; Zheng, Y.; et al. Mechanism Analysis of Small Box Girder Diseases and Summary of Reinforcement Treatment Strategies. *Journal of Physics: Conference Series* **2020**, *Vol.1578*, 012184, doi:10.1088/1742-6596/1578/1/012184.
6. Wang, C.; Zhang, Y. Influence of geometric characteristics on distortion effect of thin-walled box girders. *Dongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Southeast University (Natural Science Edition)* **2020**, *Vol.50*, 89-95, doi:10.3969/j.issn.1001-0505.2020.01.012.
7. Wang, C.; Zhang, Y. Transverse internal force analysis on box girder based on external load correction. *Dongnan Daxue Xuebao (Ziran Kexue Ban)/Journal of Southeast University (Natural Science Edition)* **2021**, *Vol.51*, 23-29, doi:10.3969/j.issn.1001-0505.2021.01.004.
8. Zhang, Y.; Long, J.; et al. Research on Influence of Mid-span Diaphragm on Distortion Effect of Box Girders. *Journal of the China Railway Society* **2022**, *Vol.44*, 150-156.
9. Huang, J. On Effect of Middle Diaphragm in Precast Concrete Small-box Girder Structure. *Urban Roads Bridges & Flood Control* **2022**, 77-79, doi:10.16799/j.cnki.csdqyfh.2022.03.019.
10. Guan, L.; Jia, P.; et al. Study on the Influencing Factors of Transverse Distribution Coefficients in Composite Small Box Girders. *Fujian Building Materials* **2020**, 10-13.
11. Zhu, W. Analysis on the Influence of the Number of Cross-Middle Diaphragms of Prefabricated Small Box Girder on the Overall Stress of Structure. *Northern Communications* **2020**, 19-21，25, doi:10.15996/j.cnki.bfjt.2020.09.005.
12. Xie, J.; Zhang, H.; et al. Influence of diaphragm on mechanical properties of fabricated small box girder. *Engineering Construction* **2021**, *Vol.53*, 45-48，78, doi:10.13402/j.gcjs.2021.03.040.
13. Xu, C.; Li, X.; et al. Experimental Research on Lateral Stress of Multi-box Small Box Girder Mode. *Northern Communications* **2024**, 13-16.
14. Mai, X. Study on optimal layout of cross-diaphragm in oblique small box girder. *Journal of China & Foreign Highway* **2023**, *Vol.43*, 150-154.
15. Deng, Q.; Xiao, K.; et al. Influence of Diaphragm Parameters on Wide Bridge of Fabricated Box Girder. *Journal of Shenyang University：Natural Science* **2019**, *Vol.31*, 62-65，72, doi:10.16103/j.cnki.21-1583/n.2019.01.012.
16. Miao, W. Research on the setting method of transverse diaphragms for 30m prefabricated small box girders. *Engineering and Construction* **2023**, *Vol.37*, 977-981.
17. Zhou, J.; Zhang, H.; et al. Study on Load Transverse Distribution Rule of New Small Box Girder before and after Hinge Joint Damage. *Journal of Chongqing Jiaotong University(Natural Science)* **2019**, *Vol.38*, 34-40, doi:10.3969/j.issn.1674-0696.2019.11.06.

18. Rafieizonooz, M.; Jang, H.; et al. Performances and properties of steel and composite prestressed tendons – A review. *Heliyon* **2024**, *Vol.10*, e31720, doi:10.1016/j.heliyon.2024.e31720.
19. Ding, Z.; Cao, Q. A state-of-the-art review of flexural behaviors of PC beams with corroded prestressing tendons. *Structures* **2024**, *Vol.63*, 106430, doi:10.1016/j.istruc.2024.106430.
20. Zhang, H.; Liu, X.; et al. Design of prestressed tendons in prestressed concrete small box girder based on topology optimization of asymptotic evolutionary algorithms. *Engineering Journal of Wuhan University* **2022**, *Vol.55*, 1135-1140, doi:10.14188/j.1671-8844.2022-11-007.
