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Calculation Method for Prestress Loss in Post-Tensioned Bonded Prestressed Concrete Wind Turbine Towers

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Abstract: Post-tensioned bonded prestressed concrete towers have gained wide recognition and application in the wind power industry because of their excellent integrity and high load-bearing capacity. During the design process, crack verification under normal service conditions is often a controlling factor in structure design, and this verification is closely related to the calculation of prestress losses. This paper, which combines Chinese and European codes, introduces in detail the calculation method for prestress loss in internally post-tensioned structures. Additionally, the differences in the calculation methods specified in the Chinese and European codes are compared and, considering the characteristics of wind turbine towers, methods and recommendations for selecting relevant parameters are provided, with the aim of serving as a reference for the design of similar structures.

Keywords: wind turbine tower; prestress loss; code comparison; parameter selection

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1 Introduction

Prestress loss is a phenomenon in which the tensile stress in prestressing tendons decreases due to factors such as construction methods, material properties, and environmental conditions. Prestress can be categorized into losses occurring during transfer and anchoring, also known as the first batch losses or instantaneous losses, and losses after transfer and anchoring, referred to as the second batch losses or long-term losses. The instantaneous losses can be further subdivided into friction losses between the prestressing tendon and the duct, losses due to anchor deformation and wedge draw-in, and elastic compression losses of the concrete. The long-term losses include stress relaxation losses of prestressing tendons and shrinkage and creep losses of concrete [1].

Wind turbine towers in China have undergone significant transformations over more than two decades of development. In terms of structural form, we can roughly use 2021 as a turning point. Early designs used steel monopole towers as the primary support structure, whereas later developments revealed the coexistence of multiple technological routes. Bonded prestressed concrete towers (internally prestressed) have gained considerable attention within the industry because of their high load-bearing capacity, good structural integrity, and durability, and they have been widely applied in actual engineering projects [2].

The structural calculations for wind turbine hybrid towers consist of two parts: bearing capacity verification and serviceability verification. Serviceability verification includes stress verification, crack verification, and deflection verification. Owing to their high operational loads from wind turbines and generally being segmentally prefabricated and assembled structures, hybrid towers have strict requirements for crack value. The crack values are directly related to precompression, which is closely linked to the effective prestress. Effective prestress refers to the residual stress remaining after various losses are deducted from the tension stress of the prestressing tendon. Therefore, given the constant tension stress of the prestressing tendon, prestress loss is the most critical factor for crack size, and the magnitude of prestress loss often directly affects the quantity of prestressing steel required and the economic efficiency of hybrid towers. This paper introduces in detail the influencing factors, calculation methods, and parameter selection for various types of prestress losses; discusses the differences between the Chinese and European Code calculation methods in the context of hybrid towers; and offers practical suggestions with the aim of improving the accuracy of calculations for similar structures, thereby enhancing their applicability.

2 Calculation Methods for Prestress Loss

2.1 Chinese Codes

According to the "Code for Design of Concrete Structures" (GB50010—2010) [3] (hereafter referred to as the GB Code) and the "Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG 3362—2018) [4] (hereafter referred to as the JTG Code), both provide methods for calculating prestress losses.

2.1.1 Calculation of Short-term Stress Losses

(1) Stress loss due to friction between the steel strands and prestressing ducts

Wind turbine towers typically use low-relaxation steel strands for prestressing. Owing to the generally significant height of wind turbine towers, it is common practice to apply prestresses via a single-end tensioning method, with the tensioning end located at the foundation and the fixed end located at the top of the tower. Stress loss due to friction occurs during the tension process.

The method for calculating the stress loss σ_{l1} due to friction in the prestressing ducts according to the GB Code and the JTG Code is given by Equation (1):

$$\sigma_{l1} = \sigma_{con}\left(1 - e^{-(kx+\mu\theta)}\right) \tag{1}$$

where

σ_{con} represents the tension control stress of the prestress tendon at the anchorage, in MPa;

k represents the influence coefficient of local deviations per meter of the duct on friction, in m^{-1};

x represents the length of the duct from the tensioning end to the calculation section, which can be approximated by the projection length of that segment along the longitudinal axis of the member, in meters;

μ represents the friction coefficient between the prestressing steel strands and the duct wall; and

θ represents the sum of the tangential angles of the curved portions of the duct from the tensioning end to the calculation section, in radians.

For in situ prestressed hybrid towers, metal corrugated tubes are typically used as the material for the prestressing ducts. The values of the coefficients k and μ according to the GB Code and the JTG Code are shown in Table 1.

Table 1 Values of coefficients k and μ according to the GB code and JTG code

Code	k (m^{-1})	μ (radians)
GB Code	0.0015	0.25
JTG Code	0.0015	0.20~0.25

(2) Stress losses due to anchor deformation, prestressing tendon draw-in, and joint compression

From the base to the top of the tower, the prestressing corrugated tubes are not straight lines but may involve bends, so the steel strands should be considered curved or zigzag lines. Therefore, the prestress loss due to reverse friction must be considered, as shown in Figure 1.

