Design and Construction

Construction Technology and Application of Bonded Prestressed Tendons in Wind Turbine Mixed Towers

Heming Zhang and Bin Wei *

Shanghai Fengling Renewables Co., Ltd., Shanghai 200021, China
* Correspondence: weibin@flrenewables.com

Abstract: The post-tensioned bonded prestressing technology has been widely applied in wind power support structures due to its safety, reliability, economic efficiency, and durability. This paper provides a comprehensive introduction and explanation of the construction technology of post-tensioned bonded prestressed tendons based on an actual engineering case. Starting from key procedures such as construction preparation, tendon cutting and fabrication, placement of duct, tendon threading, tensioning and anchoring, and grouting and sealing, this paper details the critical points and precautions based on practical engineering experience. This work can serve as a reference for similar projects, aiming to promote the application and adoption of post-tensioned bonded prestressing technology in the wind power industry.

Keywords: wind turbine tower; post-tensioned bonded prestressing; construction technology

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1 Introduction

Prestressed concrete structures are a type of concrete structure that can be classified into pre-tensioned and post-tensioned methods based on the construction technique. Post-tensioning methods can be further divided into internal and external prestressing methods. Among them, internal prestressed concrete structures can be further subdivided into bonded and unbonded internal prestressing structures based on whether the prestressing tendons can slide relative to the concrete. Bonded internal prestressing involves the process where, after tensioning the prestressing tendons, grouting is performed to bond the prestressing steel to the concrete, achieving the goals of protecting the prestressing tendons, forming a reliable load transfer mechanism, and preventing tendon slippage. Compared to other types of prestressing, bonded internal prestressing offers advantages such as high load-bearing capacity and good durability.

The post-tensioned bonded internal prestressing technology has been widely applied in building structures, bridge structures, and special structures. Its application fields include beams, columns, nuclear containment tankers, water towers, silos, and television towers. In recent years, with the rapid development of the wind power industry, this technology has also gained significant attention and application in wind turbine towers. Due to the constraints of the construction period, wind turbine towers typically adopt a segmented prefabricated assembly structure, where post-tensioned prestressing is used to connect the segments into a whole. This paper focuses on the construction technology of post-tensioned bonded internal prestressing, taking into account the engineering characteristics of wind turbine towers and specific case studies. From the perspective of the full construction cycle, it introduces the key stages of the process, including the acceptance of foundation interfaces, tendon cutting and fabrication, placement of duct, tendon threading, tensioning and anchoring, grouting, and sealing. It also provides operational key points and risk warnings for each stage, aiming to serve as a reference and guide for similar construction technologies.

2 Construction Preparation

2.1 General

Prestressing tendon tensioning should not be performed when the ambient temperature is below -15°C. Grouting should not be conducted if the ambient temperature exceeds 35°C or if the daily average temperature remains below 5°C for five consecutive days. If grouting must be carried out under such conditions, specific measures should be adopted to ensure the construction quality.

During the tension prestressing stage, the concrete strength of the prefabricated segments, tower base, vertical seam grout, and horizontal seam grout must meet the design requirements. The compressive strength of concrete cured under the same conditions should not be less than 75% of the design strength grade value of the concrete and should also comply with the minimum strength requirements specified in the product technical manual provided by the anchorage supplier [1].

2.2 Material Preparation

Prestressing tendons can be classified by steel type into steel wires, strands, high-strength steel bars, and steel rods. The choice of prestressing tendons should consider structural stress characteristics, environmental conditions, and construction methods. Steel strands, known for their high breaking strength, good flexibility and easy construction, are commonly used as prestressing tendons in wind turbine mixed towers. A typical prestressed component is shown in Figure 1.

Anchorage devices for prestressing tendons include wedge anchorages, button head anchorages, nut anchorages, swaging anchorages, compression anchorages, knurled anchorages, cold-cast anchorages, and hot-cast anchorages. The selection of anchorage devices should be based on the type of prestressing tendons, anchorage requirements, and tensioning processes. Wedge anchorages work by clamping the wedges to create anchoring force on the tendons, providing high anchoring force, easy installation, and convenient use. Wedge anchorages are generally used at both the tensioning and anchoring ends, with anti-loosening measures applied. The grout for prestressing ducts should be cement-based, ensuring good flowability and dense grouting.