21. Zhang, H.; Liu, X.; et al. A topological optimization design method for prestressed steel strands of prestressed small box girder bridges. 202110217734.5, 2021.
22. Luis Bernardo Fargier Gabaldón, A.M.A.; Chacón-Valero, E. Sizing Continuity Tendons in Segmental Cantilever Bridges. *Practice Periodical on Structural Design and Construction* **2024**, *Vol.29*, 06023002, doi:10.1061/ppscfx.Sceng-1351.
23. Xiao, Y. Adaptability Analysis of Transverse Distribution Coefficients and Steel Tendons in Variable-Width Small Box Girders. *Engineering and Technological Research* **2021**, *Vol.6*, 33-34, doi:10.19537/j.cnki.2096-2789.2021.14.014.
24. Kou, Y. Optimal Design of Prefabricated Prestressed Concrete Box Girder Bridges. *Communications Science and Technology Heilongjiang* **2018**, *Vol.41*, 90-91，93, doi:10.16402/j.cnki.issn1008-3383.2018.03.050.
25. Chen, H. Analysis of Optimization Measures of Longitudinal Prestress Tensioning Process on Long-span PC Beam Bridge. *Highway Engineering* **2019**, *Vol.44*, 131-137, doi:10.19782/j.cnki.1674-0610.2019.02.024.
26. Liu, M.; Zeng, H.; et al. Reasonable Construction Sequence and Anti-cracking Measures of Long-span Prestressed Concrete Small Box Girder Bridge. *Journal of Wuhan University of Technology（Transportation Science & Engineering）* **2021**, *Vol.45*, 1123-1127, doi:10.3963/j.issn.2095-3844.2021.06.022.
27. Sheng, X.; Sun, Q.; et al. Refinement research on mechanical behaviors of prestressed anchorage area of new-type standard concrete box girder. *Journal of Railway Science and Engineering* **2023**, *Vol.20*, 2572-2581, doi:10.19713/j.cnki.43-1423/u.T20221355.
28. Liu, Y.; Wang, H.; et al. Grouting test of prestressed duct and slurry characteristics. *Journal of Shandong Jiaotong University* **2021**, *Vol.29*, 84-90，98, doi:10.3969/j.issn.1672-0032.2021.04.012.
29. Yao, Z.; Fan, L.; et al. Construction Quality Control of Prestressed Post Tensioning Method Based on Effective Prestressed Detection of Anchor. *Journal of China & Foreign Highway* **2020**, *Vol.40*, 179-183, doi:10.14048/j.issn.1671-2579.2020.04.039.
30. Qu, G.; Zhou, G.; et al. The detection of grouting compactness of pre-stressed ducts based on the impact-echo method. *Geophysical and Geochemical Exploration* **2019**, *Vol.43*, 919-924, doi:10.11720/wtyht.2019.1098.
31. Zhong, J.; Wei, G. Application of the Impact-Echo Method in Non-Destructive Testing of Grouting Quality in Prestressed Ducts. *Transportation Technology and Management* **2021**, 146-147.
32. Wei, Z.; Zhang, H. Research on detection of grouting defects intendons of small box girder by impact echo method. *Shanxi Architecture* **2021**, *Vol.47*, 146-149，198, doi:10.13719/j.cnki.1009-6825.2021.07.052.
33. Lee, D.-I.; Choi, H.; et al. Utilization of Unsupervised Machine Learning for Detection of Duct Voids inside PSC Box Girder Bridges. *Applied Sciences* **2022**, *Vol.12*, 1270, doi:10.3390/app12031270.
34. Jiang, F. Key Points and Technology Process of Prefabrication Construction of 25 m Small Box Girder. *Construction & Design for Engineering* **2022**, 146-148, doi:10.13616/j.cnki.gcjsysj.2022.05.245.