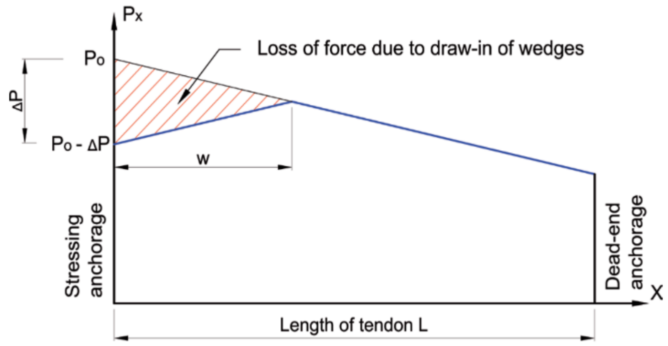

Figure 1 Schematic of the prestress loss calculation considering reverse friction

The formulas in Appendix J of the GB Code and Appendix G of the JTG Code are identical, with only slight differences in parameter values. According to Figure 1, the calculation method for the reverse friction influence length l_f is given by Equation (2).

$$l_f = \sqrt{\frac{\Sigma\Delta l \cdot E_p}{\Delta\sigma_d}} \tag{2}$$

where

$\Sigma\Delta l$ represents the sum of the deformation of the anchor at the tensioning end and the draw-in value of the prestressed tendon, in m;

E_p represents the elastic modulus of the prestressed tendon; and

$\Delta\sigma_d$ denotes the prestress loss per unit length caused by friction, representing the overall gradient of prestress, which is calculated via Equation (3).

$$\Delta\sigma_d = \frac{\sigma_{con} - \sigma_l}{l} \tag{3}$$

where

σ_{con} represents the controlled stress at the tensioning end, in MPa;

σ_l represents the residual anchorage stress of the prestressed tendon after accounting for friction losses along the duct, in MPa; and

l represents the distance from the tensioning end to the anchorage.

Since the hybrid tower is tall and the prestressing steel strands are long, the calculated length l_f is generally less than l, i.e., $l_f < l$. The formula for calculating the prestress loss $\sigma_{l2}(x)$ at distance x from the jacking end while considering reverse friction is given by Equations (4-1) and (4-2).

$$\sigma_{l2}(x) = \Delta\sigma \frac{l_f - x}{l_f} \tag{4-1}$$

$$\Delta\sigma = 2\Delta\sigma_d l_f \tag{4-2}$$

(3) Elastic shortening

The cross-section of the hybrid tower is generally annular, with metal corrugated tubes uniformly distributed along the annular section. After the steel strands are placed, tensioning can begin. Tensioning is performed on 1 or 2 bundle tendons (symmetrically) at a time, with the tensioning method being overall tensioning. The first bundle tendon experiences the maximum elastic stress loss, whereas the last bundle tendon experiences the minimum elastic stress loss.

According to the GB Code, when the prestressing tendons of post-tensioned members are tensioned in batches, the effects of the subsequent batch of tensioned tendons on the elastic compression or elongation of the previously tensioned tendons of the concrete should be considered. The formula for calculating the elastic

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compression loss of each batch of prestressing tendons is given by Equation (5-1). In Appendix H of the JTG Code, the average elastic compression loss of each strand bundle is calculated via Equation (5-2).

$$\sigma_{l3i} = \alpha_{EP} \Delta\sigma_{pci} \tag{5-1}$$

$$\sigma_{l3} = \frac{m-1}{2} \alpha_{EP} \Delta\sigma_{pc} \tag{5-2}$$

where

m represents the number of prestressing steel strand bundles;

α_{EP} represents the ratio of the elastic modulus of the steel strands to that of the concrete;

$\Delta\sigma_{pci}$ represents the normal stress in the concrete at the centroid of the prestressing tendons due to the tensioning of the subsequent batch of prestressing tendons; and

$\Delta\sigma_{pc}$ represents the normal compressive stress in the concrete at the centroid of the prestressing tendons in the calculation section due to the tensioning of one bundle of prestressing tendons, taking the average value of each bundle, with the stress of the steel tendons being the prestress after deducting the frictional losses and reversing frictional losses.

2.1.2 Calculation of Long-term Stress Losses

(1) Prestressing steel strand relaxation loss

The method for calculating the relaxation loss of low-relaxation steel strands in the GB Code is related to the controlled stress during tensioning, as shown in Equation (6), where f_{ptk} is the tensile strength standard value of the prestressed tendons.

$$\sigma_{l4} = \begin{cases} 0, & \sigma_{con} \le 0.5 f_{ptk} \\ 0.125\left(\sigma_{con}/f_{ptk} - 0.5\right)\sigma_{con}, & 0.5 f_{ptk} < \sigma_{con} \le 0.7 f_{ptk} \\ 0.2\left(\sigma_{con}/f_{ptk} - 0.575\right)\sigma_{con}, & 0.7 f_{ptk} < \sigma_{con} \le 0.8 f_{ptk} \end{cases} \tag{6}$$

The method for calculating σ_{l4} in the JTG Code is related to the tensioning method and the relaxation coefficient, and the calculation formula is as follows:

$$\sigma_{l4} = \psi \cdot \zeta (0.52 \frac{\sigma_{pe}}{f_{ptk}} - 0.26) \sigma_{pe} \tag{7}$$

where

ψ represents the tension coefficient, $\psi = 1.0$ for single tensioning, and $\psi = 0.9$ for over-tensioning;

ζ represents the relaxation coefficient of the steel strand, $\zeta = 1.0$ represents ordinary relaxation (Grade I), and $\zeta = 0.3$ represents low relaxation (Grade II); and

σ_{pe} represents the stress of the prestressing steel strand at the anchorage, which can be taken as the prestress after short-term stress loss.