Methods for forming post-tensioned internal ducts include embedding metal corrugated pipes, plastic corrugated pipes, iron pipes, steel pipes, and core pulling to form channels. Owing to their high strength, corrosion resistance, abrasion resistance, good bonding with concrete, and strong engineering adaptability, metal corrugated pipes are commonly used in prefabricated segments of concrete towers, considering their stress characteristics and economic efficiency.

Materials and equipment used in prestressing construction and their on-site acceptance should comply with relevant regulations. For steel strands and anchorage devices, ensure their performance meets the above requirements and fatigue performance standards, supported by third-party test reports or certification. Prestressing tendons should be smooth after unfolding, without bends, surface cracks, burrs, mechanical damage, corrosion, or oil stains. Anchorage devices, wedges, connectors, and anchor bearing plates should be free from dirt, rust, mechanical damage, and cracks. The inner and outer surfaces of ducts for post-tensioned prestressing should be clean, rust-free, oil-free, free of holes and irregular wrinkles, and the seam should be free of cracks or detachment.

Figure 1 Diagram of a prestressed component

2.3 Equipment Preparation

The equipment needed for the prestressing construction phase mainly includes tensioning equipment sets (jacks, pressure devices, high-pressure oil pumps, pressure gauges, etc.), winches, manual hoists, truck cranes, manual hydraulic forklifts, guide pulleys, electric steel strand payoff racks, generators, grouting pumps, pulling heads, swaging devices, and steel strand pulleys.

The tensioning equipment must be calibrated by an authorized testing company before the tensioning construction. The testing company should create calibration curves based on the calibration results, which will be used to determine the tensioning parameters before starting the tensioning work.

2.4 Worksite Preparation

Before starting prestressing construction, construction measurements and site cleaning should be conducted (Figure 2). The age and strength of the segment and foundation concrete should be checked to ensure that they meet the design requirements. Inspection of the precast concrete segments of the tower includes, (1) Checking the quality and geometric dimensions of the precast concrete segments. (2) Before threading the tendons, ensure the prestressing ducts are clear and through-holes (Figure 3). Remove any blockages, and if there is communication with adjacent ducts, address it promptly. (3) Clean welding slag, burrs, concrete residues, and other debris from the contact areas of embedded parts, anchorages, and bearing plates [1].

Figure 2 Grooves in the interface between the foundation and concrete tower

Figure 3 Through-hole of prestress ducts

3 Fabrication and Installation

3.1 Tendon Preparation

The cutting length of the prestressing tendons should be determined through calculation, taking into account the requirements of subsequent prestressing tensioning operations. Mechanical methods such as abrasive wheel saws or cutting machines should be used for cutting. Care should be taken to avoid damage from welding slag or grounding electric sparks during the preparation or installation of the prestressing tendons [1].

3.1.1 Calculation of Steel Strand Cutting Length

When using wedge anchorages for steel strand bundles in post-tensioned prestressed concrete and steel structures, the cutting length L of the steel strand can be calculated using the following formulas (Formula 1 and Formula 2) [2]:

For single-end tensioning:

$$L = l + 2(l_1 + l_3) + l_2 \quad (1)$$

For double-end tensioning:

$$L = l + 2(l_1 + l_2 + l_3) \quad (2)$$

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where l is the length of the duct in the component, with parabolic ducts calculated based on the actual length. l_1 is the thickness of the wedge-type working anchorage. l_2 is the working length of the jack used for tensioning (including the tool anchorage). l_3 is the length of the steel strand extending beyond the anchorage at the fixed end, generally taken as 100~200 mm.

3.1.2 Fixation of the Pulling Head

After cutting the steel strands to the required length, a specific length of the six surrounding wires of each steel strand is removed. Then, using a hydraulic swaging device, the head of the central wire of the steel strand is cold-swaged into a 7.5 mm round head, see Figure 4 to Figure 6.

Figure 4 Swaging device

Figure 5 Round head center wire

Figure 6 Bundled steel strands

After swaging the single steel strand's center wire, it is fixed in the slot of the pulling head (Figure 7), and the cutting wires are wrapped with tape to ensure no sharp changes and prevent the cutting wires from scratching the duct corrugated pipe's inner wall during threading (Figure 8). Using tendon preparation equipment, the cut strands are coiled for ease of transport and installation.