35. Shi, B. Discussion on the Cause of Cracks in Web of Prestressed Concrete Box Girder. *Construction & Design for Engineering* **2019**, 133-134，137, doi:10.13616/j.cnki.gcjsysj.2019.04.045.
36. Ma, X.; Chen, B.; et al. Optimal design for a 30 m prestressed UHPC box girder. *Journal of Fuzhou University(Natural Science Edition)* **2019**, *Vol.47*, 398-404.
37. Ma, X.; Tang, Z.; et al. Experimental Study on Flexural Behaviors and Structural Optimization of 30 m-Long Prestressed UHPC Box Girder. *Bridge Construction* **2024**, *Vol.54*, 93-99, doi:10.20051/j.issn.1003-4722.2024.03.013.
38. Lu, Z.; Du, P.; et al. Optimal Design of Small Box Girder of Lightweight Ultra-high Performance Concrete Beam. *The World of Building Materials* **2022**, *Vol.43*, 123-126.
39. Guan, W.; Duan, L. Optimization design of UHPC-NC continuous box girder bridge based on response surface method. *Journal of China & Foreign Highway* **2023**, *Vol.43*, 76-82.
40. Wu, S.; He, H.; et al. Section optimum design of continuous structures based on full stress criterion. *Journal of Vibration and Shock* **2021**, *Vol.40*, 250-257, doi:10.13465/j.cnki.jvs.2021.18.032.
41. Guo, Y.; Peng, J.; et al. Disease Cause Analysis and Treatment of Local Cracks in Continuous End Web of Prestressed Concrete Small Box Girder. *Northern Communications* **2021**, 23-26，31, doi:10.15996/j.cnki.bfjt.2021.12.006.
42. Zhao, S.; Li, G. Analysis on the Causes of Cracks in Curved Box Girder Bridges with Small Radius. *IOP Conference Series: Earth and Environmental Science* **2020**, *Vol.510*, 052069, doi:10.1088/1755-1315/510/5/052069.
43. Chen, Y.-J.; Huang, X.-C.; et al. Propagation Effect Analysis of Existing Cracks in Box Girder Bridges Based on the Criterion of Compound Crack Propagation. *Buildings* **2024**, *Vol.14*, 2958, doi:10.3390/buildings14092958.
44. Sun, M.; Liu, S.; et al. Analysis of Deteriorations of Precast Segmental Small Box Girder Bridge and Modification Design. *World Bridges* **2022**, *Vol.50*, 112-117.

45. Wang, Q.; Zheng, G.; et al. Local Stress Analysis and Structural Optimization of Small Box Girder Webs Based on ANSYS. *Highway* **2023**, *Vol.68*, 268-271.
46. Foster, S.J.; Bentz, E. Design of UHPC prestressed girders for shear. *Structural Concrete* **2024**, *Vol.25*, 1, doi:10.1002/suco.202300738.
47. Mohaisen, K.O.; Ahmad, S.; et al. Effect of Curing Methods on the Performance of UHPC. *Arabian Journal for Science & Engineering (Springer Science & Business Media B.V.)* **2023**, *Vol.48*, 13791-13805, doi:10.1007/s13369-023-07982-8.
48. Xu, T.; Xu, Z.; et al. Linear and nonlinear tensile creep of steam-cured UHPC. *Cement and Concrete Composites* **2024**, *Vol.145*, 105323, doi:10.1016/j.cemconcomp.2023.105323.
49. Li, B.; Han, F. Study on Design of Transverse Prestressed System of Large-Diameter Steel Strand and its Application to Practical Bridges. *Journal of China & Foreign Highway* **2020**, *Vol.40*, 130-133, doi:10.14048/j.issn.1671-2579.2020.05.025.
50. Zhou, J.; Zhang, X.; et al. Investigation on flexural behavior of pretensioned prestressed steel strand high strength concrete large-diameter pipe piles. *Journal of Building Structures* **2022**, *Vol.43*, 282-292, doi:10.14006/j.jzjgxb.2021.0219.