(2) Prestress losses due to concrete shrinkage and creep

Since the hybrid tower usually has a bidirectional symmetric section and the applied loads are random, the section does not distinguish between the compression zone and the tension zone. The reinforcement and prestressing steel strands are uniformly distributed, and their centroids coincide with the centroid of the section. Thus, the effect of eccentricity between the strands and the reinforcement on prestress loss does not need to be considered.

In the GB Code, the method for calculating σ_{l6} is as follows:

$$\sigma_{l6} = \frac{0.9 \alpha_{EP} \sigma_{pc} \varphi_{\infty} + E_P \varepsilon_{\infty}}{1 + 15\rho} \tag{8}$$

where

σ_{pc} represents the normal compressive stress in the concrete due to prestress and the self-weight of the tower, considering only short-term stress losses;

φ_∞ represents the ultimate creep coefficient of the concrete, which is related to the concrete strength, annual average humidity, and thickness of the tower wall; and

ε_∞ represents the ultimate shrinkage strain of the concrete, which is related to the concrete strength, annual average humidity, and thickness of the tower wall.

In the JTG Code, the method for calculating σ_{l6} is as follows:

$$\sigma_{l6}(t,t_0)=\frac{0.9\left[E_P\varepsilon_{cs}(t,t_0)+\alpha_{\mathrm{EP}}\sigma_{\mathrm{pc}}\varphi(t,t_0)\right]}{1+15\rho} \tag{9-1}$$

$$\rho=\frac{A_P+A_s}{A} \tag{9-2}$$

where

$\sigma_{l6}(t,t_0)$ represents the prestress loss due to concrete shrinkage and creep at the centroid of all longitudinal reinforcing bars, which is a function of the calculation time t (in days) and the loading time t_0;

σ_{pc} represents the normal compressive stress in the concrete at the centroid of all longitudinal reinforcing bars due to prestress, considering only short-term stress losses;

E_P represents the elastic modulus of the prestressing steel strands;

α_{EP} represents the ratio of the elastic modulus of the steel strands to that of the concrete;

ρ represents the longitudinal reinforcement ratio;

A represents the cross-sectional area of the member, and for post-tensioned members such as hybrid towers, the net cross-sectional area should be used;

A_P, A_s represent the areas of the prestressed tendons and reinforcement bars, respectively;

$\varepsilon_{cs}(t,t_0)$ represent the concrete shrinkage strain at age t when the prestressing steel strands are tensioned at age t_0, which is related to the concrete strength, annual average humidity, and thickness of the tower wall; and

$\varphi(t,t_0)$ represents the creep coefficient of the concrete at loading age t_0 and calculation age t, which is related to the concrete strength, annual average humidity, and thickness of the tower wall. The effects of fly ash on creep should also be considered.

2.2 *European Codes*

The method for calculating prestress losses is based on the provisions specified in the European concrete code EN 1992-1-1 [5] (hereafter referred to as the EN Code).

2.2.1 Calculation of Short-term Stress Losses

(1) Friction losses between steel strands and prestressing ducts

The method for calculating friction losses in the EN Codes is essentially the same as that in the Chinese codes, as shown in Equation (10):

$$\sigma_{l1}\ =\ \sigma_{con}\left(1-e^{-\mu(\theta+kx)}\right) \tag{10}$$

The form of the equation is similar to that in the Chinese codes, and the meanings of parameters μ, θ, k, and x are consistent. The values of these parameters for the bonded prestressed tendons of hybrid towers are listed in Table 2.

Table 2 Values of the coefficients k and μ according to EN 1992-1-1

Code	k (m^{-1})	μ (radians)
EN Code	0.005~0.01	0.19

(2) Losses due to anchor deformation, prestressing steel strand draw-in, and joint compression

Although the EN Codes mention this, they do not directly provide a method for calculating this prestress loss. The calculation can be performed based on the draw-in values provided by the manufacturer, following the principle of equal positive and reverse friction [6].

(3) Elastic compression loss

The method for calculating elastic compression losses in the EN Code is consistent with that in the JTG Code.