Figure 7 Fixing steel strand at pulling head

Figure 8 Wrapping steel strand at pulling head

3.2 Placement of Duct

In post-tensioned bonded prestressed concrete towers, prestressed metal corrugated ducts need to be embedded in the precast concrete segments. During installation, these ducts are inserted from top to bottom within the rebar frame, where they are secured with a special positioning cone to ensure the ducts and positioning cone are tight. At the bottom, the ducts are pulled down with iron wire and tied to the rebar frame to prevent floating during construction (Figure 9). A seamless round pipe of matching size can be inserted inside the metal corrugated duct to prevent displacement and bending deformation during concrete pouring and vibration. The top of the metal corrugated duct should be 3-5 cm higher than the top surface of the segment to prevent slurry from entering the duct during segment hoisting (Figure 10). The top opening of the metal corrugated duct should be sealed to prevent concrete from entering during segment casting.

Figure 9 Fixing the bottom of the metal corrugated duct

Figure 10 Sealing the top of the metal corrugated duct

3.3 Tendon Threading

Prestressing steel strand threading can be done by arranging the entire bundle on the ground and then pulling it from bottom to top into place or threading it from the top of the tower, assembling it into a bundle within the duct. The method should be chosen based on structural characteristics, construction conditions, and schedule requirements.

Before threading, the specifications, dimensions, and quantities should be checked, and the reliability of the end assembly components should be confirmed. During threading, contact with dirt should be avoided, and plastic bending of the steel strands should be prevented. The bending radius of the strands should exceed 600 mm. Ensure no overall twisting of the bundle or individual strand twisting within the bundle.

A common threading method involves hoisting the top crane frame or cross steel beam to the top of the tower and fixing it. After arranging the winch and the guiding steel wire rope through pulleys, the steel wire rope is installed at the required threading position. All ropes and pulleys are inspected for safety before the threading operation begins.

For prestressed concrete towers, threading ducts can be embedded in the foundation. During threading, steel strands enter the foundation cavity through these ducts. A steel wire rope used as a guide line is threaded into the prestressing duct, and the pulling device fixes the steel strands. The steel wire rope pulls the entire bundle of steel strands from bottom to top through the corrugated duct, continuing until it reaches the top (Figure 11 to Figure 14). On the ground, the strands are placed on pulleys to reduce friction during pulling.

After threading, the prestressing steel strands are fixed to the anchors with wedges. The wedges are gently hammered to grip the strands tightly, ensuring that the exposed face of the wedges is uniform and the working anchor head fits into the recess of the anchor bearing plate. The lower end of the steel strand is threaded through the corresponding hole of the anchor, and wedges are installed, completing the installation of a single strand. During cable threading, attention should be given to the hole arrangement when installing limit plate and tool anchorage head plate, and the holes of anchorage head plate at upper and lower ends should correspond one by one without dislocation. Each steel strand should be installed without twisting or order errors. Repeat these steps until all ducts are threaded with steel strands.