51. Rao, Z.; Liu, K.; et al. Application of large diameter steel strand in jacking bridge structure. *Port & Waterway Engineering* **2019**, 51-55，77, doi:10.16233/j.cnki.issn1002-4972.20190904.005.
52. Zhang, D.; Qin, S.; et al. Experimental Research on Bond Properties of Large-Diameter Prestressed Steel Strands. *Industrial Construction* **2021**, *Vol.51*, 33-39, doi:10.13204/j.gyjzG21081711.
53. Liu, Z.; Dong, Z.; et al. Stress recovery behaviour of a large-diameter Fe-SMA stranded wire developed for structural prestressing loss compensation. *Advances in Structural Engineering* **2023**, *Vol.26*, 966-982, doi:10.1177/13694332221149475.
54. Jiang, X.; Guo, J.; et al. Experimental Study on Load Transfer Behavior of UHPC Anchorage Zone and Analysis of Strut-and-Tie Model. *Railway Engineering* **2023**, *Vol.63*, 49-53.
55. Feng, Z.; Li, C.; et al. Study on Local Compressive Performance for Anchorage Zone of UHPC Box-Girder with Densely Distributed Diaphragms. *Engineering Mechanics* **2020**, *Vol.37*, 94-103，119, doi:10.6052/j.issn.1000-4750.2019.06.0295.
56. Duan, X.; Li, F. Analysis on Simple-Supported Girder Bridge has Continuous Deck with UHPC and without Prestressing Method. *Structural Engineers* **2022**, *Vol.38*, 137-144, doi:10.15935/j.cnki.jggcs.2022.02.013.
57. Pan, Z. Application of Ultra High Performance Concrete in Negative Moment Zone of Simply Supported-Continuous Bridge. *Construction & Design for Engineering* **2021**, 39-41, doi:10.13616/j.cnki.gcjsysj.2021.08.212.
58. Zhu, J.; Liu, Z.; et al. Bending performance of wet joints in negative moment zone of prefabricated small-box girder bridges: Experimental and numerical study. *Structures* **2024**, *Vol.62*, 106103, doi:10.1016/j.istruc.2024.106103.
59. Li, J. Study on Crack Resistance of New UHPC-NC Composite Bridge Deck in Negative Moment Region of a Continuous Bridge Converting from Simple-support Bridge with Small Box-Girder Section. *Railway Standard Design* **2024**, *Vol.68*, 75-81，96, doi:10.13238/j.issn.1004-2954.202210260004.
60. Shi, X.; Gao, Y.; et al. Experimental Study on Mechanical Behavior of UHPC Joint of Precast Bridge Deck. *Journal of South China University of Technology(Natural Science Edition)* **2020**, *Vol.48*, 82-90，124, doi:10.12141/j.issn.1000-565X.190742.
61. Wang, X. Optimization of Joint Design and Study of Construction Technology for Elevated Small Box Girder Based on UHPC Material. *Urban Roads Bridges & Flood Control* **2020**, 154-157，121, doi:10.16799/j.cnki.csdqyfh.2020.06.047.
62. Zhu, A.; Tian, Z.; et al. Tensile Property Test of UHPC Wet Joints Model of Precast Segmental Bridge. *Journal of Civil Engineering and Management* **2022**, *Vol.39*, 7-13, doi:10.13579/j.cnki.2095-0985.2022.20210280.
63. Zhu, J.; Tong, X.; et al. Research on flexural behavior and design method of formwork free UHPC wet joint in prefabricated small box girder bridges. *Structures* **2024**, *Vol.69*, 107333, doi:10.1016/j.istruc.2024.107333.
64. Huang, X.; Li, L.; et al. Experimental Study on UHPC Formwork-free Wet Joint Bending Resistance Model with Corrugated Steel Web. *Railway Engineering* **2024**, *Vol.64*, 7-13.