2.2.2 Calculation of Long-term Stress Losses

In the EN Code, the prestress losses due to relaxation of the steel strands and those due to concrete shrinkage and creep are combined into a single formula, as shown in Equation (11):

$$\sigma_{p,c+s+r} = \frac{\varepsilon_{\mathrm{cs}}(t,t_0)E_P + 0.8\Delta\sigma_{\mathrm{pr}} + \dfrac{E_P}{E_{\mathrm{cm}}}\varphi(t,t_0)\cdot\sigma_{c,\mathrm{QP}}}{1+\dfrac{E_P}{E_{\mathrm{cm}}}\dfrac{A_P}{A_c}(1+\dfrac{A_c}{I_c}z_{\mathrm{cp}}^2)[1+0.8\varphi(t,t_0)]} \tag{11}$$

where

$\sigma_{p,c+s+r}$: the prestress loss due to concrete shrinkage, creep, and relaxation at location x at time t (days);

$\varepsilon_{\mathrm{cs}}(t,t_0)$: the total shrinkage strain from t_0 to t, consisting of the drying shrinkage strain and autogenous shrinkage strain;

E_P: elastic modulus of the prestressing steel strand;

$\Delta\sigma_{\mathrm{pr}}$: the absolute value of the variation in stress in the tendons at location x, at time t, due to the relaxation of the prestressing steel;

$\varphi(t,t_0)$: the creep coefficient at time t and load application at time t_0;

$\sigma_{c,\mathrm{QP}}$: the stress in the concrete under initial prestress, self-weight, and quasipermanent loads, where the initial prestress can be taken as the prestress after short-term stress loss;

A_P: the area of the tendons at location x;

A_c: the area of the concrete section;

I_c: the second moment of the area of the concrete section; and

z_{cp}: the distance between the center of gravity of the concrete section and the tendons.

Since the concrete tower section is bilaterally symmetrical and the prestressing steel strands are uniformly distributed, the effect of eccentricity on the prestress loss is generally not considered.

3 Comparison and Discussion

This section discusses the differences in prestress losses according to the Chinese codes (GB Code and JTG Code) and the EN Code from the perspectives of short-term and long-term stress losses.

3.1 Comparison of Short-term Stress Losses

(1) Comparison of friction loss

The formulas for calculating friction loss in various codes are very similar, with differences, primarily in the selection of parameters. When written in a uniform format (refer to Equation (1)), if steel strands and metal corrugated tubes are used, the parameter selections for different codes are as follows:

Table 3 Values of the coefficients k and μ for different codes

Code	k (m^-1^)	μ (radians)
GB Code	0.0015	0.25

Code	k (m^{-1})	μ (radians)
JTG Code	0.0015	0.20~0.25
EN Code	0.00095~0.0019	0.19

(2) Comparison of prestress losses due to anchor deformation, steel strand draw-in, and joint compression

The methods for calculating these prestress losses in various codes are almost identical, with differences in the selection of parameters.

(3) Comparison of prestress losses due to elastic shortening of concrete

The principles are the same across codes and involve the calculation of concrete strain under prestress and the computation of the elastic compression loss of the prestressing steel strands based on the principle of deformation compatibility. However, the GB Code calculates the loss for a single strand of prestressing steel, whereas the JTG Code and the EN Code calculate the average loss for all strands of steel strands.

3.2 Comparison of Long-term Stress Losses

In this section, we discuss the differences in the calculation methods for long-term prestress losses between the Chinese codes (GB Code and JTG Code) and the EN Codes by comparing key parameters and overall formulas.

3.2.1 Creep and Shrinkage Strain of Concrete

The creep coefficient φ and shrinkage strain ε_{cs} are key parameters for calculating long-term losses. Both the GB Code and the EN Code use similar methods to calculate φ and ε_{cs}, with the JTG Code referring to the CEB-FIP Code. Although the formulas are different, the influencing factors are the same, including the ambient relative humidity, cross-sectional thickness, concrete strength class, and amount of fly ash used. In practical engineering, the cross-sectional thickness and concrete strength class are relatively fixed, but the ambient relative humidity has a greater impact on the calculation results of φ and ε_{cs}.

Assuming a concrete strength class of C80 (Chinese standard), a cross-sectional thickness of 300 mm, and ambient relative humidity ranging from 60% to 85%, we can plot the relationship curves between the creep coefficient φ and time history and between the shrinkage strain ε_{cs} and time history based on the EN Code/GB Code and the JTG Code from the time of loading to a duration of 10 years (loading time $t_0 = 28$ days and curing time of 3 days). These relationships are shown in Figures 2 and 3, respectively.

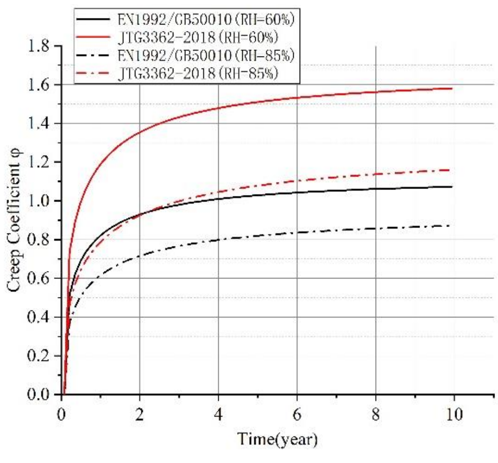


Figure 2 Relationship curve of creep coefficient φ over time according to EN/GB Code and JTG Code