Figure 11 Strands thread in the duct from the bottom of the tower

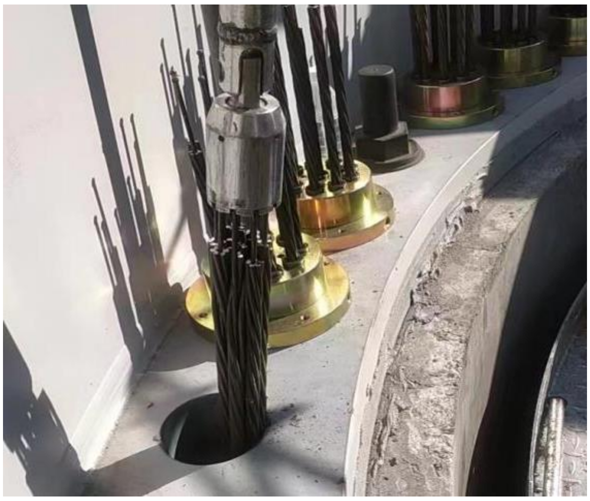

Figure 12 Strands thread out the duct from the top of the tower

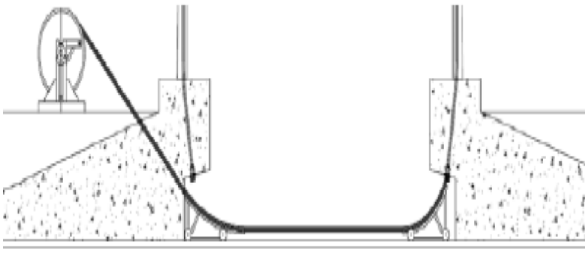

Figure 13 Strands thread in the duct from the bottom of the tower

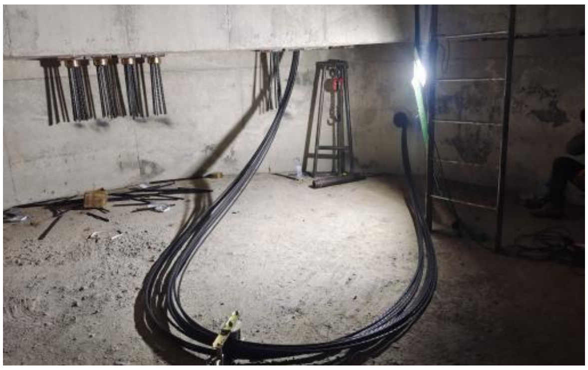

Figure 14 Strands thread in the duct from the bottom of the tower

3.4 Jack Installation

According to the design tensioning method, thread the prestressing steel strand bundle through the jack and align it with the anchor ring, ensuring that the jack and the steel strands are on the same axis (Figure 15 to Figure 17). Before tensioning, extend the jack by 2-4 cm and clamp prestressing steel strands. To facilitate the removal of pins, a small amount of lubricant can be applied to the inner wall of the tool anchor ring. Set up a safe and reliable tensioning work platform as required by the project.

Figure 15 Dead end anchorage (Top end)

Figure 16 Jack installation at the tensioning end

Figure 17 Tool anchor installation at the tensioning end

4 Prestressing Tensioning

Prestressing tensioning mainly includes the following steps: installing the working anchor head plate and working wedges, installing the limit plate, installing the jack, installing the tool anchor head plate and tool wedges, applying prestressing force (Figure 18), anchoring the prestressing tendons, returning the piston and removing the jack, and cutting off the excess steel strands.

4.1 Tensioning Procedure

Post-tensioned prestressing tendons should be tensioned either at one end or both ends according to the design and special construction plan. For two-end tensioning, it is advisable to tension both ends simultaneously, although it is also acceptable to first tension and anchor one end and then apply supplementary tension to the other end. Given the mainstream turbine blade tip clearance requirements and load levels, the crack control section generally appears at the mid-height of the concrete tower. The effective prestressing force in this section is minimally affected by the tensioning method, so adjusting the tensioning method does not significantly reduce the required amount of steel strands. Typically, single-end tensioning is used, with the tensioning end at the foundation and the fixed end at the flange of the upper steel transition section.

Post-tensioned bonded prestressing tendons usually employ bundle tensioning. For linear or parallel-arranged bonded prestressing steel strand bundles, if it can be ensured that each strand is not affected by overlapping, individual strand tensioning is also permissible. The tensioning sequence for prestressing tendons in prestressed components should follow the principles of symmetrical and alternate tensioning. During prestressing tensioning, the line of action of the jack's tensioning force should coincide with the axis of the prestressing steel strand.

Tensioning should only be carried out after the concrete has reached the design-specified strength. The tensioning of prestressing tendons should use a "dual-control method," primarily controlling by stress with elongation values as a check. Detailed records of the tensioning process must be kept to ensure tensioning quality. The tensioning force and elongation were calculated, and the oil pump pressure gauge readings were determined based on the jack calibration results.

The allowable deviation between the actual elongation and the theoretical elongation of each steel strand bundle during tensioning is ±6%. If the deviation exceeds this limit, the tensioning should be immediately stopped, the cause should be investigated, and corrective measures should be taken before continuing. During tensioning, detailed records of the tensioning force, pressure gauge readings, elongation values, anchor retraction values, and handling of any anomalies should be maintained. Stop tensioning and investigating whether any of the following conditions occur:

(1) Fracture, slippage, or breakage of prestressing steel strands or anchors;
(2) Cracking or crushing of concrete or anchor plate embedding into concrete;
(3) Unusual sounds within the duct;
(4) Insufficient elongation after achieving the required tensioning force;
(5) Insufficient tensioning force with continued elongation of the prestressing steel strands.

The prestressing tendon tensioning sequence is preferably as follows: $0 \rightarrow \sigma_{initial} \rightarrow 2\sigma_{initial} \rightarrow \sigma_{con}$ (hold for 2-5 minutes to anchor). Here, $\sigma_{initial}$ is the initial stress, and σ_{con} is the control stress. The initial stress $\sigma_{initial}$ should be 10%-25% of the tensioning control stress σ_{con}. When the initial stress was reached, the elongation measurement points were marked. Ensure uniformity in ejecting and withdrawing the jack, marking, measuring elongation, and inserting pads. The tensioning stress was precisely controlled, strictly prohibiting over-tensioning. When the stress reaches the design value and the actual elongation deviation from the theoretical value is within the specified range (not exceeding 6%), record the original tensioning data on-site. During the tensioning process, the jack stroke must not exceed the maximum allowable stroke to avoid reading errors.