65. Haibo Jiang, Z.H., Jiahui Feng, Tianlong Wang, Zhenming Xu. Flexural behavior of UHPC-filled longitudinal connections with non-contacting lap-spliced reinforcements for narrow joint width. *Structures* **2022**, *Vol.39*, 620-636, doi:10.1016/j.istruc.2022.03.017.
66. Feng, Z.; Li, C.; et al. Direct shear test on UHPC key-wet-joints and the unified calculation formula of direct shear capacity of UHPC wet-joints. *China Civil Engineering Journal* **2022**, *Vol.55*, 79-91, doi:10.15951/j.tmgcxb.21070693.
67. Huang, J.; Kang, S.; et al. Experimental study on seismic performance of UHPC post-casting assembled joints. *Journal of Railway Science and Engineering* **2024**, *Vol.21*, 286-298, doi:10.19713/j.cnki.43-1423/u.T20230250.
68. Pan, R.; Cheng, L.; et al. Experimental research on direct shear performance of UHPC keyed epoxy joints. *China Civil Engineering Journal* **2022**, *Vol.55*, 38-49，117, doi:10.15951/j.tmgcxb.21100986.
69. Shao, X.; Hu, W.; et al. Experiment on Flexural Behavior of UHPC Joint in Negative Moment Area of Composite Bridges. *China Journal of Highway and Transport* **2021**, *Vol.34*, 246-260, doi:10.19721/j.cnki.1001-7372.2021.08.020.
70. Hussein, H.H.; Sargand, S.M.; et al. Field investigation of ultra-high performance concrete shear key in an adjacent box-girder bridge. *Structure & Infrastructure Engineering: Maintenance, Management, Life-Cycle Design & Performance* **2019**, *Vol.15*, 663-678, doi:10.1080/15732479.2019.1569698.
71. Qi, J.; Bao, Y.; et al. Flexural behavior of an innovative dovetail UHPC joint in composite bridges under negative bending moment. *Engineering Structures* **2019**, *Vol.200*, 109716, doi:10.1016/j.engstruct.2019.109716.

72. Zhu, Y.; Meng, D.; et al. Long-term performance of a continuous box-girder bridge constructed using precast segments with wet ultra-high-performance concrete (UHPC) joints. *Case Studies in Construction Materials* **2022**, *Vol.17*, e01285, doi:10.1016/j.cscm.2022.e01285.
73. Qiu, M.; Shao, X.; et al. Flexural behavior of UHPC joints for precast UHPC deck slabs. *Engineering Structures* **2022**, *Vol.251*, 113422, doi:10.1016/j.engstruct.2021.113422.
74. Zhu, J.; Tong, X.; et al. Research on Flexural Behavior and Design Method of Uhpc Joint Without Formwork of Prefabricated Small Box Girder Bridges. *SSRN* **2023**, doi:10.2139/ssrn.4535962.
75. Chen, B.; Huang, Q.; et al. Design and Construction of the First UHPC Highway Box-Girder Bridge in China. *Journal of China & Foreign Highway* **2021**, *Vol.41*, 74-78, doi:10.14048/j.issn.1671-2579.2021.05.016.
76. Chen, Z.; Guo, F.; et al. Experiment on flexural behaviors of a segmental pre-stressed UHPC-RC composite box beam. *Journal of Fuzhou University(Natural Science Edition)* **2020**, *Vol.48*, 755-761, doi:10.7631/issn.1000-2243.19631.
77. Peng, X.; Hu, H.; et al. Research on Whole Span Prefabricated BoxGirder with Corrugated Web in Cities. *Highway* **2021**, *Vol.66*, 90-96.
78. Shao, X.; Qiu, M. Research of high performance fabricated bridge structures based on UHPC. *Journal of Xi'an University of Architecture & Technology(Natural Science Edition)* **2019**, *Vol.51*, 160-167, doi:10.15986/j.1006-7930.2019.02.002.
79. Xiao, G.; Yang, Y.; et al. Design of Prestressed RC-UHPC Simple-supported Composite Box Girder
Urban Roads Bridges & Flood Control **2023**, 89-93，102，116.