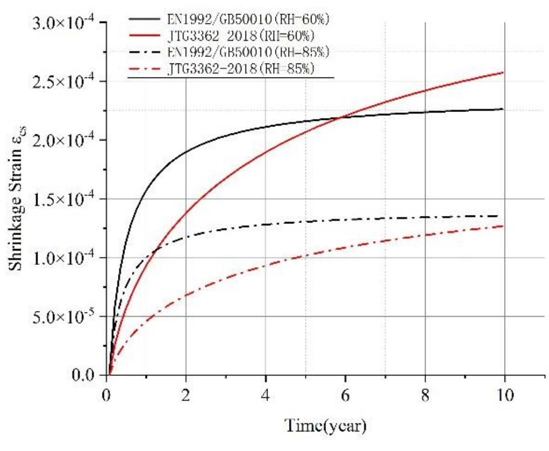


Figure 3 Relationship curve of shrinkage strain ε_{cs} over time according to EN/GB Code and JTG Code

Table 4 shows the creep coefficient φ and shrinkage strain ε_{cs} of concrete over a 10-year period under two different ambient relative humidity conditions.

Table 4 Results of the φ and ε_{cs} Calculations

Code	φ		ε_{cs}	
	RH=60%	RH=85%	RH=60%	RH=85%
EN/GB Code	1.07	0.87	2.26E-4	1.36E-4
JTG Code	1.58	1.16	2.57E-4	1.27E-4

Figure 3 shows that the concrete shrinkage strain calculated according to EN1992-2-1 develops faster than that calculated via the JTG Code. By the end of the 10-year period, the curve calculated by EN1992-2-1 has already become smooth, and ε_{cs} approaches its final value, whereas the curve calculated by the JTG Code still has a larger slope, and ε_{cs} continues to increase rapidly.

Figure 2 and Table 4 indicate that the creep parameters calculated via the JTG Code are larger than those calculated via EN1992-2-1 and are more sensitive to changes in humidity. The JTG Code introduces a correction factor $\varphi_{(\alpha,t_0)}$ to characterize the effect of fly ash content on concrete creep, as shown in Equations (12-1), (12-2), and (12-3).

$$\varphi(\alpha,t_0)=\beta(\alpha)\cdot\gamma(\alpha,t_0) \tag{12-1}$$

$$\gamma(\alpha,t_0)=[1.451-1.689\times t_0^{-0.360}\times(1+\alpha)^{0.416}]^{-0.5} \tag{12-2}$$

$$\beta(\alpha)=1-1.0273\alpha^{0.4218} \tag{12-3}$$

where α is the amount of fly ash incorporated and t_0 is the prestressed loading age.

When the fly ash content is 10%, let us plot the creep coefficient φ versus time considering the effect of $\varphi_{(\alpha,t0)}$ and compare it with the previous curves, as shown in Figure 4. When 10% fly ash is considered, the creep coefficient φ at 10 years decreases from 1.58 to 0.96, a reduction of 40%, indicating a significant effect.

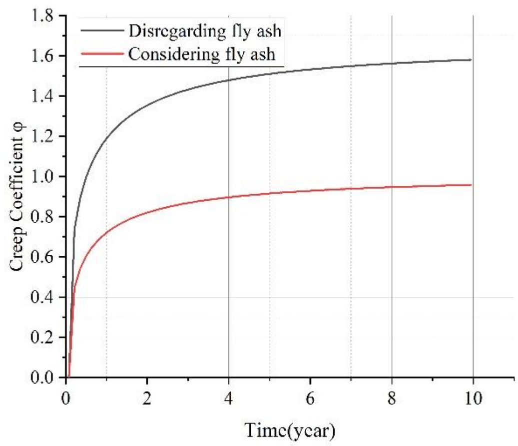


Figure 4 Effect of fly ash on the φ of the creep coefficient

3.2.2 Calculation of the Relaxation Stress

The methods for calculating relaxation stress in prestressed strands differ among the GB Code, JTG Code, and EN Code. The calculation methods according to the GB Code and JTG Code are given by Equations (6) and (7). For low-relaxation prestressing strands, the method for calculating the prestress relaxation loss according to the EN Code is shown in Equation (13):

$$\frac{\Delta\sigma_{pr}}{\sigma_{pi}}=0.66\rho_{1000}e^{9.1\mu}(\frac{t}{1000})^{0.75(1-\mu)}10^{-5} \tag{13}$$

where

$\Delta\sigma_{pr}$ represents the absolute value of relaxation stress;

ρ_{1000} represents the percentage of tendon relaxation after 1000 hours at an average temperature of 20 °C, which is related to the type of prestressing tendon, for low-relaxation strands, $\rho_{1000} = 2.5(\%)$;

σ_{pi} represents the prestress after short-term stress loss in posttensioning;

t represents the time elapsed after tensioning (hours); and

$\mu = \sigma_{pi}/f_{ptk}$, where f_{ptk} is the characteristic ultimate tensile strength of the prestressing tendon.

A comparison of the formulas for calculating relaxation losses according to the GB Code, JTG Code, and EN Code reveals that the prestress relaxation losses of prestressing strands are related to the tension control stress and the relaxation coefficient in all codes. However, the GB Code calculation method does not consider short-term losses. The EN Code also provides a function for the relationship between relaxation loss and time.