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During prestressing tensioning, avoid breakage or slippage of prestressing tendons. The number of broken or slipped steel strands should not exceed the specified limits if breakage or slippage occurs.

Table 1 Limits for breakage and slippage of post-tensioned prestressing tendons

Category	Inspection Item	Control Criteria
Steel wire bundle Steel Strand Bundle	Number of broken or slipped wires per bundle	1 per bundle
	Number of broken or slipped wires per strand	1 wire
	Total percentage of broken wires per section not exceeding the total number of wires in that section	1%

The broken wires mentioned in Table 1 refer to the broken of the steel wires in a single steel strand. When the requirements in Table 1 are not met, the steel strand should be replaced in principle. When it is impossible to replace the steel strand, under the permission of the design, remedial measures can be taken, such as increasing the prestress value of other bundles, but all must meet the design requirements of the limit states in each construction stage.

Figure 18 Tensioning prestressing tendons

Figure 19 Reading hydraulic pressure gauge

4.2 *Over-Tensioning*

The control stress σ_{con} for tensioning should include losses such as anchorage bearing plate friction, duct friction, and elastic compression losses. If the friction losses at the anchorage bearing plate are not considered in the calculation of prestress losses, over-tensioning is necessary during steel strand tensioning, with the magnitude of over-tensioning equal to the friction loss value at the anchorage bearing plate. When the friction loss at the anchorage bearing plate cannot be directly measured on-site, reference values can be provided by the prestressing manufacturer. When over-tensioning of prestressing tendons is necessary during construction or when considering anchorage bearing plate stress losses, it may be increased by up to 5% compared to the design specifications. For internal prestressing tendon systems, the maximum controlled stress σ_{con} should not exceed $0.8f_{ptk}$ [4].

4.3 *Elongation of Tendons*

The actual elongation of the prestressing tendons should be measured from the initial tensioning stage. The theoretical elongation ΔL_p^c of the prestressing tendons can be calculated using Formula (3) [2]:

$$\Delta L_p^c = \sigma_{pt} \frac{[1 + e^{-(kl+\mu\theta)}]l}{2E_p} \tag{3}$$

where l is the actual length of the prestressing tendon. μ is the friction coefficient between the prestressing tendon and the duct wall. θ is the angle (in radians) from the tensioning end to the tangent of the duct section considered. k is the friction coefficient considering local deviation per meter of duct length. E_p is the elastic modulus of the prestressing tendon. σ_{pt} is the stress value after deducting the prestress loss at the anchor opening from the tension control stress σ_{con}.

For prestressing tendons composed of multiple curved or straight segments, the elongation should be calculated segment by segment and then accumulated (refer to Formula (4)).

$$\Delta L_p^c = \sum \frac{(\sigma_{i1} + \sigma_{i2})}{2E_s} L_i \tag{4}$$

where L_i is the length of the ith segment of the prestressing tendon. σ_{i1} and σ_{i2} are the stresses at the two ends of the ith segment of the prestressing tendon.

The actual cumulative elongation during tensioning, ΔL_p^o, is calculated as Formula (5).

$$\Delta L_p^o = \Delta L_{p1}^o + \Delta L_{p2}^o - a - b - c \tag{5}$$

where ΔL_{p1}^o is the measured elongation from the initial tension to the maximum tension. ΔL_{p2}^o is the estimated elongation value under initial tension, which can be determined according to the relationship between tensile force and elongation. a is the elongation of the prestressed tendon within the hydraulic jack during tensioning. b is the retraction value of the wedge after tensioning. c is the elastic compression value of the component during the tensioning stage.

During the tensioning operation, the measured elongation values are compared with the theoretically calculated values to verify whether they fall within the allowable error range.

5 Grouting and Anchorage

5.1 Grouting of Ducts

For post-tensioned concrete components with bonded prestressing tendons, after tensioning the tendons, it is necessary to fill the ducts with grout to ensure that the prestressing tendons are protected against corrosion and bonded securely with the concrete structure. Grouting should ideally commence soon after tensioning is completed, and the grout inside the ducts should be full and compact.