80. Zhao, M.; He, X.; et al. Research on Design and Application of Fully Prefabricated Steel-UHPC Lightweight Composite Girder in Medium and Small Span Girder Bridge. *Highway Engineering* **2019**, *Vol.44*, 63-66, doi:10.19782/j.cnki.1674-0610.2019.05.013.
81. Liu, S.; Corte, W.D.; et al. Mechanical properties of curved composite box girders with corrugated steel webs. *Steel and Composite Structures* **2021**, *Vol.41*, 65-84, doi:10.12989/scs.2021.41.1.065.
82. YEPES, V.; PEREZ-LOPEZ, E.; et al. Optimization of high-performance concrete post-tensioned box-girder pedestrian bridges(Article). *International Journal of Computational Methods and Experimental Measurements* **2019**, *Vol.7*, 118-129, doi:10.2495/cmem-v7-n2-118-129.
83. Wang, J.; Li, S.; et al. Analysis on Bearing Capacity of Large-diameter High-strength Prestressed Concrete Beams. *Journal of Shenyang Jianzhu University：Natural Science* **2019**, *Vol.35*, 411-419, doi:10.11717/j.issn:2095-1922.2019.03.04.
84. Akhnoukh, A.K. Application of large prestress strands in precast/prestressed concrete bridges. *Civil Engineering Journal (Iran)* **2020**, *Vol.6*, 130-141, doi:10.28991/cej-2020-03091458.
85. Zhan, Y.; Wang, Z.; et al. Numerical Simulation on Reasonable Clearance of Large Diameter Strands in UHPC Girder. *Railway Engineering* **2021**, *Vol.61*, 8-12，22, doi:10.3969/j.issn.1003?1995.2021.12.02.
86. Zhan, Y.; Li, Z.; et al. Bond between 0.7-inch-diameter steel strands and UHPC: Pullout test, finite element simulation, and estimation of transfer length. *Construction and Building Materials* **2024**, *Vol.417*, 135217, doi:10.1016/j.conbuildmat.2024.135217.
87. Zhan, Y.; Li, Z.; et al. Bond behavior and anchorage length of 18-mm-diameter steel strands embedded in ultra-high-performance concrete: an experimental and analytical study. *Structure and Infrastructure Engineering* **2024**, doi:10.1080/15732479.2024.2346583.
88. Fray F. Pozo-Lora , P.D., A.M.ASCE; Marc Maguire , P.D., A.M.ASCE; et al. Benchmarking the Bond of 19-Wire–28.6-mm-Diameter Prestressing Strands to Normal-Weight Concrete. *Journal of Materials in Civil Engineering* **2024**, *Vol.36*, doi:10.1061/jmcee7.Mteng-18044.
89. Tamayo, C.A.; Bahram M. Shahrooz, F.A.; et al. Performance Evaluation of Prestressed Girders with 17.8-mm (0.7-in.) Strands. *Journal of Bridge Engineering* **2023**, *Vol.28*, 04023098, doi:10.1061/jbenf2.Beeng-6300.
90. Alabdulkarim, A.; Kent A. Harries, F.A.; et al. Bond Characterization of 17.8-mm (0.7-in.) Diameter Prestressing Strand. *Journal of Bridge Engineering* **2024**, *Vol.29*, 04024013, doi:10.1061/jbenf2.Beeng-6586.
91. Zhan, Y.; Sun, C.; et al. Review on mechanical properties of retard-bonded prestressed concrete. *Concrete* **2019**, 11-13, doi:10.3969/j.issn.1002-3550.2019.05.004.
92. Ma, K.; Xu, J. Summary of research and application of retard-bonded prestressed technology. *Sichuan Building Science* **2020**, *Vol.46*, 58-62，100, doi:10.19794/j.cnki.1008-1933.2020.0037.