3.2.3 Comparison of Complete Calculation Formulas

The formulas for long-term losses according to the GB Code, JTG Code, and EN Code are listed in Table 5.

Table 5 Comparison of long-term stress loss calculation formulas

Code	Prestressing Strand Relaxation	Shrinkage and Creep
GB Code	$\sigma_{l4} = 0.2(\sigma_{\mathrm{con}}/f_{\mathrm{ptk}} - 0.575)\sigma_{\mathrm{con}}$	$\sigma_{l6} = \dfrac{0.9\alpha_{\mathrm{EP}}\sigma_{\mathrm{pc}}\varphi_{\infty} + E_P\varepsilon_{\infty}}{1+15\rho}$
JTG Code	$\sigma_{l4} = \psi \cdot \zeta(0.52\dfrac{\sigma_{pe}}{f_{\mathrm{ptk}}} - 0.26)\sigma_{pe}$	$\sigma_{l6}(t,t_0) = \dfrac{0.9\left[E_P\varepsilon_{cs}(t,t_0) + \alpha_{\mathrm{EP}}\sigma_{\mathrm{pc}}\varphi(t,t_0)\right]}{1+15\rho}$
EN Code	$\sigma_{p,c+s+r} = \dfrac{\varepsilon_{\mathrm{cs}}E_P + 0.8\Delta\sigma_{\mathrm{pr}} + \dfrac{E_P}{E_{\mathrm{cm}}}\varphi(t,t_0)\cdot\sigma_{c,\mathrm{QP}}}{1+\dfrac{E_P}{E_{\mathrm{cm}}}\dfrac{A_P}{A_c}(1+\dfrac{A_c}{I_c}z_{\mathrm{cp}}^2)[1+0.8\varphi(t,t_0)]}$	

Note: In actual engineering, the tension control stress σ_{con} of the hybrid tower is generally no less than $0.7f_{\mathrm{ptk}}$. Therefore, the formula for the prestressing strand relaxation loss in the GB Code listed in this table only covers the case in which $0.7f_{\mathrm{ptk}} < \sigma_{\mathrm{con}} < 0.8f_{\mathrm{ptk}}$.

As shown in Table 5, the formulas for calculating prestress losses due to concrete shrinkage and creep are largely similar among the JTG Code, GB Code, and EN Code, all of which consider the influence of the reinforcement ratio on the prestress loss of the tower wall.

However, there are differences. The EN Code integrates the prestressing strand relaxation loss and the prestress loss due to concrete shrinkage and creep. The JTG Code considers a reduction factor of 0.9 for shrinkage and creep, whereas the GB Code only reduces the creep coefficient by 0.9. The EN Code adds a term $[1 + 0.8\varphi(t,t_0)]$ in the denominator to reduce the result. Additionally, the formula in the EN Code includes a reduction factor of 0.8 for tendon relaxation to account for the effects of concrete shrinkage and creep on prestress relaxation loss.

3.3 Case Study Analysis

This section uses a prestressed wind turbine hybrid tower as a case study to calculate its prestress losses according to the GB Code, JTG Code, and EN Code. The concrete strength grade of the hybrid tower is C80 (Chinese standard), with a height of approximately 150 m, and the prestress tensioning end is located at the foundation, whereas the fixed end is at the top of the tower. The effective prestress curves of the prestressing strands are calculated separately for environments with ambient relative humidities RH=60% and RH=85%, as shown in Figure 5 and Figure 6, respectively.

An analysis of the data in Figures 5 and 6 reveals that the results from the three codes are similar. Within the more common range of humidities, the results of the concrete code are the most conservative, those of the EN Code are the most aggressive, and those of the JTG Code fall in between those of the other methods. When the ambient relative humidity increases from 60% to 85%, the calculation results of the JTG Code and EN Code become closer.

To further analyze the differences between the codes, the calculated short-term prestress losses under RH=60% conditions are compared, as shown in Figure 7.

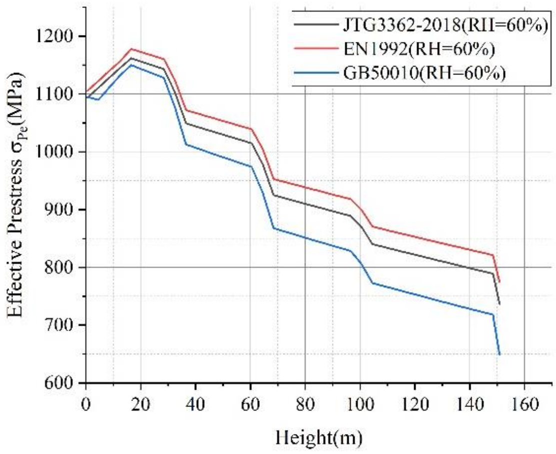


Figure 5 Effective Prestress Calculation Results (RH=60%)