Figure 20 Installation grouting injection holes at the bottom tension end

Figure 21 Mixing grouting material

Before grouting, a comprehensive inspection should be conducted to ensure that the prestressing tendon ducts, grout injection holes, air vent holes, and water seepage pipes are unobstructed. High-strength cement slurry or grouting material should be used to seal any gaps in anchor wedges, bearing plate holes, or other potential leakage points. The sealing material should achieve sufficient strength before grouting

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can proceed. Water injection testing can be used to verify the sealing integrity of prestressing ducts. If leakage is found at horizontal joints or ducts, these should be sealed using epoxy resin. After sealing material has cured to a certain strength, another water injection test is conducted to ensure its effectiveness. The specific grouting process is as follows [1].

(1) Grouting should start from the lower ducts and proceed to the upper ducts.
(2) Grouting should be continuous until the grout flowing out of the air vent pipes matches the consistency at the grout injection holes and is free of bubbles. After all the air vent pipes were closed, apply pressure of 0.5 MPa to 0.7 MPa and maintain it for 1 minute to 2 minutes before sealing the grout injection holes.
(3) If significant water seepage occurs, secondary grouting should be performed, focusing on gravity grouting for seepage holes.
(4) If grouting needs to be stopped midway, pressured water is used to flush out all the cement slurry in the ducts.
(5) For extremely long or high prestressing tendon ducts, multiple grouting pumps may be used sequentially (using intermediate grout injection holes in segment joints). Grouting is carried out from the front grouting hole until the rear grouting hole gushes, and then the rear grouting hole can continue to grout, and reliable inspection measures should be adopted to ensure the compactness of grouting. After the grouting material in the grouting hole solidifies, the water seepage pipes, etc., should be cut to the surface of the component. If voids are found inside the water seepage pipes, carefully refill them with grout. If gaps are detected at grout injection points, secondary grouting and gravity grouting measures can be used for refilling.

Prestressing tendon anchors at tensioning ends should be protected with fine stone concrete or non-shrink waterproof mortar of the same strength grade as the structure. Anchorage caps should be installed at the anchors, securely connected to the main structure using bolts, and sealed appropriately.

5.2 *Anchorage Sealing Measures and Requirements*

After grouting is completed, the excess prestressed tendons are cut (Figure 22). When cutting, a grinding wheel saw should be used, electric arcs should not be used for cutting, and the anchors should not be damaged at the same time. The exposed length of the prestressing tendons after cutting should not be less than 30 mm and should be at least 1.5 times the diameter of the prestressing tendon. Anti-corrosion and rust prevention treatment should be promptly applied to exposed prestressing tendons and anchors. It is advisable to completely encase exposed prestressing tendons and anchors in concrete and pour them into a regular shape (Figure 23).

Figure 22 Cutting prestressing tensions

Figure 23 Installation anchorage caps

6 Conclusions

This article has systematically outlined the construction process of post-tensioned prestressed concrete structures used in wind turbine towers. The detailed operational steps are provided, along with insights into critical process points and risks.

With the rapid development of wind turbine generator units and blade technologies, increasingly higher demands are placed on support structures. These structures are required to possess ultra-high load-bearing capacity, fatigue resistance, and must conform to specific geometric dimensions and weight limits. In this context, concrete wind turbine towers have emerged as a solution.

Post-tensioned prestressed concrete towers, utilizing bonded prestressing tendons internally, are favored in the industry due to their advantages such as high load-bearing capacity, structural integrity, and stiffness. Moreover, internal prestressing systems can effectively utilize material strength, resulting in lower overall costs compared to external prestressing systems. Another advantage of internal prestressing systems is their excellent durability. Through duct grouting and anchorage sealing, they significantly reduce the need for post-installation inspection and maintenance, making them particularly attractive for offshore wind power projects.

However, the adoption of these systems poses challenges in prefabricated component production and prestressing construction. It is hoped that through the introduction and explanation in this article, more practitioners will understand the application of this technology in wind turbine towers. This will promote its development in the wind power industry, further enhancing the levels of design and construction.

Conflict of Interest: All authors disclosed no relevant relationships.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Wei, upon reasonable request.

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AUTHOR BIOGRAPHIES

	**Heming Zhang** M.E., Professional Engineer in Civil Engineering, State of California, USA. Research Direction: R&D of Support Structures for Wind Turbine Tower. Email: zhangheming@flrenewables.com		**Bin Wei** B.E., Engineer, Level-one Constructor. Research Direction: Wind Turbine Tower Building and Construction. Email: weibin@flrenewables.com