93. Li, D.; Li, W. Experiment on Flexural Behavior of UHPC Joint in Negative Moment Area of Composite Bridges. *Building Science* **2022**, *Vol.38*, 1-7, doi:10.13614/j.cnki.11-1962/tu.2022.01.001.
94. Zuo, Z.; Zhang, F.; et al. Research on durability of retard-bonded prestressed concrete beams. *China Civil Engineering Journal* **2019**, *Vol.52*, 69-78, doi:10.15951/j.tmgcxb.2019.09.005.
95. Shang, R.; Tian, J.; et al. Experimental study on cohesive property of steel strand in retard-bonded prestressed concrete beams. *Building Structure* **2020**, *Vol.50*, 56-60，66, doi:10.19701/j.jzjg.2020.02.010.
96. Xiong, X.; He, L.; et al. The bond-slip constitutive model of retard-bonded prestressing steel strand. *Construction & Building Materials* **2023**, *Vol.365*, 129995, doi:10.1016/j.conbuildmat.2022.129995.
97. Li, W.; Liu, Y.; et al. Experimental study on the behavior of bunched-retard-bonded prestressed concrete beams. *Building Science* **2022**, *Vol.38*, 56-63, doi:10.13614/j.cnki.11-1962/tu.2022.03.008.

98. Xiong, X.; He, L.; et al. Experimental study on flexural behavior of full-scale retard-bonded prestressed UHPC variable section cantilever beams. *Engineering Structures* **2023**, *Vol.284*, 115943, doi:10.1016/j.engstruct.2023.115943.
99. Sui, W.-N.; Wang, Z.-Y.; et al. Failure mechanism and mechanical properties of a retard-bonded prestressed concrete girder while curing(Article). *Advances in Civil Engineering* **2019**, *Vol.2019*, 1-14, doi:10.1155/2019/7153235.
100. Xiao, Q.; Xiong, X. Meso-Scale Simulations of Pull-Out Tests for Retarded Bonded Tendons. *Industrial Construction* **2021**, *Vol.51*, 28-32，39, doi:10.13204/j.gyjzg21061507.
101. Xiong, X.; Xiao, Q. Meso-scale simulation of bond behaviour between retarded-bonded tendons and concrete. *Engineering Structures* **2021**, *Vol.228*, 111410, doi:10.1016/j.engstruct.2020.111410.
102. Changhai;, Y.; Huang, S.; et al. Experimental study and finite element analysis on stress transfer mechanism of prestressed concrete beams with delayed bonding. *Concrete* **2022**, 46-50.
103. Li, L.; Mao, J.; et al. Experimental Study on Flexural Behavior of Precast Segmental UHPC Beams with External Tendons. *Journal of Hunan University:Natural Sciences* **2022**, *Vol.49*, 67-76.
104. Jiang, H.; Hu, Z.; et al. Experimental Study on Shear Behavior of Externally Prestressed Segmental UHPC Beam without Stirrup. *Journal of Highway and Transportation Research and Development* **2024**, *Vol.41*, 105-115，138.
105. Jiang, H.; Feng, J.; et al. Experimental study on shear behavior of externally prestressed ultra-high performance concrete beams without stirrups. *Acta Materiae Compositae Sinica* **2022**, *Vol.39*, 707-717, doi:10.13801/j.cnki.fhclxb.20210316.001.
106. Li, L.; Fang, Y.; et al. Experimental Study on Shear Behavior of Externally Prestressed UHPC Beams Without Stirrups. *Railway Engineering* **2024**, *Vol.64*, 67-74.
107. Feng, J.; Li, P.; et al. Shear behavior of externally prestressed UHPC beams without stirrups. *Case Studies in Construction Materials* **2023**, *Vol.18*, e01766, doi:10.1016/j.cscm.2022.e01766.

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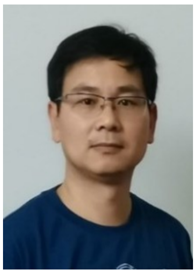

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