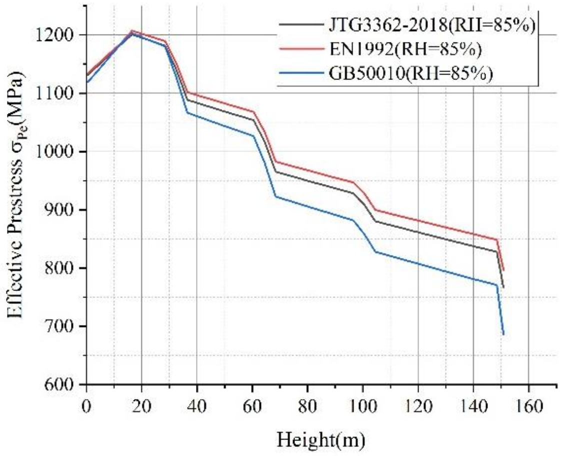


Figure 6 Effective Prestress Calculation Results (RH=85%)

An analysis of the data in Figure 7 reveals that the calculation results for short-term prestress losses are relatively similar among the codes. The results of the GB Code are the most conservative, and those of the EN Code are the most aggressive. The reason is that short-term prestress losses are mainly friction losses of the prestressing strands, and the GB Code uses the most conservative values for friction parameters, as shown in Table 3.

Further analysis of the long-term loss calculation results involves breaking down the long-term losses into prestressing strand relaxation losses and prestress losses due to concrete shrinkage and creep, respectively, as shown in Figures 8 to 10.

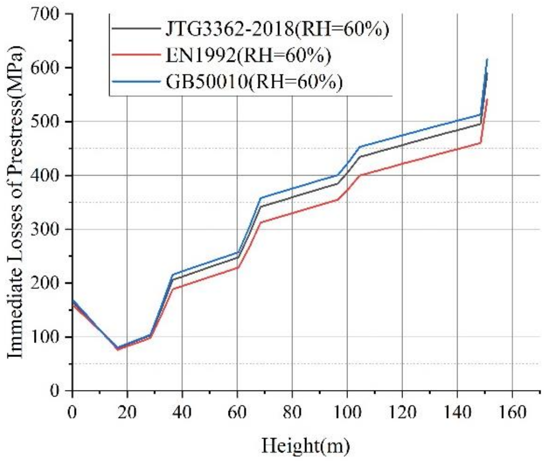


Figure 7 Short-term prestress loss calculation results (RH=60%)

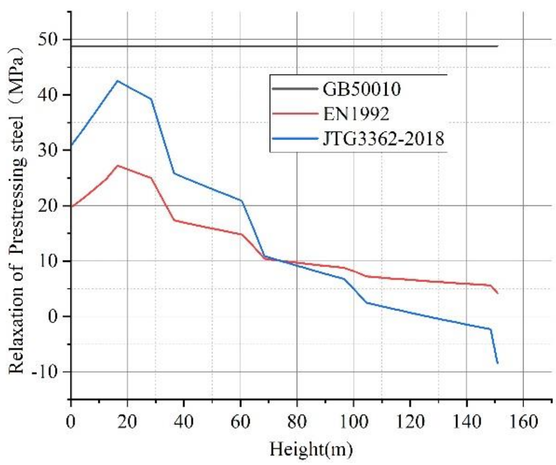
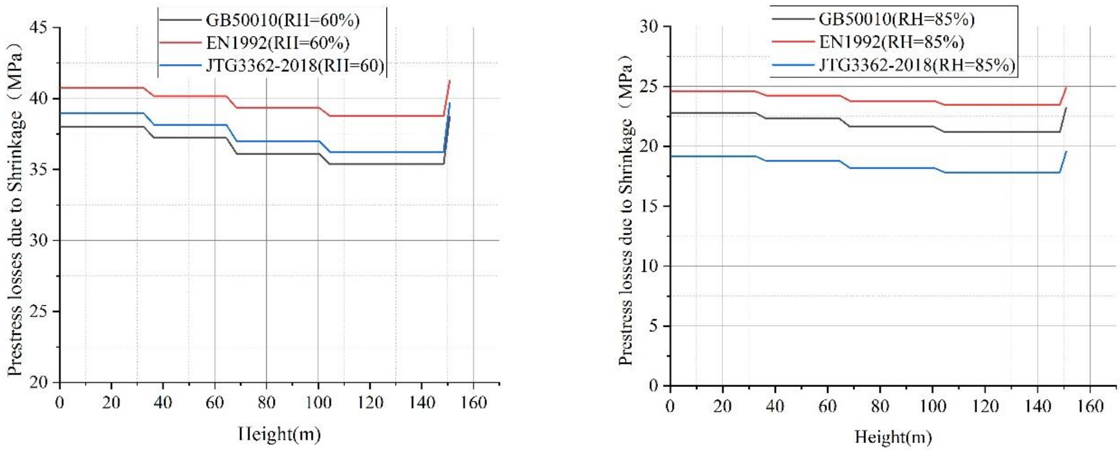
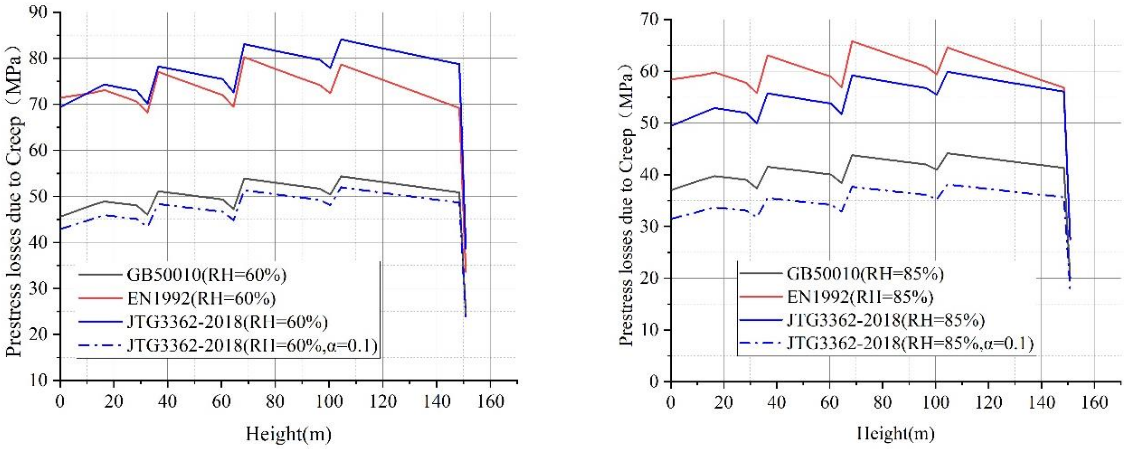


Figure 8 Comparison of prestressing strand relaxation loss calculation results



a) relative humidity RH=60% b) relative humidity RH=85%

Figure 9 Comparison of prestress loss due to concrete shrinkage



a) relative humidity RH=60% b) relative humidity RH=85%

Figure 10 Comparison of prestress loss due to concrete creep

An analysis of the prestress loss due to concrete shrinkage calculated by each code, as shown in Figure 9, reveals that the results from all three codes are similar. The EN Code is the most conservative. As shown in Table 4, when RH=60%, the concrete shrinkage strain ε_{cs} of the EN Code is smaller than that of the JTG Code. One reason why the EN Code still has the most conservative results is that it does not consider a reduction factor of 0.9 as the JTG Code does. Additionally, the effect of the reinforcement ratio in the denominator of the formulas of the JTG Code and GB Code is greater. Notably, the results of the JTG Code are more affected by the ambient relative humidity than are those of the other two codes.

An analysis of the prestress loss due to concrete creep calculated by each code, as shown in Figure 10, reveals that the calculation results of the EN Code and JTG Code are relatively similar, whereas the results of the GB Code are the most aggressive. As shown by the data in Table 4, under general humidity conditions, the concrete creep coefficient φ of the EN Code/GB Code is smaller than that of the JTG Code, but the calculation results of the EN Code and JTG Code are still relatively close. The reason is that the JTG Code and GB Code consider a reduction factor of 0.9 for concrete creep, and the effect of the reinforcement ratio in the denominator is greater. The JTG Code can also consider the influence of fly ash content. When the fly ash content is $\alpha = 0.1$, the calculation results of the JTG Code decrease significantly.

4 Design Recommendations

On the basis of the comparisons and calculation results presented in Section 3, as well as the analysis of various codes, recommendations for the calculation of prestress losses in bonded prestressed hybrid towers are provided, with a focus on both short-term and long-term prestress losses.

Recommendations for short-term stress loss calculation: The methods for calculating short-term prestress losses are broadly similar across the GB Code, JTG Code, and EN Code. The GB Code yields the most conservative results for prestress friction losses.

Recommendations for long-term stress loss calculations:

(1) With respect to prestressing strand relaxation losses, since short-term prestress losses constitute a significant proportion, the calculation method of the GB Code may yield larger deviations. When using the JTG Code method, one should pay attention to its applicable conditions. Compared with the GB Code and JTG Code, the EN Code additionally considers the effects of concrete shrinkage and creep on prestress relaxation losses.

(2) With respect to prestress losses due to concrete shrinkage, the results from all three codes are relatively similar and can all be adopted. Notably, the JTG Code method is more sensitive to changes in ambient relative humidity than the other two codes are.

(3) With respect to prestress losses due to concrete creep, if the effect of fly ash content is not considered, the results from the EN Code and JTG Code are closest and most conservative; thus, either the EN Code or JTG Code is recommended. If the concrete contains fly ash, the JTG Code is recommended to leverage the beneficial effects of fly ash, thereby reducing the usage of prestressing strands and enhancing the economic efficiency of the structure.

5 Conclusions

This paper introduces methods for calculating various prestress losses in bonded prestressed hybrid towers. By combining case studies, examples were provided following Chinese and European codes, and the sources of differences were analyzed. With the arrival of the era of cost-parity in the wind power industry, the trend toward larger wind turbines is irreversible. In addition to the increase in turbine size, greater demands are placed on supporting structures. Traditional steel tube towers are no longer sufficient to meet the development needs of wind turbine generators, leading to the emergence of hybrid towers. Bonded prestressed hybrid towers have gained industry attention and recognition because of their integrity, safety, and durability. It is hoped that through this paper, more practitioners will gain a better understanding of a key factor to consider in design calculations—the method for calculating prestress losses—thus deepening their understanding of the codes and promoting wider and more reliable application of such hybrid towers.

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, Han, upon reasonable request.

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